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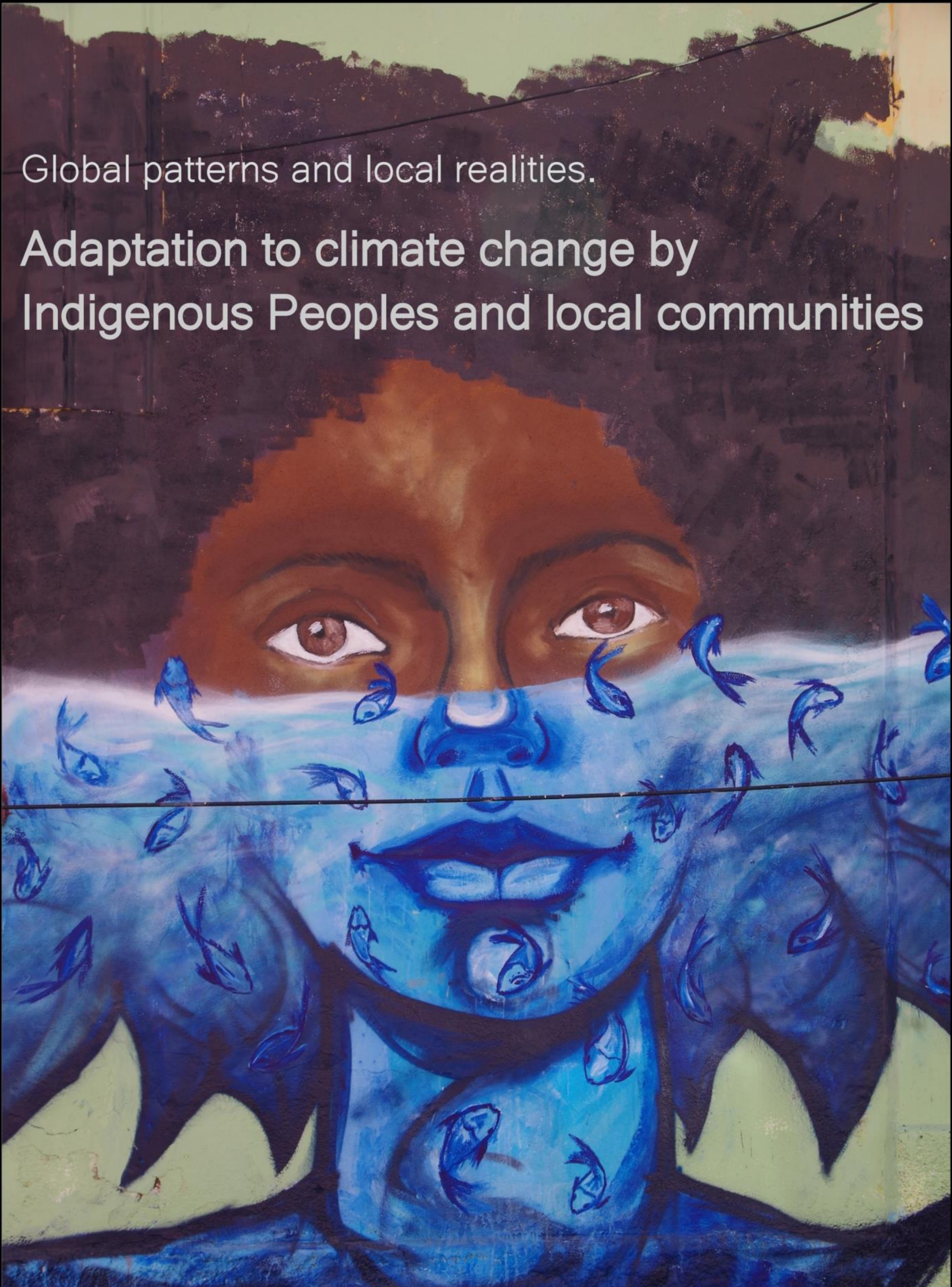

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Global patterns and local realities.

Adaptation to climate change impacts by Indigenous Peoples and local communities

PhD Thesis

Anna Schlingmann

Directed by:

Dr. Victoria Reyes-García

Dr. Katharina Waha

PhD Programme in Environmental Science and Technology
Institut de Ciència i Tecnologia Ambientals, ICTA
Universitat Autònoma de Barcelona, UAB
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“The first scenario involves sweeping global action to lower greenhouse emissions, led by nations and other privileged parties and influencers. Yet, without respecting the relational qualities of consent, trust, accountability, and reciprocity, the implementation of the solutions harms indigenous peoples widely, whether through displacement, land dispossession, unfair payment schemes and employment practices, exclusion from markets, or denial of indigenous agency in planning and leadership [...]

The second scenario is that nations and other privileged parties and influencers seek to first establish and repair the qualities of consent, trust, accountability, and reciprocity. Yet the time it takes to do so unfolds slowly, meaning that curbing emissions takes longer because key projects take more time to get off the ground. While in this scenario indigenous peoples eventually have relationships with other societal institutions that are conducive to justice-oriented coordination, there is nonetheless a 2ºC rise, leading to risky environmental disturbances, whether to indigenous peoples or others [...]”

(Whyte, 2020)

The thesis was submitted in fulfilment of the requirements of the PhD Programme at the Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona (ICTA-UAB) in February, 2024.

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First director & tutor:

Dr. Victoria Reyes-García

Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona (ICTA-UAB), 08193 Cerdanyola del Vallès, Barcelona, Spain; Institució Catalana de Recerca i Estudis Avançats (ICREA), 08010 Barcelona, Spain.

Second director:

Dr. Katharina Waha

Centre for Climate Resilience, University Augsburg, 86159 Augsburg, Germany.

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Contents

Main acronyms and abbreviations

CCI	Climate Change Impact index
CCA	Climate Change Adaptation index
CMIP6	Coupled Model Intercomparison Project phase 6
COP	Conference of the Parties
FAIR	Findable, Accessible, Interoperable, Re-usable
FPIC	Free Prior and Informed Consent
GHG	Greenhouse gasses
ICTA	Institut de Ciència i Tecnologia Ambientals
ILK	Indigenous and Local Knowledge
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IP	Indigenous Peoples
LACCI	Local Adaptation to Climate Change Impacts
LC	Local communities
LICCI	Local Indicator of Climate Change Impacts
NAP	National Adaptation Plan
NGO	Non-government organization
SSP	Shared Socioeconomic Pathway
RCP	Representative Concentration Pathways
UAB	Universitat Autònoma de Barcelona
UN	United Nations
UNFCCC	United Nation Framework Convention on Climate Change

Summary

This PhD thesis contributes to the still neglected but gradually growing research field of climate change adaptation among Indigenous Peoples and local communities. Anthropogenic global warming results in many local impacts that affect nature-dependent communities. To secure livelihood, income, food, water, and general well-being, Indigenous Peoples and local communities across the globe need to adapt and increase their resilience against experienced and expected adverse climate change impacts. However, manifold constraints hamper adaptation implementation. This thesis addresses the question of vulnerability and resilience among Indigenous Peoples and local communities in the context of climate change adaptation. Specifically, it addresses the threats and challenges they encounter and the opportunities ahead for Indigenous and local knowledge-based adaptation.

This work was conducted under the framework of the Local Indicators of Climate Change Impacts (LICCI) project (http://www.licci.eu), which builds on a global network of researchers to assess local climate change impacts and adaptation strategies among Indigenous Peoples and local communities. The thesis includes four empirical chapters structured in three parts addressing the following overarching topics: i) the need for adaptation (Chapter 2), ii) the nature of local adaptation (Chapter 3 and 4), and iii) the challenges for adaptation (Chapter 5).

In Chapter 2, I provide a method to detect current and future hotspots of potential climate change risks, which may provide important insights for adaptation planning. The results of the chapter build on a mixed-method approach that jointly interpret primary data from 16 sites, including 2,676 individual and 1,971 household surveys, and -for each site- secondary meteorological data on past and projected temperature changes. The method proposed uses local reports of climate change impacts on local livelihoods and well-being to estimate climate change sensitivity and to detect climate change risk hotspots. The findings show that the 16 sites differ significantly with respect to past and potential future changes in temperature, climate sensitivity, and adaptation implementation rates, resulting in the detection of five potential climate change risk hotspots.

In Chapter 3, I document global patterns of adaptive responses locally implemented by Indigenous People and local communities. The analysis draws on a systematic review of 119 peer-re-viewed scientific publications from 2015 to 2019. I document a total of 1,851 adaptive responses to local climate change impacts across different climates and main livelihood activities, and classify them according to seven adaptation domains, i.e., changes in practices and techniques, resource input, livelihood products, capacity building, practiced livelihood system, location and mobility, and time

management. The findings show that Indigenous Peoples and local communities across the world apply diverse adaptive responses -for which various knowledge systems are used-, including social (e.g., co-operations and sharing), ecological (e.g., soil and water management), and economic livelihood adjustments (e.g., livelihood diversification). The findings also reveal that adaptation strategies are more often steered by local livelihood practices than by the climate zone.

In Chapter 4, I assess the potential of local adaptive responses in agricultural and aquatic food systems for sustainable adaptation. Results from a literature review based on 98 peer-re-viewed scientific articles published between 2019 and 2021 highlight the strengths of Indigenous and local knowledge-based climate adaptation responses with respect to their high social components (e.g., knowledge sharing in traditional weather forecast, community-based irrigation systems) and their high contribution to environmental sustainability (e.g., resource-saving, including low energy-intensive activities). Furthermore, I find both economic disadvantages, such as low potential to generate high income (e.g., due to low market prices of traditional crops) but also certain economic advantages that are often overseen and ignored by researchers and policy-makers, such as low investment costs, and low-cost access to natural products such as natural fertilizers and plant-based medicine.

In the last empirical chapter of this thesis (Chapter 5), I assess prevalent adaptation constraints based on primary data from 10 field sites. The results build on a mixed-method approach, including 1,349 individual and 1,045 household surveys. The findings show that local adaptation implementation increases with the experience of climate change impacts, but that implementation is often hampered by socio-economic and behavioral constraints. Such constraints are highly diverse and often context-specific, sometimes as a result of personal and traditional preferences. However, there are also recurrent patterns across sites indicating that higher climate change risk appraisals and lower adaptation implementation are associated with lower access to socio-economic capital and lower food and water security.

In the concluding chapter and based on the results of the thesis, I argue that there is an urgent need to immediately support Indigenous Peoples and local communities in their adaptive behavior and to provide substantial efforts to remove persistent adaptation constraints. To foster adaptation success and avoid maladaptation, it is important to conceptualize adaptation under a sustainable development perspective based on bottom-up approaches in research and policy. Further research is especially needed on assessing the effectiveness of adaptation measures under a multi-stressor perspective.

Resumen

Esta tesis doctoral contribuye al campo de investigación, aún descuidado pero en crecimiento gradual, de la adaptación al cambio climático entre los pueblos indígenas y las comunidades locales. El calentamiento global antropogénico provoca numerosos impactos locales que afectan a las comunidades que dependen de la naturaleza para sobrevivir. Para garantizar sus medios de vida, ingresos, alimentos, agua y bienestar general, los pueblos indígenas y las comunidades locales de todo el mundo necesitan adaptarse y aumentar su resiliencia frente a los efectos adversos del cambio climático experimentados y previstos. Sin embargo, existen múltiples limitaciones que dificultan la puesta en práctica de la adaptación. Esta tesis aborda la cuestión de la vulnerabilidad y la resiliencia entre los Pueblos Indígenas y las comunidades locales en el contexto de la adaptación al cambio climático. En concreto, aborda las amenazas y los retos a los que se enfrentan y las oportunidades que tienen por delante para desarrollar una adaptación basada en el conocimiento indígena y local.

Este trabajo se ha realizado en el marco del proyecto Indicadores Locales de los Impactos del Cambio Climático (LICCI) (http://www.licci.eu), que se apoya en una red mundial de investigadores para evaluar los impactos locales del cambio climático y las estrategias de adaptación de los pueblos indígenas y las comunidades locales. La tesis incluye cuatro capítulos empíricos estructurados en tres partes que abordan los siguientes temas estructurales: i) la necesidad de adaptación (Capítulo 2), ii) la naturaleza de la adaptación local (Capítulos 3 y 4), y iii) los retos de la adaptación (Capítulo 5).

En el Capítulo 2, presento un método para detectar los focos actuales y futuros de posibles zonas con alta vulnerabilidad al cambio climático. Significativo en la medida que puede aportar información importante para la planificación de cualquier adaptación futura. Los resultados del capítulo se basan en una metodología basada en un método mixto que interpreta conjuntamente datos primarios de 17 emplazamientos, incluidas 2.676 encuestas individuales y 1.971 encuestas de hogares, y -para cada lugar- datos meteorológicos secundarios sobre cambios de temperatura pasados y previstos. El método propuesto utiliza informes locales sobre los efectos del cambio climático en los medios de subsistencia y el bienestar locales para estimar la sensibilidad de la zona al cambio climático y detectar los puntos críticos de riesgo de cambio climático. Los resultados muestran que los 17 emplazamientos difieren significativamente en cuanto a cambios pasados y posibles cambios futuros de la temperatura, sensibilidad climática e índices de aplicación de medidas de adaptación, lo que da lugar a la detección de cinco posibles puntos críticos de riesgo de cambio climático.

En el capítulo 3, estudio patrones globales de respuestas adaptativas implementadas localmente por pueblos indígenas y comunidades locales. El análisis se basa en una revisión sistemática de 119

publicaciones científicas consultadas entre el 2015 i el 2019. Documento un total de 1851 respuestas adaptativas a los impactos locales del cambio climático en diferentes climas y principales actividades de subsistencia, y las clasifico según siete dominios de adaptación, es decir, cambios en las prácticas y técnicas, entrada de recursos, productos de subsistencia, desarrollo de capacidades, sistema de subsistencia practicado, ubicación y movilidad, y gestión del tiempo. Los resultados muestran que los pueblos indígenas y las comunidades locales de todo el mundo aplican diversas respuestas de adaptación -para las que se utilizan varios sistemas de conocimiento-, entre las que se incluyen ajustes sociales (por ejemplo, cooperaciones y puesta en común), ecológicos (por ejemplo, gestión del suelo y el agua) y económicos de los medios de subsistencia (por ejemplo, su diversificación). Los resultados también revelan que las estrategias de adaptación suelen estar más dirigidas por las prácticas locales de subsistencia que por la zona climática.

En el capítulo 4, evalúo el potencial de las respuestas adaptativas locales en los sistemas alimentarios agrícolas y acuáticos para una adaptación más sostenible. Entre los resultados de una revisión bibliográfica basada en 98 artículos científicos publicados entre 2019 y 2021 destacan las respuestas de adaptación al clima basadas en el conocimiento indígena y local con respecto a sus altos componentes sociales (por ejemplo, el intercambio de conocimientos en el pronóstico del tiempo tradicional, los sistemas de riego basados en la comunidad) y su alta contribución a la sostenibilidad ambiental (por ejemplo, el ahorro de recursos, incluidas las actividades de bajo consumo de energía). Además, encuentro tanto desventajas económicas, como un bajo potencial para generar ingresos elevados (por ejemplo, debido a los bajos precios de mercado de los cultivos tradicionales), pero también ciertas ventajas económicas que los investigadores y los responsables políticos suelen pasar por alto e ignorar, como los bajos costes de inversión y el acceso a bajo coste a productos naturales como los fertilizantes naturales y la medicina basada en plantas.

En el último capítulo empírico de esta tesis (Capítulo 5), evalúo sobre el terreno las limitaciones de adaptación prevalentes basándome en datos primarios de 10 lugares. Los resultados se basan en un método mixto que incluye 1.349 encuestas individuales y 1.045 encuestas domésticas. Las conclusiones muestran que la aplicación local de medidas de adaptación aumenta con una mejor percepción de los efectos del cambio climático, pero que a menudo se ve obstaculizada por limitaciones socioeconómicas y de comportamiento. Dichas limitaciones son muy diversas y a menudo específicas de cada contexto, a veces como resultado de preferencias personales y tradicionales. Sin embargo, también existen patrones recurrentes en todos los lugares que indican que una mayor percepción de los riesgos del cambio climático y una menor aplicación de medidas de adaptación están asociadas a un menor acceso al capital socioeconómico y a una menor seguridad alimentaria e hídrica.

En el capítulo de conclusiones y basándome en los resultados de la tesis, sostengo que existe una necesidad urgente de apoyar inmediatamente a los Pueblos Indígenas y a las comunidades locales en su comportamiento adaptativo y de realizar esfuerzos sustanciales para eliminar las limitaciones persistentes de la adaptación. Para fomentar el éxito de la transformación y evitar la mala adaptación, es importante conceptualizar la adaptación bajo una perspectiva de desarrollo sostenible basada en enfoques ascendentes en la investigación y la política. Es especialmente necesario seguir investigando sobre la evaluación de la eficacia de las medidas de adaptación bajo una perspectiva de múltiples factores de estrés.

Resum

Aquesta tesi doctoral contribueix al camp de recerca, encara minoritari però en creixement gradual, d'adaptació al canvi climàtic entre els pobles indígenes i les comunitats locals. L'escalfament global antropogènic provoca molts impactes locals que afecten comunitats fortament dependents de les activitats en la natura. Per garantir el manteniment, els ingressos, l'alimentació, l'aigua i el benestar general, els pobles indígenes i les comunitats locals de tot el món han d'adaptar-se i augmentar la seva resiliència contra els impactes adversos del canvi climàtic, ja sigui els experimentats anteriorment com els que s'esperen en un futur. No obstant això, múltiples restriccions dificulten la implementació de l'adaptació. Aquesta tesi aborda la qüestió de la vulnerabilitat i la resiliència entre els pobles indígenes i les comunitats locals en el context de l'adaptació al canvi climàtic. En concret, aborda les amenaces i els reptes que troben i les oportunitats que tenen per davant l'adaptació indígena i local basada en el seu propi coneixement del medi a on viuen.

Aquest treball es va dur a terme en el marc del projecte "Local Indicators of Climate Change Impacts" (LICCI) (http://www.licci.eu), que es basa en una xarxa global d'investigadors per avaluar els impactes locals del canvi climàtic i les estratègies d'adaptació entre els pobles indígenes i les comunitats locals. La tesi inclou quatre capítols empírics estructurats en tres parts que aborden els següents temes generals: i) la necessitat d'adaptació (Capítol 2), ii) la naturalesa de l'adaptació local (Capítol 3 i 4), i iii) els reptes de l'adaptació (Capítol 5).

En el capítol 2, proporciono un mètode per detectar punts, actuals i futurs, d'alta vulnerabilitat al canvi climàtic, que poden proporcionar informació important per a la planificació de l'adaptació. Els resultats del capítol s'han obtingut mitjançant un mètode mixt que interpreta conjuntament dades primàries de 17 llocs, incloent-hi 2.676 enquestes individuals i 1.971 de la llar, i -per a cada lloc- dades meteorològiques secundàries sobre canvis de temperatura passats i projectats. El mètode emprat utilitza informes locals sobre els impactes del canvi climàtic en els mitjans de vida i el benestar locals per estimar la sensibilitat al canvi climàtic i detectar els punts amb major vulnerabilitat al canvi climàtic. Els resultats mostren que els 17 llocs difereixen significativament respecte als canvis de temperatura, sensibilitat climàtica i el grau d'implementació de l'adaptació, concloent en la detecció de cinc punts de risc de canvi climàtic potencials.

Al capítol 3, classifico patrons globals en les respostes adaptatives implementades per comunitats locals i indígenes. L'anàlisi es basa en una revisió sistemàtica de 119 publicacions científiques consultades entre el 2015 i el 2019. Localitzo un total de 1.851 respostes adaptatives als impactes del canvi climàtic local en diferents climes i principals activitats de subsistència, i les

classifico segons set dominis d'adaptació, és a dir, canvis en les pràctiques i tècniques, entrada de recursos, béns de subsistència, desenvolupament de capacitats, sistema de subsistència practicat, ubicació i mobilitat, i gestió del temps. Els resultats mostren que els pobles indígenes i les comunitats locals de tot el món apliquen respostes adaptatives diverses -per a les quals s'utilitzen diversos sistemes de coneixement-, incloent-hi les socials (per exemple, les cooperacions i l'intercanvi), les ecològiques (per exemple, la gestió del sòl i l'aigua), i els ajustos econòmics de la subsistència (per exemple, la diversificació dels mètodes de subsistència). Els resultats també revelen que les estratègies d'adaptació són més sovint dirigides per les pràctiques de subsistència locals que per la zona climàtica.

En el capítol 4, avaluo el potencial de les respostes adaptatives locals en els sistemes alimentaris agrícoles i aquàtics per a una adaptació més sostenible. Després d’una consulta bibliogràfica basada en 98 articles científics publicats entre el 2019 i el 2021, destaquem les fortaleses de les respostes d'adaptació climàtica indígenes i locals basades en un coneixement amb d’alt component social (per exemple, l'intercanvi de coneixements en la previsió meteorològica tradicional, els sistemes de reg basats en la comunitat) i la seva alta contribució a la sostenibilitat ambiental (per exemple, l'estalvi de recursos, incloses les activitats de baix consum d'energia intensiva). Derivats d’aquestes respostes d’adaptació, localitzo desavantatges econòmics perquè tenen baix potencial de generar alts ingressos (per exemple, a causa dels baixos preus de mercat dels cultius tradicionals), però també certs avantatges que sovint són minimitzats i ignorats pels investigadors i els responsables polítics. Exemples d’aquests últims poden ser els baixos costos d'inversió i l'accés a baix cost a productes naturals com els fertilitzants orgànics i la medicina basada en plantes.

En l'últim capítol empíric d'aquesta tesi (capítol 5), avaluem les restriccions d'adaptació prevalents basades en dades primàries de 10 regions. Els resultats es basen en l’aplicació d’un mètode mixt, que inclou 1.349 enquestes individuals i 1.045 de llars. Els resultats mostren que la implementació de l'adaptació local augmenta amb l'experiència dels impactes del canvi climàtic, però aquesta implementació sovint es veu obstaculitzada per restriccions socioeconòmiques i de comportament. Aquestes restriccions són molt diverses i sovint específiques del context, de vegades com a resultat de preferències personals i tradicionals. No obstant això, també hi ha patrons recurrents en els enclavaments que indiquen que una major percepció del risc del canvi climàtic i una menor implementació de mesures d’adaptació s'associen amb un menor accés al capital socioeconòmic i una menor seguretat alimentària i de l'aigua.

En el capítol final, i basat en els resultats de la tesi, argumento que hi ha una necessitat urgent de fer costat immediatament als pobles indígenes i a les comunitats locals en el seu procés adaptatiu i fornir d’esforços substancials per eliminar les restriccions persistents en la seva adaptabilitat. Per fomentar l'èxit de l'adaptació i evitar la mala adaptació, és important conceptualitzar la transformació des d’una perspectiva de desenvolupament sostenible basada en enfocaments de recerca i polítiques ascendents. Especialment, es necessita més recerca per a avaluar l'eficàcia de les mesures d'adaptació des d’una perspectiva d’estrès en diversos camps.

Chapter 1

Introduction

Background and motivation

Indigenous Peoples and local communities who rely directly on the environment for their livelihoods are increasingly experiencing climate change and its impacts, often within a broader context of socio-economic, political, and cultural transitions (Ensor et al., 2019; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Reyes-García, 2024). With global greenhouse gas emissions on a continuous upward trend (Höhne et al., 2021; Liu & Raftery, 2021; Rogelj et al., 2016), climate change impacts are expected to increase in both intensity and damage potential (IPCC, 2021; Lyon et al., 2022). This reality underscores the imperative of adapting to changing climate conditions as a last resort of social-ecological systems (Pielke et al., 2007).

Focusing on climate change impacts and adaptation in Indigenous Peoples and local communities is highly relevant for several reasons. To begin, Indigenous Peoples and local communities' contribution to anthropogenic climate change is low (IPCC, 2022a), yet they are among the first to be affected by its cascading impacts (Reyes-García, 2024; Reyes-García, García-del-Amo, Álvarez-Fernández, et al., 2024). Despite this, they have not received sufficient attention in the research-policy nexus -despite some progress in recent years (Carmona et al., 2023; Chakraborty & Sherpa, 2021; Corbera et al., 2015; Díaz-Reviriego et al., 2019; Ford et al., 2012; Ford, Cameron, et al., 2016)-, and continue to have limited influence on climate policy decision-making and climate negotiations (Belfer et al., 2019; Betzold & Flesken, 2014; Comberti et al., 2019; Ford, Maillet, et al., 2016; Shawoo & Thornton, 2019; Shea & Thornton, 2019; Tormos-Aponte, 2021; Yap & Watene, 2019). Then, there is also evidence that Indigenous Peoples and local communities can simultaneously be vulnerable and resilient to climate change (Ford et al., 2020; Reyes-García, García-del-Amo, Porcuna-Ferrer, et al., 2024). Their long-term interaction with the local environment and knowledge transmission across generations has informed their way of living and dealing with climate variability and environmental changes (Berkes et al., 1994, 2000). Nonetheless, the speed of current global warming poses an unprecedented challenge to human society, and it may exceed the adaptive capacity of Indigenous Peoples and local communities (Bose, 2017; Kates et al., 2012). In addition, the increasingly common erosion and weakening of Indigenous cultures, including Indigenous and local knowledge, lead to the loss of vital sources for sustainable adaptation solutions (Fernández-Llamazares et al., 2021; IPBES, 2019). Finally, colonial history and ongoing systemic forms of oppression have resulted in the continuous marginalization of Indigenous People and local communities. This is evidenced in their exclusion from political and economic decision-making and limited access to important resources or assets such as land, institutional infrastructure and financial means, all which have direct impact on their scope of adaptive actions (Whyte, 2020).

Understanding the vulnerability and resilience of Indigenous Peoples and local communities in the context of climate change adaptation is the main general purpose of the thesis, thereby contributing to the slow but growing body of scientific literature on local (i.e., autonomous) adaptation to climate change. Specifically, through multi-site comparison studies, the thesis contributes to our understanding of the need to adapt to experienced and expected climate change impacts, opportunities and co-benefits of Indigenous and local knowledge-based adaptation strategies, and persistent challenges, i.e., adaptation constraints. By assessing common patterns and local occurrences, the thesis has the potential to inform adaptation planning by guiding prioritization processes in decision-making.

To advance climate change impact and adaptation research and policies, the thesis follows four objectives. The first objective is to assess differences in adaptation needs by identifying climate change risk hotspots, i.e., locations that are exposed to higher climate change risks than others (de Sherbinin, 2014; Hare et al., 2011). By identifying climate change hotspots, this thesis supports climate change risk management and informs adaptation planning to guide prioritization according to highest needs for adaptation. Contrary to existing approaches to identify climate change hotspots that focus on (bio-)physical and economic factors (including danger to human life) often at larger regional or global scales (e.g., Byers et al. (2018), Diffenbaugh & Giorgi (2012), Müller et al. (2014)), this thesis presents an alternative, more holistic and value-centered approach that defines hotspots based on lived experiences and people's severity appraisals of experienced climate change impacts. Thereby, the approach developed allows for a definition of risks, impacts and hotspots based on people's subjective interpretation of what matters to them, including cultural values and subjective well-being

(McNamara et al., 2021; O’Brien & Wolf, 2010; Pill, 2022; Tschakert et al., 2017; van der Linden, 2015).

The second objective of this thesis is to document current adaptive measures practiced by Indigenous Peoples and local communities around the world. Indeed, overtime Indigenous Peoples and local communities have developed manifold strategies in response to environmental changes, including natural climate variability (Berkes et al., 2000; E. Gómez-Baggethun et al., 2013; Makondo & Thomas, 2018; McLean, 2009). By visualizing the dimension, scope and diversity of local adaptive strategies, often overseen and neglected in research and policy (Betzold & Flesken, 2014; Carmona et al., 2023; Chakraborty & Sherpa, 2021; Ford, Cameron, et al., 2016; Shea & Thornton, 2019; Tormos-Aponte, 2021), this thesis moves local adaptation into the center of attention and calls for stronger acknowledgment and consideration of Indigenous and local knowledge-based adaptive strategies. While adaptation strategies in industrialized countries focus on technological solutions and adaptation planning, Indigenous cultures play a key role in guiding traditional practices according to principles of environmental and social integrity (Berrang-Ford et al., 2021; Ford et al., 2011; Shaffril et al., 2020; Taylor et al., 2023). By defining social and environmental norms that promote reciprocity and respect for nature, traditional practices increase social cohesion, restrict natural resource extractions, and support biocultural diversity (IPBES, 2019).

In this line, the third objective of the thesis is to assess the potential of Indigenous and local knowledge-based adaptive strategies for sustainable adaptation by looking at the social, environmental and economic trade-offs associated with frequently applied strategies in agricultural and aquatic food systems. While sustainability is an important element of successful adaptation that supports co-benefits across spatial and temporal scales, the prevalence of adaptation determinants (i.e., opportunities and constraints) ultimately define the feasibility of adaptation (Klein et al., 2014; Piggott-McKellar et al., 2019; Shackleton et al., 2015; C. Singh et al., 2020; Spires et al., 2014).

Therefore, the fourth objective of the thesis is to identify common patterns as well as context-specific adaptation opportunities and constraints to inform policy about prevalent challenges that need to be tackled from the local to the global scale.

The thesis also addresses two main methodological challenges: the need for interdisciplinary and hybrid epistemologies that use information from natural and social sciences and Indigenous and local knowledge systems, and the need for increasing transferability of knowledge by upscaling insights beyond the local context. First, although there is increasing attention on multiple evidence-based approaches, and interdisciplinary science is gaining traction in climate change adaptation research, achieving successful knowledge co-production remains challenged (David-Chavez & Gavin, 2018; Klenk et al., 2017; Lam et al., 2020). By proposing new methods for the estimation of communities' sensitivity to climate change and the identification of climate change hotspots based on the synthesis of information from different knowledge systems, the thesis directly contributes to stronger joint interpretation of evidence from different knowledge systems. Second, a common critique of adaptation research is that it mainly builds on case studies and therefore remains highly fragmented. There is a lack of systematic approaches from multi-site comparison studies (but see Berman et al. (2020) for exception). This thesis directly responds to the call for upscaling local information. Specifically, it provides important hands-on tools to improve transferability of local insights in order to make them relevant beyond the local context, while at the same time ensuring space for context-specific occurrences.

State-of-the-art

Framing the climate crisis

The global climate is changing, thereby altering biophysical systems with unprecedented consequences for human societies. Global warming manifests in simultaneous and sequential impacts, and already affects social-ecological systems around the globe (IPCC, 2022b). Changes in temperature and precipitation patterns highly influence biophysical systems, including the atmosphere, cryosphere and hydrosphere, as well as the pedosphere and biosphere, thereby affecting both natural and human-managed systems (Bezner Kerr, Hasegawa, et al., 2022; Caretta et al., 2022; Cooley et al., 2022; Parmesan et al., 2022; Pecl et al., 2017). Pushing the Earth system beyond certain critical climatic thresholds, so-called tipping points, might provoke abrupt and irreversible changes in the Earth system with unknown consequences for human societies (Hoegh-Guldberg et al., 2018; Lenton et al., 2008, 2019).

Anthropogenic greenhouse gas (GHG) emissions have caused an increase in the global mean temperature by 1.09ºC since the pre-industrial era (Eyring et al., 2021; IPCC, 2021; Rosenzweig & Neofotis, 2013; Trenberth, 2011). While the Global North is the major GHG emitter, countries from the Global South tend to be most vulnerable to negative climate change impacts, and experience substantial economic losses due to global warming (Althor et al., 2016; Callahan & Mankin, 2022; Hickel, 2020). Revealing such unequal distributions in GHG emissions is important in the context of climate (in)justice, as it highlights discrepancies between those who carry the main burden from climate change and those who contributed most to it (Vanderheiden, 2008) Drawing on the idea of a climate debt (Matthews, 2015) and justified by experienced or expected damages caused by climate change, Warlenius (2017) raises the need for a compensatory adaptation debt.

Global climate change impact models have provided robust evidence for anthropogenic climate change, included evidence on temporal and spatial trends in temperature and precipitation (e.g., Diffenbaugh & Giorgi, 2012; Fan et al., 2021; Torres & Marengo, 2014), and on climate-related risks for ecosystems, but also for agriculture, health, the energy system, and water sector (Asseng et al., 2015; Byers et al., 2018; Cramer et al., 2001; Füssel & van Minnen, 2001; Kour et al., 2016; Rosenzweig et al., 2017; Rötter et al., 2018). Based on socio-economic pathways that describe different possible future developments of human society, including trends in population and economy, climate models offer insights into potential climate futures and associated risks (Arnell et al., 2004, 2013; Kriegler et al., 2012; Lyon et al., 2022; Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017; van Vuuren & Carter, 2014). In a similar line, to inform decision-making, climate change hotspots assessments have become a meaningful tools to identify locations of highest climate change risks (de Sherbinin, 2014; Ericksen et al., 2011; Hare et al., 2011; Müller et al., 2014; Spinoni et al., 2020; P. K. Thornton et al., 2008; Turco et al., 2015).

However, such evidence has not yet led to successful mitigation actions. Instead, there is growing recognition that climate change and arising impacts are now unavoidable to some extent because human society has failed in cutting GHG emissions to tolerable levels (Barnett, 2007; Höhne et al., 2021; Khan & Roberts, 2013; Liu & Raftery, 2021; Roelfsema et al., 2020; Rogelj et al., 2016). This has initiated a paradigm shift in climate policy and research from an initial focus on impact and mitigation to a new focus on vulnerability and adaptation (Burton et al., 2002; Khan & Roberts, 2013; Orlove, 2022). Mitigation and adaptation are the two fundamental response options to alleviate climate change impacts and risks. While mitigation aims to reduce the occurrence and intensity of climate harms by addressing the driving forces behind, adaptation aims at moderating climate harm by reducing the vulnerability and increasing the resilience of the system of concern against arising climate hazards and impacts.

The nexus of climate change risks, vulnerability, resilience, and successful adaptation

Climate change impacts, risks, vulnerability, resilience, and adaptation are highly intertwined, coalescing, and complementary concepts; therefore applying one concept requires the understanding of the others (Engle, 2011; Folke et al., 2010; Miller et al., 2010; Smit & Wandel, 2006; Turner et al., 2003). In the following, I introduce the different aspects of relevant conceptual framings, whereby I make largely use of the definitions provided by the IPCC (2018).

Climate change vulnerability and resilience

The IPCC (2018) defines climate change risks as the potential for adverse consequences for social-ecological systems that result from dynamic interactions between climate-related hazards and the system's exposure and vulnerability to such hazards, and climate change impacts aa the “consequences of realized risks”. Climate change hazards comprise slow- and fast-onset trends and events, including climate extremes, that differ across spatial and temporal scales (Seneviratne et al., 2021; Turco et al., 2015). In addition to the occurrence and magnitude of climate hazards, the vulnerability and resilience of social-ecological systems, which depend on the political and socio-economic context, has a substantial influence on realized impacts and potential climate risks (Füssel & Klein, 2006). Therefore, climate change impacts and risks evolve not only over time but also differ across regions, communities, and even between households and individuals (De Souza et al., 2015; Tucker et al., 2015).

Vulnerability refers to a system’s predisposition to be adversely affected by climatic variability or change. Vulnerability depends on the system’s sensitivity to harm and adaptive capacity, hence, its ability to adequately respond to potential harm through adjustments (Berkes, 2007; Füssel & Klein, 2006; IPCC, 2018). In contrast, resilience refers to a system’s ability to absorb and cope with hazardous events, trends, or disturbances, such as natural disasters, by responding or reorganizing in ways that maintain their essential function, identity, and structure (Berkes, 2007; Folke, 2016; IPCC, 2018). Since social and ecological systems are coupled, the vulnerability of societies directly and indirectly depends on the ecosystem’s vulnerability and resilience (Folke et al., 2016). The sensitivity and adaptive capacity of biophysical systems is mainly driven by biophysical and chemical processes that manifest in heterogeneous biological and ecological responses to changes in temperature and precipitation (Li et al., 2018). In contrast, the sensitivity and adaptive capacity of social-ecological systems is additionally steered by political and social-economic conditions (Thornton et al., 2014). In climate change research, there are two main conceptual framings of vulnerability, the biophysical or outcome vulnerability and the social or contextual vulnerability (Bruno Soares et al., 2012; Tucker et al., 2015). The biophysical definition is an impact-driven approach that focuses on the extent of loss derived from a climate hazard, thus on the outcome of climate change impacts moderated by adaptation. In contrast, the social approach considers vulnerability as socially constructed embedded in the political, social, historical and economic context (O’Brien et al., 2007).

The relationship between vulnerability, resilience, and adaptive capacity - all of which are socially constructed - suggests that exposure to climate harm is not the sole determinant of the ensuing damage (Ford et al., 2020; Ribot, 2022). In this vein, approaches such as the one of the Collaborative Adaptation Research Initiative in Africa and Asia define vulnerability hotspots as ‘geographical area[s] where a strong climate signal is combined with a large concentration of vulnerable, poor or marginalized people’, thus acknowledging the political and socio-economic context (De Souza et al., 2015; Tucker et al., 2015).

Reducing climate harms through adaptation

Through adaptation, socio-ecological systems adjust “to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities” (IPCC, 2018) either by building adaptive capacity or by implementing adaptation, thus transforming such adaptive capacity into action (Adger et al., 2005) with the aim to increase resilience and reduce vulnerability to climate change (Burton et al., 2002; Leary, 1999; Smit et al., 2000).

The adaptation literature differentiate between autonomous adaptations, which are local adaptive strategies initiated by private actors, such as individuals, households or communities without larger planning, and planned adaptations, which are prepared and implemented by public agents, such as regional and national governments (Fenton et al., 2017; Füssel, 2007; Mersha & van Laerhoven, 2018; Smit et al., 2000). Local (i.e., autonomous) adaptive responses comprise reactive, spontaneous, and rather short-term coping strategies in the face of emergencies, incremental, and -to a lesser extent- transformational adaptive strategies (Fedele et al., 2020; Zant et al., 2024). Incremental adaptation is typically more anticipatory than coping and seeks to build stronger resilience by accommodating smaller-scale adjustments in the system, but without altering its original functions and trajectory (Kates et al., 2012). In the light of exacerbating climate trends, an increasing number of researchers have criticized coping and incremental adaptation as insufficient to effectively deal with climate change and instead emphasize on the need for transformational adaptation, which are large in scale and fundamentally alter the entire system (Fazey et al., 2018; Fedele et al., 2019; Feola, 2015; Kates et al., 2012; O’Brien, 2012, 2018; Olsson et al., 2014; Park et al., 2012; Ribot, 2014; Termeer et al., 2017; Walker et al., 2004).

Successful adaptation - considering feasibility, effectiveness, and sustainability

Not all responses to climate change impacts are successful in achieving their intended goals in an effective and sustainable manner. Furthermore, not only is it possible that certain measures fail in their effectiveness, some might result in trade-offs and potential negative, unintended side-effects, i.e., maladaptive outcomes (Adger et al., 2005; Atteridge & Remling, 2018; Magnan et al., 2016; D. R. Nelson, 2011; Schipper, 2020). Therefore, defining successful adaptation is difficult. Several authors have emphasized the need to evaluate adaptation to climate change in a sustainability context by connecting climate actions with the Sustainable Development Goals and analyzing adaptation success based on environmental, social, cultural, and economic criteria (e.g., Folke et al., 2016; Fuso Nerini et al., 2019). Sustainable adaptation combines principles of environmental integrity with social justice (Eriksen et al., 2011), defining adaptation success under equity and legitimacy aspects (Adger et al., 2005; C. Singh et al., 2022). Differently, based on a literature review, Owen (2020) identifies adaptation effectiveness through indicators such as improved resilience, vulnerability, adaptive capacity and/or preparedness. Defining successful adaptation in the context of sustainability also requires looking beyond spatial and temporal scales. For example, maladaptive measures can reinforce existing inequalities by providing benefits for some and negative externalities and spillovers for others (Adger et al., 2005). And what may appear successful today may be unsustainable in the long-term, affecting future generations (Adger et al., 2005; Magnan et al., 2016).

Successful adaptation, however, is not solely dependent on the sustainability of its outcomes, but also depends on the feasibility of adaptation options, which links to the adaptive capacity of the system in question (C. Singh et al., 2020). Since climate change adaptation occurs in a broader context, its feasibility is not only influenced by biophysical factors, but is also determined by political and socio-economic factors and the interactions between them (Bezner Kerr, Naess, et al., 2022; C. Singh et al., 2020; Thomas et al., 2021). Adaptation feasibility depends on the persistence of supporting or enabling factors and conditions (i.e., adaptation opportunities), compounding factors and conditions (i.e., adaptation constraints or barriers), and impeding factors and conditions (i.e., adaptation limits) (Klein et al., 2014). While the term adaptation constraints refers to factors that make adaptation planning and implementation more challenging, less effective or efficient and more expensive, the term adaptation limits refers to factors that make adaptation not possible, resulting in catastrophic and intolerable climate risks (Dow et al., 2013; Klein et al., 2014; Moser & Ekstrom, 2010).

While there is a growing number of studies on the topic of adaptive capacity (Mortreux & Barnett, 2017; Siders, 2019), adaptation feasibility (Williams et al., 2021), constraints (i.e., barriers) and limits (Biesbroek et al., 2013; Piggott-McKellar et al., 2019; Shackleton et al., 2015; Spires et al., 2014; Thomas et al., 2021), certain caveats persist in the literature. For example, most studies define adaptive capacities based on five socio-economic categories: financial, physical, social, human, and environmental capitals (Morse & McNamara, 2013). And although recent studies suggest widening the definition of adaptive capacity by taking aspects such as flexibility, learning, and agency into account (Cinner et al., 2018; Green et al., 2021), cognitive aspects, as well as cultural aspects are still largely missing (see Burnham & Ma (2017); Dang et al., (2018); Freduah et al. (2019) as exceptions).

The relevance of cognitive factors for adaptation decision-making has been first raised by Grothmann & Patt (2005). Since then, a small but growing number of case studies have confirmed the importance of cognitive factors, such as climate change risk and adaptation appraisals, for adaptation action (Khanal et al., 2018).

Culture, values and worldviews, including Indigenous and local knowledge and place attachment, play a crucial role in shaping the perception of climate risks and the implementation and success of adaptive responses (Adger et al., 2013; Clarke et al., 2018; Heyd & Brooks, 2009; McNeeley & Lazrus, 2014; O’Brien, 2009). According to Adger et al. (2009) and Nielsen & Reenberg (2010) ethics and values, knowledge, risk perception, and culture can also constitute endogenous social constraints and limits to adaptation within a society. However since they are socially constructed, they are in many cases mutable.

Climate change vulnerability and resilience of Indigenous Peoples and local communities

There are two seemingly opposing positions in research and policy on the vulnerability and resilience of Indigenous Peoples and local communities to environmental, including climatic, changes. Some identify Indigenous Peoples and local communities as “at-risk” and the most vulnerable to climate change due to high and direct dependence on nature and the ongoing discrimination and marginalization (Lahsen & Ribot, 2022). In contrast, others argue against featuring Indigenous Peoples and local communities as passive victims, and propose that they should be considered active agents in tackling climate change. This body of work acknowledges that the extensive body of Indigenous and local knowledge strengthens climate resilience (Etchart, 2017; Makondo & Thomas, 2018; Nyong et al., 2007) and also contributes to the understanding of how global warming manifests in local impacts (Reyes-García et al., 2016; Reyes-García, García-del-Amo, Álvarez-Fernández, et al., 2024; Riedlinger & Berkes, 2001; Savo et al., 2016). Indeed, evidence suggests that the two positions are rather complementing than contrasting and that Indigenous Peoples and local communities can be at the same time resilient and vulnerable to climate change (Ford et al., 2020).

The resilience of Indigenous Peoples and local communities

Many Indigenous Peoples and local communities have developed nature-dependent livelihoods that allow them to live in places with extreme environmental and climatic conditions, such the Arctic or small islands with limited land resources, or large parts of the Saharan region with limited access to water (McLean, 2009). Their dynamic knowledge systems have allowed them to adapt to changing conditions and increase resilience to climate variability and social-ecological changes (Berkes et al., 2000; E. Gómez-Baggethun & Reyes-García, 2013).

During the last decade, an increasing number of studies has documented the value of Indigenous and local knowledge for climate change adaptation and mitigation by providing evidence from different parts of the world (Galappaththi et al., 2021; Leal Filho et al., 2022;

Lebel, 2013; Nyong et al., 2007; Reyes-García, 2024; Shaffril et al., 2020). In a context of increasing risks of extreme events such as droughts and floods, cold spells and heat waves, Indigenous and local knowledge-based practices constitute potentially important contributions to climate change mitigation and sustainable adaptation. For example, traditional agricultural practices in land, soil, and water management are diverse and show high potential to improve soil quality, water availability and yield safety (Rivera-Ferre et al., 2021). Indigenous and local knowledge also plays a key role in strengthening resilience through agrobiodiversity (Tarit Kumar Baul & McDonald, 2014; Kahane et al., 2013; Kerr Bezner, 2014; Labeyrie et al., 2021).

Many Indigenous and local knowledge based practices and worldviews exist that could play a crucial role for climate change adaptation, from traditional weather forecast and climate observation, mobility, social networks, to worldviews that support reciprocity, and taboos that strengthen sustainable use of natural resources, to mention only some (E. Gómez-Baggethun et al., 2012; Ingty, 2017; Leal Filho et al., 2022; Makondo & Thomas, 2018). Indigenous and local knowledge, place attachment, traditional institutions, receptiveness for learning, and collective action contribute to Indigenous Peoples and local communities' adaptive capacity, thereby proving to be important tools for climate change adaptation (Ford et al., 2020).

The vulnerability of Indigenous Peoples and local communities

While Indigenous and local knowledge constitutes an important source for climate change resilience of Indigenous Peoples and local communities, several challenges have the potential to undermine potential benefits, enhance vulnerabilities, and increase climate change risks and experienced impacts. Such challenges relate but are not limited to i) high exposures and livelihood-related sensitivities to unprecedented climate change and cascading impacts, ii) observed erosion of Indigenous and local knowledge in many parts of the world, and iii) ongoing discrimination and marginalization of Indigenous Peoples and local communities that reduce their adaptive capacities by limiting access to critical resources.

Climate change is posing a threat to millions of Indigenous Peoples and local communities worldwide, especially those with nature-dependent livelihoods (Reyes-García, 2024; Reyes-

García, García-del-Amo, Álvarez-Fernández, et al., 2024; Savo et al., 2016, 2017). For example, in the Arctic regions trends towards unpredictable weather and changes in sea-ice stability challenges hunting activities of Inuit, thereby affecting people's culture and traditions but also posing a direct danger to life (Ford, Smit, & Wandel, 2006; Hovelsrud & Smit, 2010). Manifold evidence highlights the increased risk of droughts in dry regions with dangerous impacts on crops and livestock, posing food security at risk (Dai, 2011). With advancing climate change and increasing risks that affect the inhabitability of places, a growing number of Indigenous Peoples and local communities will have to undertake efforts to adapt, and not few will ultimately be forced to leave their homelands and migrate to other places (Farbotko et al., 2020; McNamara & Des Combes, 2015).

Climate change impacts also impact cultures, and well-being (Adger et al., 2022; McLean, 2009), however, the importance of identity, tradition, and place attachment for people's well-being, and the implications of climate change impacts on such values are often underrated and neglected in climate policy decision-making (Adger et al., 2011, 2013, 2022).

At the same time, multiple stressors put Indigenous and local knowledge systems under pressure, leading to the erosion of knowledge in many parts of the world (Fernández-Llamazares et al., 2021; E. Gómez-Baggethun et al., 2013; Erik Gómez-Baggethun, 2022). The drivers of such knowledge erosion stem from loss of biodiversity, globalization, modernization, and market integration (Shankar Aswani et al., 2018; Fernández-Llamazares et al., 2015; Kai et al., 2014). In addition, there is increasing evidence that climate change affects the practicability and effectiveness of Indigenous and local knowledge-based practices. For example, trends towards more unpredictable climates challenge the reliability of traditional weather forecasts with impacts on people's safety (Garteizgogeascoa et al., 2020).

Finally, the pre-existing vulnerabilities and precarities on the ground, including issues of undermined sovereignty, power, and social justice rooted in colonial history and exploitative international systems, ultimately define who is most affected by climate hazards (Bezner Kerr, Naess, et al., 2022; Carmona, 2024; Lahsen & Ribot, 2022). Colonialism, capitalism and industrialization has resulted in distrustful behavior of governments and private companies against Indigenous Peoples, resulting in relationships that lack consents, trust, accountability, and reciprocity, and include systematic violations of their rights (Scheidel et al., 2023; Whyte, 2020). This implies that underlying drivers for limited access to resources among Indigenous Peoples and local communities often stem from higher institutional and political levels. Systemic vulnerabilities traced back to past and ongoing discrimination and marginalization are multifaceted and manifest in many social-political and economic spheres, that are often intertwined and interdependent, such as limited participation in climate change policy decision-making, limited official recognition of Indigenous rights, and economic marginalization.

For example, Indigenous Peoples remain underrepresented and with limited participation in decision-making processes in international climate policy and negotiations, including in the United Nations (UN) Conference of the Parties (COP) (Betzold & Flesken, 2014; Comberti et al., 2019; Ford, Maillet, et al., 2016; Shea & Thornton, 2019; Tormos-Aponte, 2021) and the development of the Sustainable Developments Goals (Yap & Watene, 2019). And although there are currently some efforts in international climate-policy towards higher representation and recognition of Indigenous Peoples and local communities, for example, through the creation of the "Local Communities and Indigenous Peoples Platform", concerns about unequal power relations and limited decision-making power by Indigenous Peoples and local communities remain (Belfer et al., 2019; Shawoo & Thornton, 2019). Similarly, despite some recent progress towards achieving stronger representation of Indigenous Peoples and local communities in the science-policy interface, such as the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES), Indigenous and local knowledge systems remain underrepresented (Carmona et al., 2023; Chakraborty & Sherpa, 2021; Corbera et al., 2015; Díaz-Reviriego et al., 2019; Ford et al., 2012; Ford, Cameron, et al., 2016).

Since existing political and economic structures, power dynamics and inequalities influence the adaptive capacity of a system by providing, hindering, or limiting access to resources, the large exclusion in relevant political and climate-related decision-making processes and limited official recognition of Indigenous and local knowledge and Indigenous rights have far-reaching consequences on other resources such as access to Indigenous lands, financial and technological resources and involvement and leadership in climate change adaptation planning and implementation (Bezner Kerr, Naess, et al., 2022; Carmona et al., 2024; Nyantakyi-Frimpong & Bezner Kerr, 2017; Williams et al., 2021).

Aims of the thesis and research questions

In response to the prevailing challenges and research gaps in climate change impact and adaptation research concerning Indigenous Peoples and local communities, the main objective of the thesis is to assess and compile evidence on climate change impacts, risks, vulnerability, resilience among Indigenous Peoples and local communities. Specifically, I look at climate change sensitivities among different communities, available opportunities for Indigenous and local knowledge-based adaptation strategies, and prevailing adaptation constraints that hamper the implementation of adaptive responses.

The first empirical chapter of this thesis addresses the topic of climate change risks, whereas the second and third empirical chapters have their focus on potential benefits and opportunities of local adaptive responses to contribute to climate change resilience. Finally, the last empirical chapter focuses on persistent adaptation challenges and constraints, thereby addressing concerns related to climate change vulnerability. Each chapter is guided by a set of specific research questions that relate to the overall objective of the thesis. I detail these questions below

> **Chapter 2**: How strong are currently experienced climate change impacts among Indigenous Peoples and local communities? How do climate change impacts appraisal levels manifest in adaptation implementation rates? How do Indigenous Peoples and local communities differ in their climate change sensitivity? And how does the interplay of climate change sensitivity, projected temperature trends and adaptive behavior manifest in different potential climate change risks and future hotspots ?

Chapter 3: How is current research on local adaptation among Indigenous Peoples and local communities distributed across the globe? What is the reported portfolio of local adaptation strategies that Indigenous Peoples and local communities draw from? How do such strategies differ or resemble across climates, regions, and main livelihood activities?

Chapter 4: How can Indigenous and local knowledge-based adaptive strategies contribute to sustainable adaptation? And in particular, what are the social, environmental, and economic benefits and drawbacks of these strategies?

Chapter 5: Does experience with climate change impacts translate into adaptation action? What are locally relevant and context-specific factors that constrain adaptation implementation? What are socio-economic factors that steer adaptation across sites?

To respond to these research questions, through this thesis, I apply the multiple evidence-based approach (Tengö et al., 2014) by considering and jointly interpreting information derived from Indigenous and local knowledge systems, social science and natural science. In addition, my primary interest lies in detecting common patterns over local singularities through a multi-site comparison approach.

Research context and methodological approach

A global multi-evidence based research approach

Climate change is a complex phenomenon that concerns various spatial and temporal scales, and affects social-ecological systems in manifold ways. To better understand such complex relationships at various dimensions, scientists emphasize the need for interdisciplinary approaches and hybrid epistemologies (David-Chavez & Gavin, 2018; Hill, Walsh, et al., 2020; Klenk et al., 2017; Lam et al., 2020; Tengö et al., 2014) and call for additional efforts on large-scale comparison studies to make local findings relevant for other places (Berkhout & Dow, 2023; Reyes-García et al., 2019; Siders, 2019). In response to such needs, this thesis follows two methodological approaches. First, it aims at synthesizing information from different knowledge systems with a focus on Indigenous and local knowledge. Second, it applies a multi-site comparison approach to detect common patterns alongside local characteristics.

By applying a multiple evidence-based approach, I acknowledge that different knowledge systems cover different qualities and characteristics, but also differ in the challenges and limitations they face. On the one hand, natural science has contributed much to our understanding of physical processes in the global climate system (Rosenzweig & Neofotis, 2013). On the other hand, drawing on Indigenous and local knowledge helps understand how global warming manifests in context-specific impacts on local social-ecological systems (Reyes-García et al., 2016). Moreover, Indigenous and local knowledge contributes to adaptive responses that correspond to the local context and builds on diverse value systems and worldviews (Galappaththi et al., 2021; Leal Filho et al., 2022; Lebel, 2013; Nyong et al., 2007; Reyes-García, 2024; Shaffril et al., 2020). In recent years, and in response to the dominance of Western science over other knowledge systems in research and policy, a growing number of researchers and practitioners have called for a paradigm shift from top-down towards bottom-up and participatory approaches, and towards a stronger representation of Indigenous and local knowledge with the aim to strengthen knowledge co-production (Hill, Walsh, et al., 2020; McNamara & Buggy, 2017). Linking information from diverse knowledge systems is a promising approach that supports a comprehensive and holistic understanding of complex relationships in social-ecological systems based on multiple perspectives (Tengö et al., 2014).

And although a growing number of studies have increased their efforts towards multiple evidence-based approaches, challenges and limitations for successful knowledge co-production remain high (David-Chavez & Gavin, 2018; Klenk et al., 2017; Lam et al., 2020). One of the many critics refers to the lack of comparison studies (but see Berman et al. (2020) for exception). Since research on Indigenous and local knowledge is mainly supported by case studies, our understanding of the importance of Indigenous and local knowledge in the context of climate change adaptation remains dispersed, selective, and limited to the specific location (Berkhout & Dow, 2023; Siders, 2019). Therefore, there is a need for global and multi-site comparison studies that help upscale local findings and make them relevant for other places.

This thesis addresses these research gaps by linking information from natural and social science with Indigenous and local knowledge, and by applying a multi-site comparison approach.

The LICCI project - a global research approach

This thesis was elaborated within the framework of the Local Indicators of Climate Change Impacts (LICCI) project (https://www.licci.eu), funded by the European Research Council. The LICCI project is a multi-site comparison study aiming to assess common patterns of local climate change impacts among nature-dependent Indigenous Peoples and local communities, while at the same time acknowledging site-specific singularities. Aiming for data collection in approximately 50 sites from around the globe, the LICCI project has built an international network of collaborating researchers from different countries, continents, and backgrounds. Over a period of 5 years, the LICCI Core team developed a standardized data collection protocol (Reyes-García et al., 2023), selected and trained collaborating researchers, and coordinated data collection across field sites (in the following LICCI sites).

This thesis extended the original aims of the LICCI project by adding a focus on climate change adaptation. Specifically, the work presented here used the extensive LICCI network to gather information on local adaptive measures in response to experienced climate change impacts and encountered adaptation constraints.

The data collection within the LICCI project was initially planned for the time period between August 2019 and December 2020. Through the onset of the COVID-19 pandemic in the first quarter of 2020, data collection was heavily disrupted and delayed for two years. In some places, the pandemic impeded data collection, leading to a reduced number of total sites, and in other sites the delay in data collection resulted in a reduced number of data points, either because only some of the methods could be applied, or because data could be gathered only among small samples. Even efforts towards training additional partners could not completely compensate for the consequences of the pandemic on the final data scope, for which, the final data set was smaller, and arrived later than originally expected.

To compensate for the incertitude around data collection arising from the pandemic, during that period I devised an alternative strategy, and opted to rely on published information. In consequence, Chapter 3 and 4 of the thesis build on secondary data from literature reviews, while Chapter 2 uses data from 16 LICCI sites and Chapter 5 uses data from 10 LICCI sites.

Sampling and data collection within the LICCI project

All sites in the LICCI project correspond to rural communities with high natural-resource dependent livelihoods for food and income and with a long history of relation with the environment. Moreover, communities participating in the LICCI project generally represent marginalized populations with general low financial income and political power in decision-making. The LICCI core team applied two main criteria for the selection of project sites. The first criteria was to collaborate with researchers who had established relationships with the community through previous research activities in the same field site or who had planned a 12-month stay in the field site, which will allow them to establish strong links. The second selection criteria was to a relatively homogenous distribution of a) different climate zones and b) main livelihood activities, and c) favored understudied regions.

The insights on climate change adaptation presented in this thesis are derived from diverse regions across the globe, including Central and South America, North and Sub-Saharan Africa, and Central, South and South-East Asia. Included sites cover a wide range of environmental conditions, covering various different climates and multiple altitudes, ranging from coastal areas and islands to alpine mountains at altitudes above 4,000 meter above sea level. Communities in the LICCI sites also represent a high cultural diversity. For example, iTaukei in the tropical island of Viti Levu in Fiji and ribeirinhos in the Juruá region of the Brazilian

Amazonas are mainly fishing communities, while the main livelihood of Kolla-Atacameños in the Andean plateau in Argentina and Mongolians in the Mus Desert in China is pastoralism.

The data collection process consisted of two phases. During the first phase, qualitative data from semi-structured interviews and focus group discussion were collected. During a second phase, quantitative data were collected through household and individual surveys. In each field site, the LICCI project targeted approximately 25 semi-structured interviews, 1-3 focus groups discussions, and 150 household and 175 individual surveys. Qualitative data comprised site and village information (e.g., timeline, infrastructure, seasonal calendar, and main livelihoods), as well as information on people's observation of climate change and impacts. During this phase, researchers also collected information on site-specific local adaptive measures that had been implemented in response to such impacts. Through the surveys, the LICCI project collected socioeconomic information of households and individuals, such as access to financial, physical, human, social and natural capitals, and quantitatively assessed experienced climate change impacts, applied adaptive responses, and encountered adaptation constraints.

Before data collection all collaborating researcher received training. During and after data collection, researchers were in regular contact with the LICCI Core team for consultation, exchange, and feedback. In an iterative process, data was cross-checked to guarantee high data quality. Furthermore, the specific design of the survey allowed for across-site comparisons while considering site-specific characteristics (Reyes-García et al., 2023). Depending on external researchers for data collection implies that the data analysis and interpretation has been carried out without first-hand experience on the respective field sites. Therefore, article drafts that have used field data are shared with the collaborating researchers to guarantee the correct interpretation of the results. Furthermore, I have visited two of the field sites, while further field site visits were impeded by the onset of the COVID-19 pandemic.

In addition to primary data, the thesis uses secondary climate data that describe past and projected temperature trends between 1961 and 2060 for the different LICCI sites. Specifically, I used the CRU TS (Climatic Research Unit gridded Time Series) global dataset for past temperature trends (Harris et al., 2020; New et al., 2000) and temperature projections derived from the Coupled Model Intercomparison Project phase 6 (CMIP6) to describe potential temperature trends until the middle of the 21st century (Eyring et al., 2016; B. C. O'Neill et al., 2016).

Ethics and positionality

The research protocol and data collection approach of the LICCI project received ethical approval from the Ethics Committee of the Universitat Autonòma de Barcelona (CEEAH 4781). Prior to the data collection in the LICCI sites, all collaborating researchers received ethical approval from the Advisory Board of their home institution.

The LICCI project committed to several ethical guidelines and principles, including those from the European Research Council (ERC). In particular, the project requested Free Prior and Informed Consents (FPIC) before data collection, consulted with an external and independent ethics advisor who revised the research protocol and activities, and provided feedback throughout the project, and obtained the commitment that each researcher provides a "give back" of results to participating communities after data collection and analysis. The project also took measures for protecting data, especially personal and sensitive data, for example, data anonymization, and committed to the FAIR principles by providing open access to publications and making data **F**indable, **A**ccessible, **I**nteroperable, and **R**e-usable.

The LICCI project was organized in five phases: 1) development of the research protocol on data collection, including the preparation of the individual and household surveys, 2) a testing phase of the protocol in various sites and subsequently revision of the protocol, 3) selection and training of collaborating researchers, 4) data collection, and 5) data processing.

For the selection of collaborating researchers, and whenever possible, the LICCI project gave priority to Indigenous researchers and researchers with the nationality of the country where data collection should take place.

In the field sites and before starting data collection, all researchers followed a standard procedure to obtain Free Prior and Informed Consent (FPIC), first from local authorities and representatives of the communities, and subsequently from all study participants. The FPIC implies that local authorities, community representatives and study participants were informed about: i) the principal investigator and institution, ii) the goal of the project, iii) the procedure of data collection, iv) potential risks, v) the treatment and protection of data, including of confidential data, and vi) the rights of the study participants. The LICCI project used different forms to receive FPIC, including information sheets, informed consent forms, and oral consent cards for illiterate persons. Participation in the study was voluntary. All and study participants had the right to not refuse participation or -when agreeing to participate- refuse to answer questions they did not want to reply to. At all stages during data collection, study participants had the right to opt out. If required, collaborating researchers slightly adopted data collection methods and questions to the local cultural context to avoid irritation and discomfort by study participants. For example, when considered required, focus group discussions were conducted separately for women and men. All researchers were required to take measures to guarantee data safety. These measures include the anonymization of data, the protection of personal and sensitive data of study participants, such as the use of loggers and passwords to sensitive documents and files. In addition, the LICCI project decided not to share exact location positions.

The LICCI project, and mainly with my contribution, developed and released a data management plant, which contains all relevant information on data collection, data treatment, storage and processing.

Finally, I acknowledge that being a non-Indigenous researcher from the Global North, and with a natural science background, doing research on Indigenous Peoples and local communities, mostly from the Global South, implies certain ethical considerations, which have certainly affected my data analysis and interpretation of the results. Through my positionality, I might have forgotten, overseen or ignored important aspects and explanations in the interpretation of the study results, and therefore might have taken conclusions that do not fully reflect the experienced realities of the participating community members. To minimize misinterpretations, I consulted the collaborating field-study researchers for feedback and corrections. Related to this, and as mentioned previously, the LICCI project has undertaken certain efforts to collaborate with researchers who are native to the country where fieldwork took place and has prioritized collaborations with Indigenous researchers.

Structure of the thesis

This thesis consists of six chapters that include a general introduction (Chapter 1), four empirical chapters (Chapter 2-5) and a general concussion (Chapter 6). The empirical chapters correspond to published articles (or manuscripts submitted to peer review), and are organized around three parts, the need for adaptation (Chapter 2), the nature of adaptation (Chapter 3 and 4), and the challenges of adaptation (Chapter 5).

> **Chapter 1** provides a general introduction to the research aim, the motivation, and the main topics addressed in the thesis. The chapter also describes the general methodological approach, including the LICCI research project, in which the thesis is embedded.
>
> **Chapter 2** presents a new method to assess climate change sensitivity of social-ecological systems and to identify future climate change hotspots. Applying an interdisciplinary and hybrid epistemological approach, I jointly interpret climate data and people's reports on experienced climate change impacts and local adaptive strategies to estimate potential future climate change risks. The methodological approach proposed allows to identify places of high need for strengthening adaptation, as demonstrated by applying the methodology among 16 sites.
>
> In **Chapter 3**, I analyze how rural Indigenous Peoples and local communities respond to climate change impacts based on a literature review of peer-reviewed English articles. Thereby, I assess potential global patterns of local adaptation strategies across regions, climate zones and main livelihood activities.

Chapter 4 looks at local adaptation in the agricultural and aquatic food systems from a sustainability perspective. Based on evidence from secondary literature, I assess the social, economic and environmental dimensions of different Indigenous and local knowledge based adaptive measures.

Chapter 5 finally looks at persistent challenges of local adaptation by assessing common and context-specific adaptation constraints and opportunities among ten Indigenous Peoples and local communities. Specifically, I assess cognitive and socio-economic factors to understand differences in climate change risk experience and adaptive behavior.

Chapter 6, the general conclusion, summarizes the main findings and the theoretical and methodological contributions of the thesis. The chapter also provides policy recommendations, presents limitations and caveats of the thesis, and makes suggestions for future research.

For consistency reasons, the format of published articles and submitted manuscripts has not been modified. Consequently, the thesis shows some repetitive information across chapters, mostly related to the description of the data collection and field sites. Although efforts have been made to use terms consistently across chapters, some inconsistencies remain. For example, in Chapter 4 we refer to “adaptation barriers”, while in Chapter 5 we use the terminology of “adaptation constraints”. I also applied nuanced differences in the terminology when describing adaptation actions, alternating between adaptation, adaptive responses, measures, and strategies. The different uses in terminology reflect both the focus I want to highlight and the evolution of my understanding and interpretation of adaptation during the course of the years.

Part I: The need for adaptation

Chapter 2

Redefining risk: A new approach to identify social-ecological climate change risk hotspots

In preparation for submission to *Climatic Change*.

Co-authors:Waha, K., Álvarez-Fernández, S., Junqueira, A.B., LICCI Consortium, & Reyes-García, V.

Abstract

Anthropogenic greenhouse gasses are causing global warming of the earth system. Temperature increases up to more than 2ºC compared to the pre-industrial era are likely within the realm of possibilities, with unprecedented consequences for social-ecological systems. Understanding sensitivities of social-ecological systems to past and future changes and identifying current and potential future climate change risk hotspots is therefore needed.

We present a novel approach that extends our understanding of climate change sensitivity and risks by considering people's subjective value systems. Our approach puts people's appraisal of experienced climate change impacts, including perceived severities, and people's adaptive behavior in the context of past and projected rates of temperature change. We then explore the validity and practicability of the proposed approach by applying it to 16 Indigenous Peoples and local communities. Primary data were collected using a mixed-method approach, including a total of 1,854 household and 2,501 individual surveys. Secondary data comprise time series on historical temperature changes since 1961 and medium-term projections until 2041-2060 based on two socio-economic scenarios, a "Middle of the -Road" development and a "fossil-fueled" and emission-intensive future. Our findings show that potential future climate change risk hotspots differ considerably from those sites that already report high climate change impacts, indicating a potential gap between expected climate change risks and preparedness. In particular, from the five sites which we identified as potential future hotspots, only in one, community members are already confronting major impacts and have implemented major adaptation in response to them.

We conclude by discussing the contributions and limitations of the presented approach, and offer suggestions for further improvements.

Introduction

The world's climate is changing and there is strong evidence showing that anthropogenic greenhouse gas emissions from fossil burning, land-use changes, and other human activities are the main drivers of the recent and unprecedented global warming (S. Dhakal et al., 2022; Rosenzweig & Neofotis, 2013; Stott et al., 2010). Currently implemented mitigation policies are deemed insufficient to meet the COP21 Paris Agreements from 2015/16 of limiting global temperature rise to 1.5ºC and well below 2.0ºC above pre-industrial levels (Höhne et al., 2021; Liu & Raftery, 2021; Roelfsema et al., 2020; Rogelj et al., 2016). There is increasing evidence suggesting that climate change could alter the earth system's functioning beyond so-called planetary boundaries, thereby threatening safe operating spaces for many living beings, including humans (Hoegh-Guldberg et al., 2018; Lenton et al., 2019; Lyon et al., 2022). The increasing occurrence of hazardous climate events, including droughts, hurricanes, and wildfires, and their effects on managed and cultural systems (e.g., agriculture, settlements) pose a direct threat to human societies by affecting livelihoods, health, culture, and well-being (Adger, 2010; Adger et al., 2013; Seneviratne et al., 2021; Wheeler et al., 2013).

Climate change risks and impacts, i.e., consequences of realized risks, result from the interplay between the probability and intensity of climate-related hazards and the exposure and vulnerability of the concerned social-ecological system, thus the 'propensity or predisposition of a system to be adversely affected' (IPCC, 2018). Since these factors vary across spatial and temporal scales, climate change risks and impacts differ across geographical locations, societies, and individuals, and evolve over time. Climate hazards, i.e., changes in temperatures, that steer direct and indirect cascading effects on other atmospheric processes (e.g., changes in precipitation patterns and wind regimes) and biophysical systems (e.g., marine and terrestrial ecosystems), are not evenly distributed across the globe, with certain geographic regions experiencing magnitudes and rates of changes well above average (Fan et al., 2021; Rosenzweig & Neofotis, 2013; Turco et al., 2015). Additionally, different ecosystems react differently to changes in temperature, hence vulnerability of social-ecological systems also depend on the climate sensitivity, i.e., the "degree to which a system is affected [...] by climate variability or change" (IPCC, 2018), of the biophysical environment (Pecl et al., 2017). Finally, the vulnerability of social-ecological systems -steered by the combined effects of a system's climate change sensitivity and adaptive capacity (IPCC, 2018)- is socially and historically constructed by prevailing political and economic conditions that define pre-existing fragilities and inequalities (Lahsen & Ribot, 2022; Ribot, 2014, 2022). For example, the households' access to assets and capitals (e.g., political, financial and social capital) strongly influences its adaptive capacity (Siders, 2019). Consequently, vulnerability varies not only between societies, but also within communities and households (Porcuna-Ferrer, Calvet-Mir, et al., 2024; Ravera et al., 2016).

In the current context, the identification of geographical areas or locations where a strong climate signal in combination with high vulnerability manifest in major climate change risks, so-called climate change risk hotspots, can help develop, guide, and narrow mitigation and adaptation options (de Sherbinin, 2014; Ericksen et al., 2011; Hare et al., 2011).

We argue that locally experienced climate change impacts and potential risks differ across spatial and temporal scales, not only because global warming manifest in different spatial and temporal patterns of temperature trends and because social-ecological systems react differently to such climatic changes, but also because people differ in their evaluations of what is valuable and matters for them (McNamara et al., 2021; O'Brien & Wolf, 2010; Pill, 2022; Tschakert et al., 2017; van der Linden, 2015). The importance of divers, holistic, and locally defined value systems and related subjective well-being is mostly neglected in current approaches to estimate sensitivity or climate change risk hotspots. Therefore, current efforts to identify climate change risk hotspots are often limited as they i) examine hotspots at large scales -often national, world region or global, which do not allow for detailed analysis at community scales; and ii) often focus on biophysical processes and economic valuation (e.g., Byers et al. (2018), Diffenbaugh & Giorgi (2012), Müller et al. (2014), Thornton et al. (2008), Torres & Marengo (2014) or on singular aspects of impacts, for example food or freshwater security (e.g., Ericksen et al. (2011), Huggins et al. (2022), Stringer et al. (2021)), thereby neglecting that climate change risks imply simultaneous, interacting, and divers consequences for multiple sectors, domains. and values. Moreover, current approaches undervalue cultural and social-psychological factors, such as world views, lived realities and subjective interpretations of well-being and impacts at the local scale beyond economic considerations (McNamara et al., 2021; O'Brien & Wolf, 2010; Pill, 2022; Tschakert et al., 2017; van der Linden, 2015).

An alternative approach for the identification of climate change risk hotspots will consider evidence from different sources of knowledge, including approaches that value local peoples' knowledge, perspectives, lived realities and worldviews (Conway et al., 2019; Tengö et al., 2014). For example, many studies have shown that Indigenous and local knowledge provides evidence of climate change impacts and of the complexity of the climate cause-effect relationships, particularly useful in remote areas where weather stations are rare or absent (Reyes-García, 2024; Reyes-García et al., 2016; Reyes-García, Benyei, et al., 2024; Savo et al., 2016, 2017). We argue that this knowledge could support the identification of hotspots.

Here, we offer new perspectives on climate change sensitivity and hotspots of local social-ecological systems. We develop a method for the identification of climate change risk hotspots at the community level based on synthesized evidence from climate and survey data from 16 sites. Drawing on Tengö's et al. (2014) approach, we argue that using evidence from different knowledge systems (e.g., climate modeling and Indigenous and local knowledge) is a promising way of unveiling the complexities of climate change impacts and allows for the joint assessment and identification of potential climate change risk hotspots that reflect not only climatic, but also social realities. Our approach combines climate data on historical observation of temperature changes since 1961 and medium-term projections of temperature changes for the period 2041-2060, with information on people's appraisals of the severity of experienced climate change impacts and their adaptive behavior.

In the core of this work, we assess 1) past and projected climate hazards for 16 Indigenous and local communities, 2) local severity appraisals of experienced climate change impacts, and 3) local adaptation implementation rates. We then relate this information to estimate the climate change sensitivity for each site and identify potential future climate change risk hotspots.

A multiple evidence-based approach to identify social-ecological climate change risk hotspots

To identify climate change risk hotspots across social-ecological systems based on current climate change impacts and potential climate change risks in future, we propose a method that builds on previous concepts but extends existing approaches by acknowledging evidence that comes from different knowledge systems. Our method uses climate data on past and projected temperature trends, but also gives credits to local people's appraisal of experienced climate change impacts, which reflects what matters according to their value systems (McNamara et al., 2021; O'Brien & Wolf, 2010; Pill, 2022; Tschakert et al., 2017; van der Linden, 2015).

Our approach draws on the understanding that experienced *climate change impacts* of social-ecological systems result from the interplay between i) the magnitude of climate change and ii) the *climate change sensitivities* of the system of concern, thus the degree to which a system is affected in relation to a “climate change unit” (i.e., magnitude of climate change) (Figure 2-1).

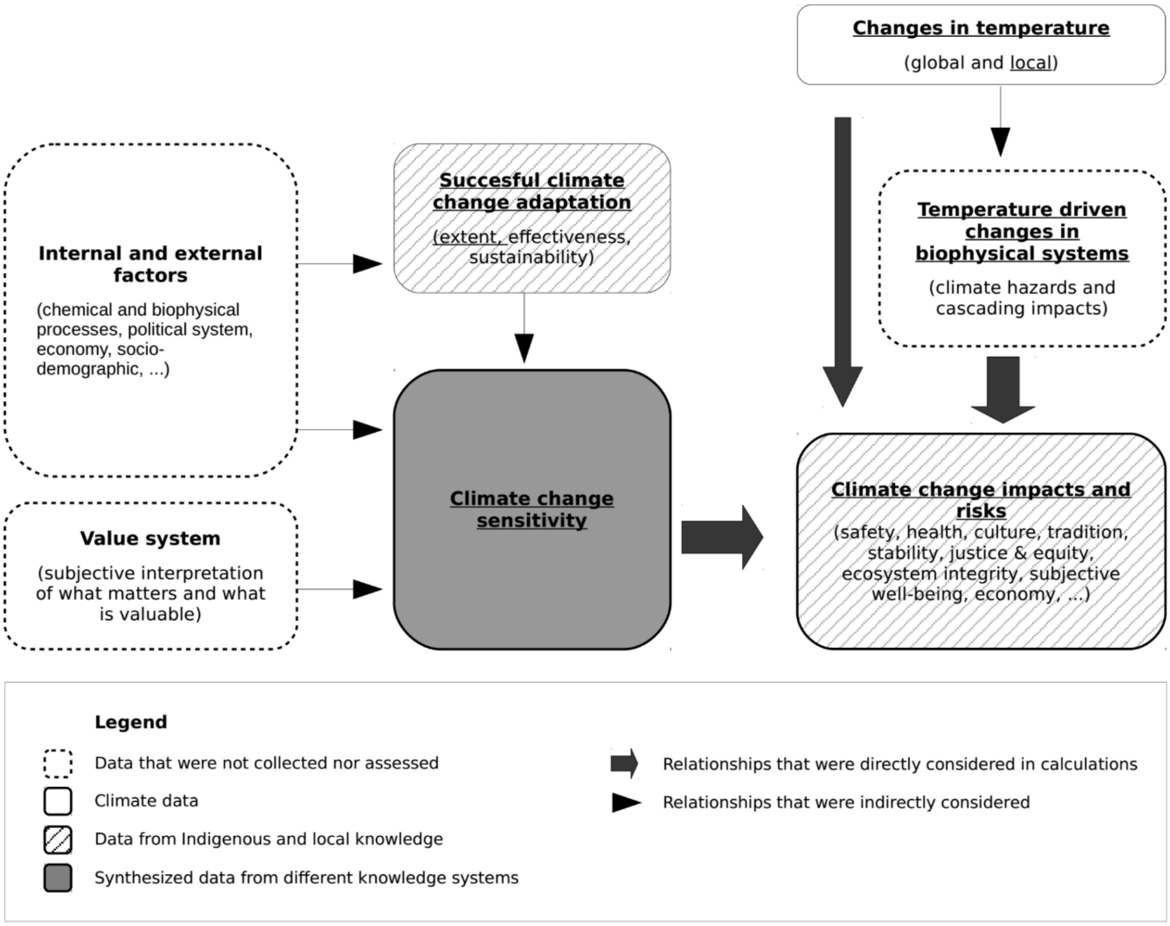

Figure 2-1: Conceptual framework to estimate climate change sensitivity of social-ecological systems and climate change risks based on information from different knowledge systems.

The higher the *climate change sensitivity* of the social-ecological system, the higher the experienced impacts, even when the rates of temperature change are relatively low. In the same vein, relative low *climate change sensitivity* can still result in high impacts if the magnitude of climate change is high or if a climate hazard is observed over a long time period.

As mentioned, the *climate change sensitivity* of a social-ecological system depends on i) internal and external factors (e.g., biophysical and chemical processes, political-economic and socio-demographic conditions), ii) successful adaptation (i.e., feasible, effective, and sustainable), which itself depends on internal and external factors, and iii) the underlying value system of the social-ecological system of concern.

Departing from previous work that mostly neglects underlying value systems, we estimate *climate change sensitivity* based on people's reports on experienced climate change impacts, including their subjective evaluation of the impact severities, in relation to locally manifested temperature trends. Specifically, we target people's subjective appraisal of impact severities for multiple locally relevant observed changes in the social-biophysical environment, such as impacts that relate to changes in precipitation and wind patterns, water and soil, and people's livelihood systems.

By asking people about how much they feel affected by observed climate-driven changes, we assess impact levels that capture the multiple and diverse values that matter for people. In addition, by assessing experienced impacts to a full list of observed climate-driven changes in the surrounding environment, we do not limit our focus to one aspect of climate change impacts (e.g., agricultural impacts, impacts on food or freshwater security, impacts on infrastructure), but rather take a more comprehensive view.

We then relate the estimated climate change impact level to the magnitude of local climate hazards for a specific time period. We consider the mean change in temperature per decade as an adequate proxy for the magnitude of local climate hazards to understand the general climate change sensitivity to locally manifested global warming. Specifically, we use historical climate data from meteorological stations on past decadal temperature trends, although other units to describe climate hazards (e.g., changes in temperature variability or precipitation) are adequate alternatives, depending on the study focus, need, or interest. In our approach, the climate change sensitivity of a social-ecological system will be considered high when reported severity of experienced impacts are high even at a relatively low rate of mean decadal temperature changes.

In a final step, we use the estimated current climate sensitivity in combination with projected temperature trends derived from climate models to estimate potential future climate risks and identify climate change risk hotspots. It is important to note that these hotspots represent potential future risk levels under the assumption that the climate change sensitivity remains constant over time, thus without the effect of future implementation of additional adaptation measures. This is due to the high uncertainties that remain with respect to future adaptive behavior and adaptation success. Therefore, we understand our results as guidance for future adaptation needs, by detecting places that show high discrepancy between potentially high future climate-related risks and currently low adaptation implementation rates.

Materials and methods

This study combines primary data from 16 sites on local reports on observed temperature changes, experienced climate change impacts, and implemented adaption measures and secondary meteorological data of past and projected temperature trends for the same sites. Primary data collection was carried out by an international network of research collaborators and followed a standardized protocol (Reyes-García et al., 2023). The most relevant information on sampling and data collection are summarized below.

Data

Primary data

This study uses primary data from 16 Indigenous Peoples with nature-dependent livelihoods. For the selection of sites, we used two main criteria: 1) diversity across different Köppen-Geiger climate zones and nature-dependent livelihood activities and 2) a well-established relationship between researcher and local community. The included sites are distributed across five continents and 4 Köppen-Geiger climate zones, and cover four different livelihood activities: agriculture, pastoralism (including agropastoralism), fishing, and hunting/gathering (Table 2-1).

Table 2-1: Overview of site characteristics and data collection

Group name	Main livelihood	Site name	Country	Climate	Topography	Household surveys	Individual surveys
Tuareg	agro-pastoralism	Illizi	Algeria	arid	mid-mountains	125	173
Kolla-Atacameños	pastoralism	Puna	Argentina	arid	high mountains	114	151
Ribeirinhos	fishing	Juruá River	Brazil	tropical	low land	121	165
Mapuche	agropastoralism	Lonquimay	Chile	temperate	mid-mountains	74	75
Mongolians	pastoralism	Mu Us Desert, Ordos	China	arid	mid-mountains	173	316
Tibetan	agropastoralism	Shangri-la county	China	temperate	high mountains	124	143
iTaukei	fishing	Ba province, Viti Levu	Fiji	tropical	coast	104	155
Dagomba-Gur	agriculture	Kumbungu district	Ghana	tropical	low land	116	175
Mam	agropastoralism	Western highlands	Guatemala	temperate	high mountains	70	70
Daasanach	agropastoralism	Ileret Ward	Kenya	arid	low land	163	256
Betsimisaraka	hunting/gathering	Vavatenina district	Madagascar	tropical	low land	37	41
Gurung	agriculture	Laprak	Nepal	snow	high mountains	133	133
Pai Tavytera	agriculture	Amambay	Paraguay	tropical	low land	116	157
Bassari	agriculture	Bassari Country	Senegal	tropical (Aw)	low land	138	177
Coastal-Vedda	fishing	Eastern region	Sri Lanka	tropical	coast	125	168
Farmers	agriculture	Chiredzi district	Zimbabwe	arid	low land	121	146
Total						1,854	2,501

Note: coast and low land: <1.000 meters above sea level (masl), mid-mountains: 1.000-2.500, high mountains: >2.500 masl

We used a mixed-method approach to collect primary data. Data collection was divided into two phases. In the first phase, researchers collected qualitative data through semi-structured interviews and focus group discussions and in the second phase they collected quantitative data through individual and household surveys. Data collection took place between December 2019 and December 2022.

In each site, researchers targeted between 1-5 villages (except for one site, where 8 villages were included) with a population size ranging between 20 and 500 households. Villages selected were homogeneous regarding environmental and socio-cultural conditions and representative for the area. Researchers conducted semi-structured interviews to get a comprehensive list of locally observed and experienced climate change impacts, as well as site-specific adaptive measures locally implemented in response to climate-related impacts. Specifically, we asked informants: ‘Compared to your young adulthood, what environmental changes have you observed? And what has driven such changes?’ For each reported change that was related to changes in elements of the climate, we subsequently asked: ‘And how have you and your household, or other people in the community, responded to this specific change?’ To cover the full range of impacts and adaptive measures that people with different characteristics might experience, we selected informants using a convenience sampling targeting a balanced distribution across gender, age group, and main livelihood activity. Saturation of information was normally achieved after 20-30 interviews.

Focus group discussions were held to assess group level agreement when contradictory or inconsistent reports on local climate change impacts were found in semi-structured interviews. Specifically, we conducted focus group discussions when respondents did not agree on the direction of change (e.g., decrease vs. increase), when the change had been mentioned by less than three persons, or when respondents disagreed on the driver(s) of the observed change. Based on the outcomes of the semi-structured interviews and focus groups discussions, for each site we compiled a comprehensive list of the reported and group-validated local indicators of climate change impacts and local adaptive responses.

In each site, researchers originally targeted 125 household and 150-175 individual surveys. The COVID-19 pandemic interrupted data collection and led to a reduced number of surveys in some sites (Table 2-1). The survey included questions for households and individuals. Households were selected at random from the community census and individuals were selected among the household heads based on convenience sampling. In the survey, we collected data on 1) individual reports of observed changes in temperature (i.e., observed temperature changes), 2) individual experiences with climate change impacts and appraisal of impact severities (i.e., climate change impact appraisals), and 3) household's adaptation implementation rates. In the first section of the survey, we asked respondents specifically about how - compared to the respondent's young adulthood - temperature has changed. For each question, we noted the reported direction of change by distinguishing between "increase", "decrease", "no trend", and "no answer". The second section of the survey contained a list of 15 local indicators of climate change impacts, that were randomly selected from the site-specific list of group-validated local indicators of climate change impacts. For local indicators of climate change impacts, we asked respondents if they have observed the specific change (i.e., climate change impact observation), and if so, the experienced severity each impact has on their livelihood (i.e., climate change impact severity). We distinguish between three levels: "does not affect me at all", "affects me a little", and "affects me a lot". In the third section of the survey, we included 10 randomly selected adaptations from the comprehensive list of site-specific reported adaptive responses to assess the household's adaptive behavior. For each of the 10 adaptive responses, we asked if the household had implemented in the past, or was implementing the respective measure at the moment of the survey by distinguishing between "yes" and "no".

Secondary data

We downloaded available spatial data on past and projected temperature trends in NetCDF format from the IPCC Interactive Atlas webpage[1] (downloaded on January 06, 2024) (Gutiérrez

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[1] https://interactive-atlas.ipcc.ch/regional-information

et al., 2021; Iturbide et al., 2021). To extract past and projected temperature changes for each field site, we used the R package ‘raster’ and the site's geographic coordinates (Hijmans, 2023).

To describe changes in observed near-surface air temperature for past periods (i.e., recorded temperature trends), we downloaded the dataset CRU TS version 4.04. Spatial CRU TS (Climatic Research Unit gridded Time Series). The CRU TS data present interpolated spatial climate data on 0.5º latitude by 0.5º longitude of monthly climate anomalies since 1901 derived from an extensive network of weather stations (Harris et al., 2020; New et al., 2000). We downloaded data on observed past temperature changes for the period 1961 to 2015, available in changes in ºC per decade.

Projected temperature changes, downloaded from the Interactive Atlas, describe temperature changes in ºC compared to the reference period 1961-1990, based on more than 30 global model simulations, that were part of the Coupled Model Intercomparison Project phase 6 (CMIP6) (Eyring et al., 2016; B. C. O’Neill et al., 2016). For this study, we use medium-term temperature projections for the time period 2041-2060 based on two scenarios that build on Shared Socioeconomic Pathways (SSPs) on plausible future global societal developments in combination with Representative Concentration Pathways (RCPs) that describe radiative forcing target levels for 2100, based on different assumption on land use change and emissions (B. C. O’Neill et al., 2016). Specifically, for our analysis we selected the scenarios SSP2-4.5 and SSP5-8.5, thus the SSP2 pathway that describes a “Middle of the Road” development in combination with a radiative forcing level in 2100 of 4.5 W/m2 and the SSP5 pathway that describes a “fossil-fueled” development in combination with a radiative forcing level in 2100 of 8.5 W/m2 (B. C. O’Neill et al., 2017; Riahi et al., 2017). Additional information on the used pathways is provided in the Supplementary Materials SM1-1.

In our analysis, we focus on the findings that result from the SSP2-4.5 socio-economic scenario. Results based on the SSP5-8.5 socio-economic scenario are presented in the Supplementary Materials for comparison.

Data analysis

Site-specific climate change impact level and adaptation rates

For each site, we first determine a *site climate change impact index* (sCCI$_{\mathrm{idx}}$) and a *site climate change adaptation index* (sCCA$_{\mathrm{idx}}$). The sCCI$_{\mathrm{idx}}$ describes the site climate change impact level calculated as the mean of household heads' severity appraisal of experienced climate change impacts. The sCCA$_{\mathrm{idx}}$ describes the site adaptation rate calculated as the mean of the households' adaptation implementation.

The *site climate change impact index* (sCCI$_{\mathrm{idx}}$) is the site average of the *individual climate change impact index* (i.e., iCCI$_{\mathrm{idx}}$) of a site. To determine individual and site climate change impact levels, we first transformed individual responses on climate change impact observation and reported impact severity levels into numeric values. For the observation of each of the 15 local indicators of climate change impacts included in the survey, we used binary values: 1 ("observed"), 0 ("not observed"). For the experienced severity level, we distinguished between three values: 0 ("does not affect me at all"), 0.5 ("affects me a little"), and 1 ("affects me a lot"). We then multiplied the observation by the experienced severity level and determined the sum over all 15 impacts. Subsequently, we determined the average value over all individuals of a site to determine the site climate change impact level:

(1a) $$sCCI_{idx} = \overline{\iota CCI_{\iota dx}} \qquad \text{where:}$$

(1b) $$iCCI_{idx} = \frac{\sum_{k=1}^{15}(O_k \cdot S_k)}{15}, \qquad O_k \in \{0,1\}, S_k \in \{0,0.5,1\},$$

where O$_k$ is the observation of the climate change impact k and S$_k$ is the severity level reported for the climate change impact k.

Similarly, for each household, we determined *households' climate change adaptation index* (i.e., hCCA$_{\mathrm{idx}}$) by assessing the relative share of implemented adaptive responses in relation to the total of 10 adaptive responses included in the survey. The average over all households of a site provides the *site climate change adaptation index* ($sCCA_{idx}$):

(2a) $$sCCA_{idx} = \overline{hCCA_{idx}}$$ where:

(2b) $$hCCA_{idx} = \frac{\sum_{k=1}^{10} A_k}{10}, \qquad A_k \in \{0,1\},$$

where A_k is the implementation of the adaptation measure k.

Site-specific climate change sensitivity and potential future climate change risks

We then determined the *site climate change sensitivity index* ($sCCS_{idx}$), which describes how strong a site has been impacted in relation to experienced temperature trends. To assess a site's climate change sensitivity, we related the *site climate change impact index* (i.e., $sCCI_{idx}$) to recorded temperature changes between 1961 and 2015. In general, we assume climate change sensitivity is highest in sites with high experienced impact levels but relatively slow changes in past temperature.

Acknowledging uncertainties in how climate change impact levels evolve with changes in temperature, we present two approaches to determine the *site climate change sensitivity index* (i.e., $sCCS_{idx}$). The first approach describes a linear relationship between temperature change and climate change impact level, and the second one describes a quadratic relationship between them. The first approach assumes that the site's climate change impact level constantly increases with temperature change, whereas the second approach assumes that the site's climate change impact level increases slowly for low temperature changes, but intensifies for higher changes in temperature.

Approach 1:

(3a) $$sCCS_{idx} = \frac{\mathrm{sCC\,I}_{idx}}{\Delta \mathrm{T}}$$

Approach 1:

(3b) $$sCCS_{idx} = \frac{sCCI_{idx}}{\Delta T^2},$$

where ΔT is the recorded change in temperature (ºC) over the observed period (1961-2015).

Based on estimated sites' climate change sensitivities, i.e., *site climate change sensitivity index* (sCC_{idx}), and projected temperature trends until 2041-2060 according to the SSP2-4.5 "Middle of the road" and the "fossil-fueled" SSP5-8.5 scenario, we estimate potential future climate change risks under the assumption that current sites' climate change sensitivities of sites would remain constant at its current level. This allows us to identify potential climate change risk hotspots, thus sites in which current climate change sensitivity levels and projected temperature trends would result in very high climate change risks. To determine a *site-specific climate change risk index* ($sCCR_{idx}$), we multiplied the previously determined *site climate change sensitivity index* by projected temperature changes between 1961 and 2060:

(4) $$sCCR_{idx} = sCCS_{idx} \cdot \Delta T$$

where ΔT is the projected change in temperature (ºC) over the projected period (1961-2060).

In the result section, we focus on the findings that result from approach 1. Results for approach 2 are presented in the Supplementary Materials.

Site-specific climate change transformability

Finally, we determine a *site climate change transformability index*[2] ($\mathrm{sCCT_{idx}}$) which describes how strong a site has transformed (i.e., adapted) in relation to the site-specific climate change impact level.

(5) $$sCCT_{idx} = \frac{\mathrm{sCC\ A}_{idx}}{\mathrm{sCC\ I}_{idx}}$$

For data analysis and visualization, we used R, version 4.1.2 (R Core Team, 2021), and R studio, version 2021.9.0.351 (RStudio Team, 2021).

Results

Temperature changes - Past observations and future projections

Our analysis of the CRU temperature observations between 1961 and 2015 reveals different levels of decadal temperature change across the 16 sites. Decadal temperature changes range between values below or close to 0.1ºC/decade, as the case for Pai Tavytera communities in Amambay (Paraguay), ribeirinhos in the Juruá River region (Brazil), Mapuche in Lonquimay (Chile) and iTaukei in Ba Province (Fiji), to extremely high values close to 0.3ºC/decade, as for Daasanach in Ileret Ward (Kenya) or even close to 0.4ºC/decade, as the case in Mu Us Desert, Ordos (China) (Figure 2-2a).

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[2] We use here the term transformability to avoid confusion with the site climate change adaptation index (i.e., $\mathrm{sCCA_{idx}}$). The site transformability index comprises coping, incremental and transformational adaptation.

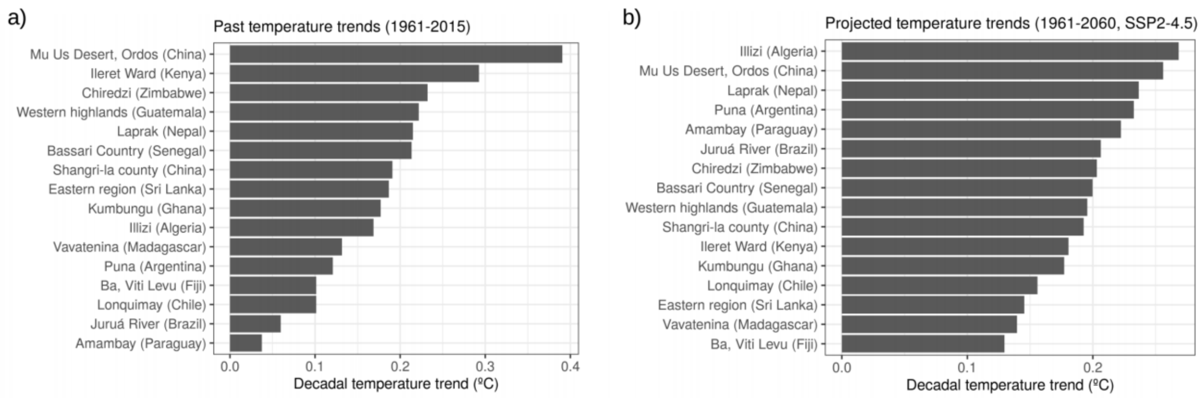

Figure 2-2: Past decadal temperature changes according to the CRU temperature time series since 1961 (a) and projected decadal temperature changes between 1961 and 2060 based on the SSP2-4.5 “Middle of the road” scenario (b).

When extending the considered time period into the future, covering the years 1961-2060, based on the SSP2-4.5 scenario, estimated mean decadal temperature trends considerably differ from past temperature trends (Figure 2-2b).

Highest temperature trends well above 0.25ºC/decade for the time period 1961-2060 are expected for the site of Tuareg agropastoralists in Illizi (Algeria) and of the Mongolians in Mu Us Desert, Ordos (China). While for some regions the peak of decadal temperature trends has already passed (e.g., Mu Us Desert, Ordos, China), implying that decadal temperature trends up to 2041-2060 are lower than in the past, other regions (e.g., Illizi, Algeria) will experience stronger and more rapid temperature changes in the future. Specifically, mean decadal temperature increase is predicted to fall to approximately 0.25ºC/decade (1961-2061) for Mongolians in Mu Us Desert, Ordos (China) and to below 0.2ºC for Daasanach communities in Ileret Ward (Kenya). In contrast, for most sites, projected temperature is expected to increase at a much higher pace than in the past. Differences in the degree of past and future projected temperature changes are especially high for Pai Tavytera in Amambay (Paraguay) and ribeirinhos in the Juruá River region (Brazil), where mean decadal temperature changes are expected to increase to above 0.2ºC/decade for the period 1961-2060. Considerable increases between past and projected decadal temperature trends from below 0.15ºC/decade (1961-2015) to more than 0.25ºC/decade (1961-2060) were found for Kolla-Atacameños communities in the Puna region (Argentina) and from below 0.2ºC/decade to almost 0.3ºC/decade for Tuareg agropastoralists in Illizi (Algeria).

When assessing potential decadal temperature trends according to the SSP5-8.5 scenario between 1961-2060, describing a “fossil-fueled” scenario with high greenhouse gas emissions, the general ranking of sites from highest to lowest values remains similar, however projected trends are much higher for all sites (Figure SM1-2). According to this scenario decadal trends in temperature of above 2.5 ªC are expected for a total of 9 sites, compared to two sites according to the SSP2-4.5 “Middle of the road” scenario.

Local reports on temperature changes, climate change impacts, and adaptation implementation

Local reports on observed changes in temperatures since young adulthood indicate a clear increasing tendency in most sites (Figure 2-3a). In 11 of the 16 sites, more than 50% of the interviewed people reported an increase in annual temperature. Very high site consensus (i.e., > 90%) on reported increases in annual mean temperatures were found in five of the sites; in another three sites the site consensus was high (i.e., > 75%).

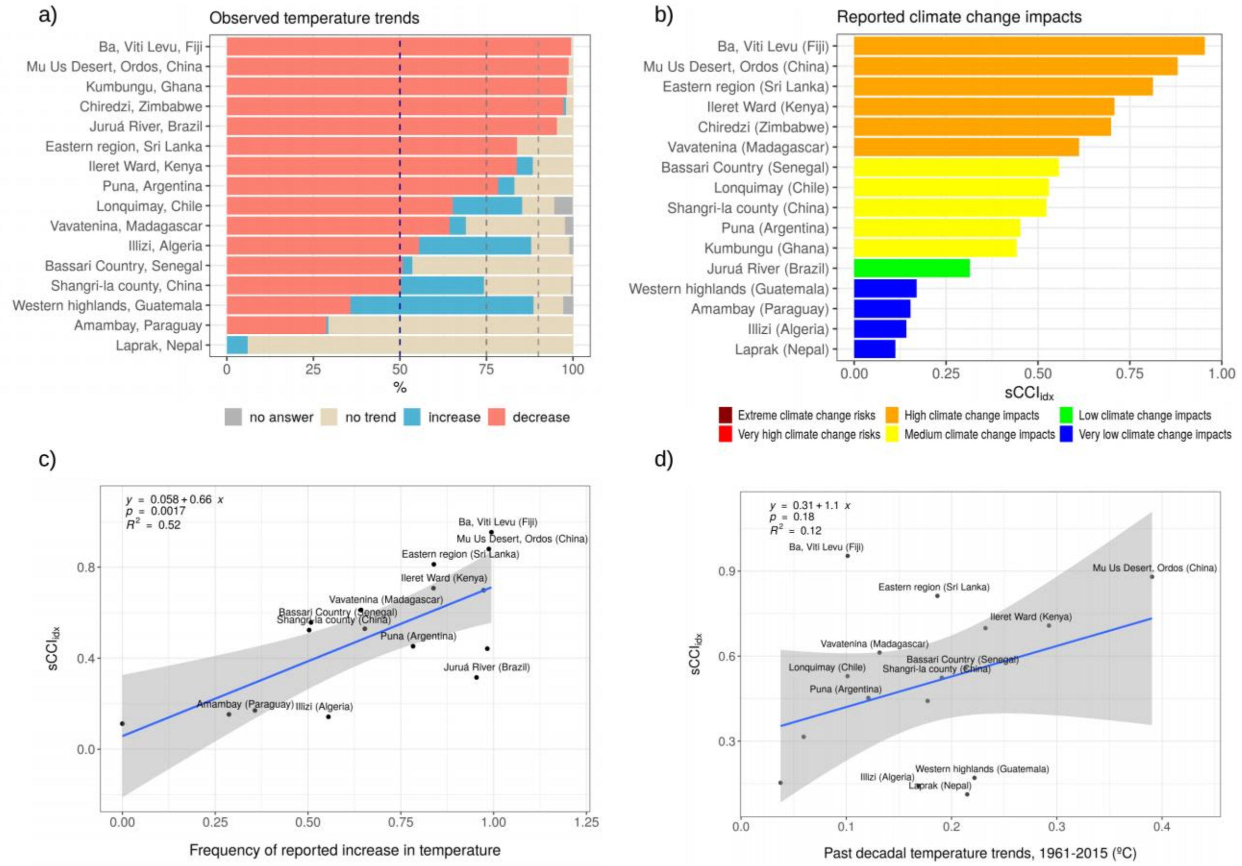

Figure 2-3. Past temperature trends reported by survey respondents (a) and respondent’s severity appraisal of experienced impacts (b). Correlations between site’s climate change impact index and frequency of reported increases in past temperature trends by respondents (c). Correlations between site’s climate change impact index and recorded trends in past temperature based on meteorological data (d).

Similarly, our analysis of sites’ climate change impact levels (i.e., $sCCI_{idx}$) shows considerable variation across sites (Figure 2-3b). In 11 of the 16 sites, people interviewed feel medium to highly affected by climate change impacts, while in only five sites people feel very little or little affected. High climate change impact levels were reported by iTaukei in Ba Province (Fiji), Mongolians in Mu Us Desert, Ordos (China), and Coastal-Vedda communities in the Eastern region (Sri Lanka), with $sCCI_{idx}$ values > 0.75. In contrast, low climate change impacts were reported by Gurung in Laprak (Nepal), Tuareg in Illizi (Algeria), Pai Tavytera in Amambay (Paraguay) and Mam agropastoralists in the Western highlands of Guatemala, with $sCCI_{idx}$ < 0.25.

The analysis of the relationship between the *site's climate change impact index* ($sCCI_{idx}$) and the site's frequencies of locally observed increases in temperature shows a strong and significant linear correlation (Figure 2-3c). The higher the number of people having observed an increase in past temperature, the higher the reported severity levels of experienced impacts, and vice versa. In contrast, there is no significant correlation between the *site climate change impact index* ($sCCI_{idx}$) and recorded past temperature trends between 1961 and 2015 (Figure 2-3d). While most sites follow a linear relationship between site's climate change impact levels and past temperature trends, there are indeed some sites for which experienced impact levels are relatively low compared to the past temperature trends (e.g., for Mam agropastoralists in the Western highlands, Guatemala, or Gurung in Laprak, Nepal).

Our data also shows considerable differences in the sites' adaptation implementation rates, i.e., the *site climate change adaptation index* ($sCCA_{idx}$) (Figure 2-4a). Highest adaptation implementation rates are found among Coastal-Vedda communities in the Eastern region (Sri Lanka) and among iTaukei in Ba Province (Fiji) with $sCCA_{idx} > 0.75$. High values are also found among Mongolians in Mu Us Desert, Ordos (China), local farmers in Chiredzi district (Zimbabwe), and Betsimisaraka in Vavatenina district (Madagascar). In contrast, low values ($sCCA_{idx} < 0.4$) are found in six sites with lowest adaptation implementation rates among Tuareg in Illizi (Algeria) and Mam agropastoralists in the Western highlands (Guatemala).

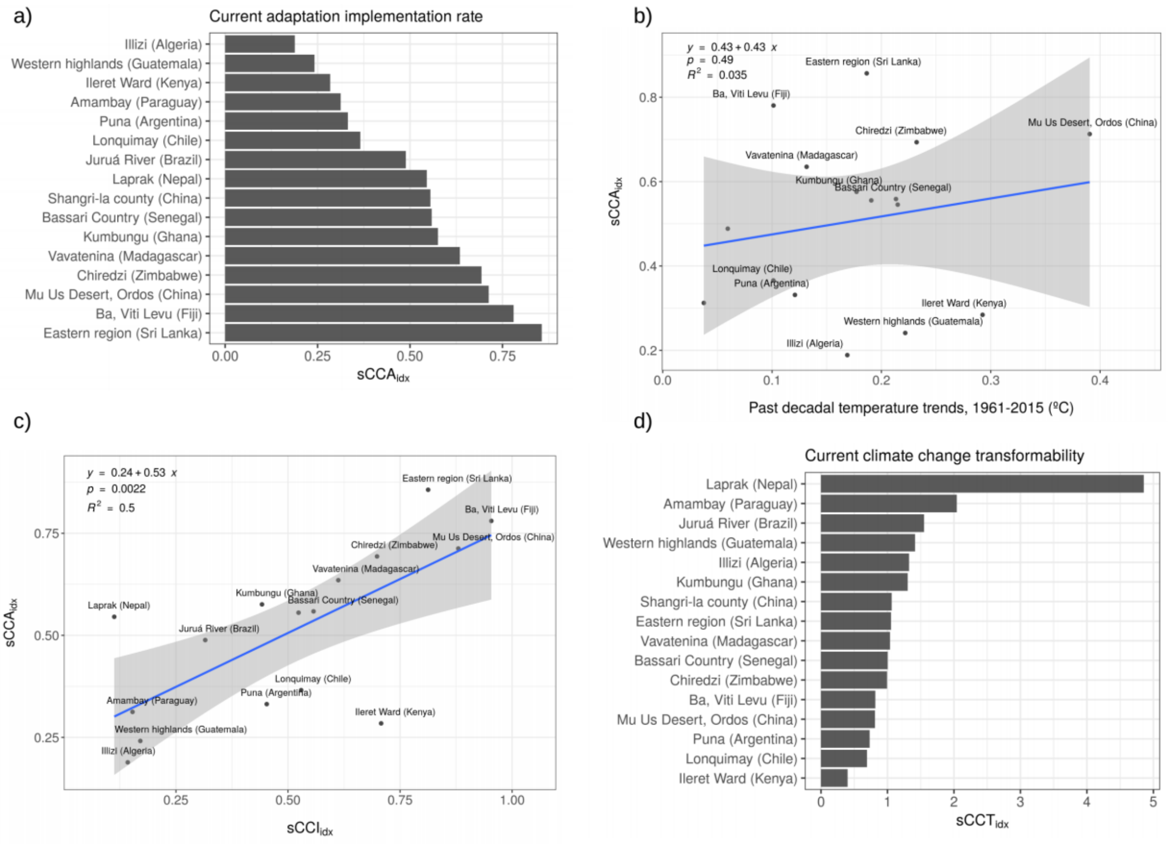

Figure 2-4: Mean climate change impact appraisal levels (a) and mean adaptation implementation rates per site (b). Correlation between the sites' climate change adaptation index and recorded trends in past temperature (c). Correlation between the sites' climate change adaptation index and the sites' climate change impact index (d).

Site's adaptation implementation rates i.e., the *site climate change adaptation index* (sCCA$_{idx}$), did not significantly correlate with recorded past temperature trends (Figure 2-4b). Hence, in sites where past changes in temperature were higher, households have not necessarily implemented more adaptive measures. In contrast, we found a strong and significant linear correlation between the *site climate change adaptation index* (sCCA$_{idx}$) and the *site climate change impact index* (sCCI$_{idx}$) (Figure 2-4c). In sites where respondents feel highly affected by climate change impacts, households' adaptation implementation rates are generally high, for example, among iTaukei in Ba province (Fiji), Coastal-Vedda communities in the Eastern region (Sri Lanka) and among Mongolians in the Mu Us Desert, Ordos (China). In contrast, results for Pai Tavytera in Amambay (Paraguay), Tuareg in Illizi (Algeria), and Mam agropastoralists in the Western highlands (Guatemala) show low site climate change impact levels together with low adaptation implementation rates. The strong correlation between the *site climate change adaptation index* ($sCCA_{idx}$) and the site *climate change impact index* ($sCCI_{idx}$) result in relatively similar values for the *site climate change transformability index* ($sCCT_{idx}$) across sites (Figure 2-4d). Lowest values are found for Daasanach in the Ileret Ward (Kenya), Mapuche in Lonquimay (Chile), and Kolla-Atacameños in the Puna region (Argentina), while highest values are found for Gurung in Laprak (Nepal) and Pai Tavytera in Amambay (Paraguay).

Identifying climate change risk hotspots among 16 sites

In the following, we apply our approach to estimate the climate change sensitivity of social-ecological systems to the 16 sites, with the aim to identify potential climate change risk hotspots.

Results from our analysis according to approach 1 indicate that five sites show evidence of being highly sensitive to climate change ($sCCS > 0.75$), while only three sites show evidence of very low sensitivity ($sCCS < 0.25$) (Figure 2-5a). A high climate change sensitivity is found for iTaukei in Ba Province (Fiji), while Gurung communities in Laprak (Nepal) show evidence of low climate change sensitivity. When applying approach 2 for the estimation of site's climate change sensitivity, our analysis provides similar results for most sites compared to approach 1 (Figure SM1-2). However, for five sites, i.e., for Pai Tavytera in Amambay (Paraguay), ribeirinhos in the Juruá River region (Brazil), and iTaukei in Ba Province (Fiji), estimated values are considerably higher, with values up to 4.5 times higher.

Our findings on potential future climate change risks show that, for all sites, the projected *site climate change risk index* ($sCCR_{idx}$) will increase, thus, for all sites future climate change risks are expected to be higher than currently experienced climate change impacts (Figure 5-2b). We identified five potential future climate change risk hotspots (i.e., sites in Ba Province (Fiji), the Juruá river region (Brazil), Amambay (Paraguay), the Puna region (Argentina), and Lonquimay (Chile)). For only two sites (i.e., Gurung communities in Laprak, Nepal, and Mam agropastoralists in Western highlands, Guatemala) projected future climate risks remain low for both socio-economic scenarios and for the two approaches to estimate climate change sensitivity.

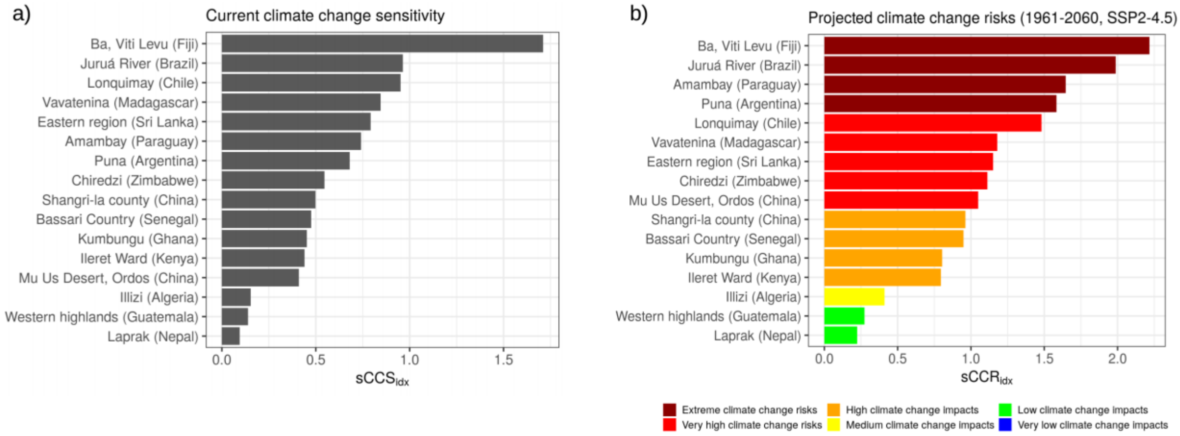

Figure 2-5: Current sites' climate change sensitivities (a) and mid-term projections of sites' climate change risks according to the SSP2-4.5 scenario (b).

In addition, the comparison of how projected levels of climate change risks for the period 2041-2060 differ from current levels of reported levels of climate change impacts allowed us to identify sites that might face rapidly changing conditions. Such rapid changes might transform low-impacted or medium-impacted places to highly impacted places.

For example, from the five sites identified as potential future climate change risk hotshots, only one, iTaukei in Ba Province (Fiji) is already showing a high level of climate change impacts together with a high level of adaptation implementation. Nonetheless, compared to current impact levels and following approach 1 for the estimation of site's climate change sensitivity, projected climate change risks will continue to increase by at least 2 times according to the SSP2-4.5 scenario, or by at least three times according to the SSP5-8.5 scenario (Figure SM1-2). When applying approach 2, projected climate change risks could increase by more than five times. In contrast to iTaukei in Ba Province (Fiji), the other four potential climate change risk hotspots have so far only experienced medium (among Mapuche in Lonquimay, Chile, and Kolla-Atacameños in the Puna region, Argentina) or low to very low climate change impacts (among ribeirinhos in the Juruá River region, Brazil, and Pai Tavytera in Amambay, Paraguay). Especially the last two sites might face unprecedented changes in their environment with projected climate change risks being estimates as more than 6 times (i.e., ribeirinhos in the Juruá River region, Brazil) or even more than 10 times higher (among Pai Tavytera in Amambay, Paraguay) compared to current levels of experienced climate change impacts. These differences between potential future levels of climate change risks and current levels of climate change impacts are even more relevant when considered in relation to current adaptation practices. As shown before, only iTaukei in Ba Province (Fiji) are currently showing high levels of adaptation implementation, while the other four sites show relatively low levels of adaptation. In particular, concerns arise for Mapuche in Lonquimay (Chile) and Kolla-Atacameños in the Puna region (Argentina) due to lowest values of site climate change transformability (i.e., $sCCT_{idx}$).

There are also some sites for which future trends in temperature increase are expected to slow down, resulting in a slight slowdown of projected increases in climate change risk levels. In this category, we found Daasanach communities in Ileret Ward (Kenya), Mongolians in Mu Us Desert, Ordos (China) and, to a lesser extent, Coastal-Vedda communities in the Eastern region (Sri Lanka). And while the current level of adaptation implementation is very low among Daasanch in Ileret Ward (Kenya), the other two sites show high levels of adaptation implementation rates.

Discussion

Drawing on evidence derived from different knowledge systems, we have presented a novel approach that helps 1) assess climate change sensitivity of social-ecological systems and 2) identify climate change risk hotspots for the time period 2041-2060 according to two socio-economic scenarios, the “Middle of the road” (SSP2-4.5) scenario and the “fossil-fueled” (SSP5-8.5) scenario.

Our study contributes to refine our understanding of climate change sensitivity of social-ecological systems and to identify climate change risk hotspots at the community level by considering people’s experiences with climate change impacts. Our method is a first attempt to define social-ecological climate change sensitivity and hotspots based on evidence from multiple knowledge systems, by combining climate data with information from lived experiences. And while this study looks at climate change impacts reported by communities with nature-dependent livelihoods, we argue that the same approach can be applied to any other community.

Looking ahead: Discussing potential entry points to advance our approach on climate change sensitivity of social-ecological systems

Before discussing the finding of the study, we acknowledge certain caveats and limitations of the presented approach.

First, we acknowledge that the use of a 3-level scale to describe the severity of climate change impacts (“does not affect me at all”, “affects me a little”, and “affects me a lot”) has limited informative value. A wider scale could provide more nuanced and differentiated results with a stronger explanatory power on experienced climate change impacts. Second, we acknowledge caveats in the multi-site comparison approach that derive from the biophysical and cultural diversity across sites. Specifically, in each site we asked interviewees about randomly selected site-specific climate change impacts and adaptive responses. Site-specific impacts and adaptive responses might differ in extent, magnitude, and relevance, and adaptive responses might also differ one to another in required investment costs, as well as in effectiveness and co-benefits. This variability affects the comparability of sites’ climate change impact levels and adaptation implementation rates. The use of weighting factors could help compensate for such differences across sites. For example, a weighting factor for local impacts on climate change could build on an additional question on the relevance of a specific climate-related change for people’s livelihood, and a weighting factor for the local adaptation could include information on adaptation effectiveness. However, developing weighting factors to improve the estimation of climate change impacts, sensitivity, and adaptation level is complex, which links to the third caveat of our approach, the lack of assessing adaptation effectiveness. Our measure of adaptation implementation rates represents the frequency of adaptation, thereby limiting our conclusions on climate change preparedness to quantitative measures while ignoring qualitative aspects. Moreover, our approach suffers from a general lack of long-term monitoring studies on climate change impacts and sensitivity of social-ecological systems. In particular, we lack evidence of potential thresholds, including tipping-points, that -once exceeded- could lead to abrupt increases in experienced climate change impacts (Lenton et al., 2008, 2019). We also lack information on how implemented adaptation could influence climate change sensitivity over time. Therefore, we emphasize that our results on potential future climate change risks and hotspots should not be understood as future predictions but as projections under specific assumptions such as neglecting potential tipping-points and the effects of future adaptation on climate change sensitivities.

From acceptable to intolerable risks: The nexus of risk preparedness and limits to adaptation

Despite these caveats, our approach is an important contribution to expanding our current understanding of climate change risks and hotspots by considering people's interpretation of climate change impacts based on their value systems. The holistic approach does not only support decision-making in adaptation prioritization, but also encourages discussion on rethinking current economic-based risk and hotspot assessments. Our approach directly respond to current needs and challenges to define and determine non-economic values, also relevant to improve approaches of loss and damage compensations (McNamara et al., 2021; McNamara & Jackson, 2019; O'Brien & Wolf, 2010; Pill, 2022; Tschakert et al., 2017; van der Linden, 2015).

Our findings provide important insights on potential climate change risk hotspots that lead to two important discussion points. First, our findings show that locations currently experiencing low levels of climate change impacts might turn into climate change risk hotspots, even under short-term projections (2041-2060). Second, our findings indicate that projected climate change risks are estimated to be many times higher than current levels of experienced climate change impacts. These results lead to two main concerns. The first concern relates to the lack of climate change preparedness. The second concern relates to the question whether adaptation can keep up with accelerating climate change impacts.

Out of five potential future climate change risk hotspots identified, four show little risk preparedness, as reflected in relative low adaptation rates. This is especially problematic because potential increases in climate-related risks at unprecedented speed demand for timely and effective adaptation actions. Reactivating the concept of proactive adaptation could therefore play a key role to compensate for currently low adaptation rates and by anticipating impacts arising from rapidly changing socio-environmental conditions (Füssel, 2007; Smit et al., 2000). However, our findings indicate that local adaptation in the considered sites are rather reactive by responding strongly to the severity level of experienced climate change impacts. Indeed, prevailing constraints and limits, including path dependency of institutions, often hamper anticipatory adaptation (Barnett et al., 2015; Boyle & Dowlatabadi, 2011).

Even if proactive adaptation occurs, the question remains if, how, and at what costs adaptation will be effective enough to keep up with accelerating climate change impacts. Dow et al. (2013) distinguish three types of climate risks: 1) acceptable risks whose impacts are so low that adaptation is not required, 2) tolerable risks, which require adaptive efforts to keep impacts within reasonable levels, and 3) intolerable risks for which feasible, i.e., practicable and affordable, adaptation options become unavailable. While, for some of the sites, current experienced impacts at low adaptation rates could be considered acceptable (e.g., for Pai Tavytera in Amambay, Paraguay and ribeirinhos in the Juruá River region, Brazil), these risks could turn into tolerable or even intolerable risks. This also opens up for discussion on the need for transformational adaptation when incremental adaptation is insufficient (Fazey et al., 2018; Fedele et al., 2019; Kates et al., 2012; O'Brien, 2018).

Transformational adaptation describes fundamental and systemic changes that are large in scale with the aim to tackle the root causes of vulnerability (Feola, 2015). Although there is evidence of Indigenous Peoples and local communities who increasingly use transformational adaptation to deal with climate change impacts, so far, most local adaptive measures tend to cover incremental adaptive strategies within traditional livelihood systems (Fedele et al., 2020;

Zant et al., 2024). Since transformational adaptations are high in scope and magnitude, they often require more resources, which could prevent households and communities, particularly those with fewer resources, from implementation (Chung Tiam Fook, 2017; Pelling et al., 2015; Rickards & Howden, 2012). Our findings, indeed, show that in some sites where reported levels of experienced climate change impacts are medium to high, adaptation implementation rates remain relatively low, potentially because constraining factors, i.e., adaptation barriers, limit people's adaptive capacities and hamper households in the implementation of adaptive measures (Shackleton et al., 2015). Intolerable climate risks might ultimately force people to give up traditional livelihoods and move to other places with social, cultural and economic implications (Adger et al., 2013).

Conclusion

This study contributes to a new and more comprehensive understanding of climate change sensitivity and to the identification of climate change risk hotspots across social-ecological systems by presenting a new approach that syntheses information from different knowledge systems and allows for the subjective interpretation of climate change impacts based on different value systems. By detecting discrepancies between current impact experiences and potential climate change risks in future, our findings inform on the urgent need of timely, effective and anticipatory adaptation measures.

By applying our approach to 16 sites under two different scenarios, we find that sites considerably differ in their current climate change sensitivity and adaptation implementation rates, and could differ in potential climate change risks by the middle of the 21st century. As sites for which reported low impacts and adaptation rates might quickly turn into climate change risk hotspots with projected severity levels that are estimated to be many times higher than currently experienced impacts, our findings highlight major gaps in risk preparedness and raise concerns regarding potential limits of adaptation. And although the focus of this study has been on identifying climate change risk hotspots, locations not classified as hotspots should not be neglected since even they can be challenged by future climate change risks. To best understand how climate change risks evolve over time and if adaptation can keep up with the pace and sufficiently reduce impacts on the ground, long-term monitoring programs are required.

How and how strongly anthropogenic global warming ultimately manifests in local impacts for Indigenous People and local communities depends on current and future efforts, achievement or failure in reducing greenhouse gas emissions and on the successful implementation of effective adaptive strategies. Therefore, we conclude that nations, especially from the Global North, have to intensify their mitigation efforts and provide extensive support to those at highest risk in their adaptation efforts so that they can stem the challenges that are ahead.

Part II: The nature of local adaptation

Chapter 3

Global patterns of adaptation to climate change by Indigenous Peoples and local communities. A systematic review

Schlingmann, A., Graham, S., Benyei, P., Corbera, E., Sanesteban, I. M., Marelle, A., Soleymani-Fard, R. & Reyes-García, V. (2021). Global patterns of adaptation to climate change by Indigenous Peoples and local communities. A systematic review. *Current Opinion in Environmental Sustainability*, *51*, 55-64.

Abstract

Indigenous Peoples and local communities have implemented myriad responses to deal with and mitigate climate change impacts. However, little effort has been invested in compiling, aggregating, and systematizing such responses to assess global patterns in local adaptation. Drawing on a systematic review of 119 peer-reviewed publications with 1851 reported local responses to climate change impacts, we show that Indigenous Peoples and local communities across the world apply a diverse portfolio of activities to address climate change impacts. While many responses involve changes to natural resource based livelihoods, about one-third of responses involve other activities (e.g., networking, off-farm work). Globally, local responses to climate change impacts are more likely to be shaped by people's livelihood than by the climate zone where they live.

Introduction

There is a 'strong, credible body of evidence, based on multiple lines of research, documenting that the climate is changing and that the changes are in large part caused by human activities', mainly by fossil fuel combustion and industrial processes (IPCC, 2014b; National Research Council, 2011). The ongoing manifestation of global warming results in local impacts such as an increase in the frequency of coastal flooding, droughts, wildfires, and a continuous decline in sea ice (IPCC, 2014b). Social scientists have shown that communities are differently affected by climate change; not only because climate change impacts are highly place-specific, but also because climate change affects communities through specific pathways, largely mediated by local economic systems and culture. Specifically, climate change threatens the livelihoods and well-being of Indigenous Peoples and local communities (IPLC) — groups who are descended from and identify with the original inhabitants of a region and maintain a deep connection to place and nature over generations (IPBES, 2019)—who urgently need to minimize associated present and future harms (McLean, 2009).

Throughout history, IPLC have experienced and responded to environmental changes and climate variability based on intricate and complex systems of knowledge about the world around them (Makondo & Thomas, 2018), broadly referred to as Indigenous and Local Knowledge (ILK) (Hill, Adem, et al., 2020).

Despite two decades of research on climate adaptation, we know little of the diversity of responses led by IPLC, and of the extent to which ILK-based measures may be transferable and beneficial across regions, cultures and environmental conditions (Barnett, 2010; Forsyth, 2013). Research on IPLC climate adaptation has focused on understanding local, so-called ‘autonomous’ (Forsyth & Evans, 2013), responses through case studies (Berman et al., 2020; Galappaththi et al., 2019), with a few reviews focusing on specific livelihoods (e.g., Savo et al. (2017)), regions (e.g., Ford et al. (2015); Lebel (2013); Shaffril et al. (2020)), or ethnic groups (e.g., Jaakkola et al. (2018)). Only a recently published scoping review (Petzold et al., 2020) represents a first step to reduce the degree of fragmentation of this literature (Siders, 2019).

Systematic literature reviews are a powerful tool for evidence-based decision-making due to their high level of transparency, objectivity and reproducibility compared to traditional reviews (Kraus et al., 2020), and increasingly applied in adaptation studies (Berrang-Ford et al., 2015; Siders, 2019). Departing from previous works, this review does not focus on institutional and governmental-driven adaptation (IPCC, 2014a; Labbé et al., 2017; Travis, 2009) or on participatory processes, such as community-based and co-produced adaptation strategies (McNamara & Buggy, 2017) that do not primarily target community-driven responses (Granderson, 2017). Rather, we focus on community-driven responses to climate change as such an approach directly addresses the need to integrate ILK into adaptation strategies by strengthening bottom-up approaches (David-Chavez & Gavin, 2018; IPCC, 2014b) and contributing to the identification of the best adaptation practices and their potential transferability (Barnett, 2010; Forsyth, 2013). Specifically, with this review we aim at answering the following questions: What is the geographical extent of research on local responses to climate change impacts? What are frequently reported local response strategies? How do responses differ across climates, livelihoods and regions?

Beyond reviewing case studies, our work also aims to develop a detailed and comprehensive classification system of local adaptation strategies that overcomes challenges of previous classifications which are either too broad for in-depth analysis (Agrawal, 2008; Biagini et al., 2014; IPCC, 2014b) or not exhaustive (e.g., Agrawal (2008); Gómez-Baggethun et al. (2013); Savo et al. (2017)). Classifying the documented local responses allows assessment of global response patterns and sheds light on the diversity, commonalities and particularities of IPLC climate adaptation strategies.

Specifically, here we i) review recent research on IPLC responses to climate change impacts, ii) propose a new and comprehensive classification of such responses, and iii) describe the global range, variability and commonalities of such local responses across different climatic zones, livelihood activities and world regions. We adopt an inclusive definition of local responses to climate change as the adaptation of IPLC 'to actual and expected impacts of climate change in the context of interacting non-climatic changes, [. . .] [which] can range from short-term coping to longer-term, deeper transformations, aim to meet more than climate change goals alone, and may or may not succeed in moderating harm or exploiting beneficial opportunities' (Moser & Ekstrom, 2010, p. 22026). We use the term 'local response', instead of 'adaptation', when referring to both direct actions to address climate change impacts and indirect measures in the form of adaptive capacity building to increase the ability of IPLC to implement direct actions (Siders, 2019; Smit & Wandel, 2006).

Methods

We examined peer-reviewed publications that appeared after the Fifth Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 2014b), from January 2015 to December 2019, including case studies documenting IPLC responses to climate change impacts. Our search encompassed, but was not limited to, responses derived from Indigenous and local knowledge (ILK) and covered a recent period of time to identify ongoing responses, that is, responses shaped by current assets, productive systems and institutions, from which we could draw lessons about how to support or mainstream local adaptations in the years to come. Detailed information on the review process, including search terms, article selection, data coding, and spatial and statistical analysis can be found in the Appendix A. Supplementary Materials 2-1 (SM2-1).

Drawing on previous classifications of ‘adaptation’ (e.g., Savo et al. (2017); Thornton & Manasfi (2011); Travis (2009)) and through an iterative process that involved analyzing similarities and differences among documented responses, we developed a 3-level classification system defining response sectors, domains, and types (see Table SM2-4.1). The response sector encompasses the main natural resource dependent livelihood activities, for example, cultivation, livestock and fishing, as well as responses in other activities, such as housing, community life, and wage labor. The response domain captures whether changes relate to activities’ timing, location, livelihood products, productive resource input, social and human capacity building, or the whole livelihood system. Finally, the response type identifies whether the response domain refers to quantitative changes, measurable in physical units (e.g., kg, ha, money) or to qualitative changes, such as changes in crop or livestock composition or in the cultivation methods applied. Each response strategy is further described by a direction (e.g., increase, decrease).

Results

Geographical distribution of case studies

The 119 articles reviewed reported 1851 local responses to climate change impacts. Results correspond to 181 case studies in 260 locations in 44 countries (Figure 3-1 and Table SM2-3). 70% (n = 126) of the case studies refer to locations in Asia (n = 68) and Africa (n = 58), and another 15% to locations in Latin America (n = 27). There were more case studies in the equatorial (n = 54), temperate (n = 53) and arid (n = 30) regions, than in the snow (n = 23) and polar regions (n = 21). About one-third of the studies were located along the coast (n = 67), in the low-lands and midlands (n = 62), and at altitudes above 1500 masl (n = 52), respectively.

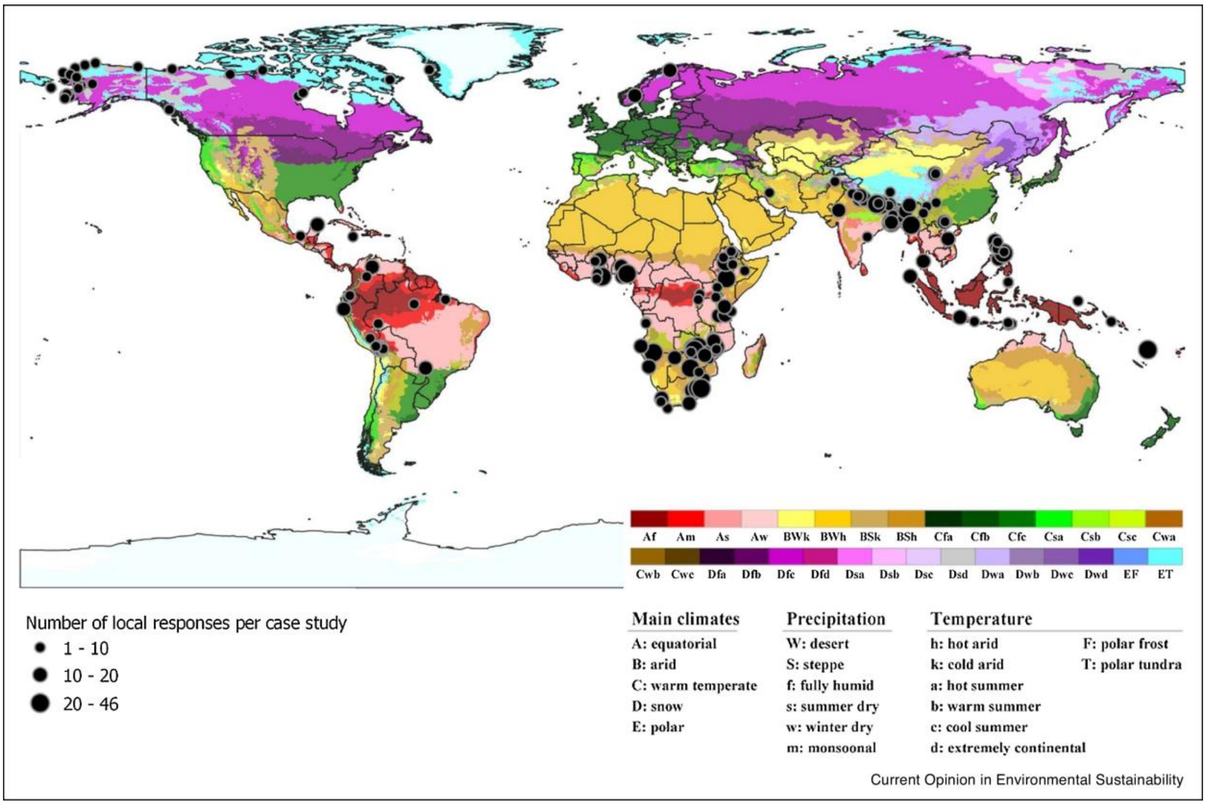

Figure 3-1. Global distribution of case studies found in the literature across different main climates according to the Köppen-Geiger classification (Kottek et al., 2006).

Classifying local responses to climate change impacts

We classified the 1851 reported responses into 187 categories, of which 57 belong to cultivation, 33 to livestock, and 22 to fishery sectors. 46 categories refer to other activities. Two-thirds (63%) of reported local responses occur in natural resource dependent livelihood sectors, and particularly in the cultivation sector (40%) (Figure 3-2, sectors). This is consistent with agriculture being practiced in 80% of the case studies. In contrast, although 45% of the communities keep livestock and 38% practice fishing or aquaculture (Table SM2-3), proportionately fewer responses were documented in these sectors, that is, 13% and 5%, respectively. As much as 37% of the responses documented do not refer to a specific livelihood, but rather to changes in other household assets, such as social capital (e.g., sharing food and other resources), or infrastructure (e.g., building dykes).

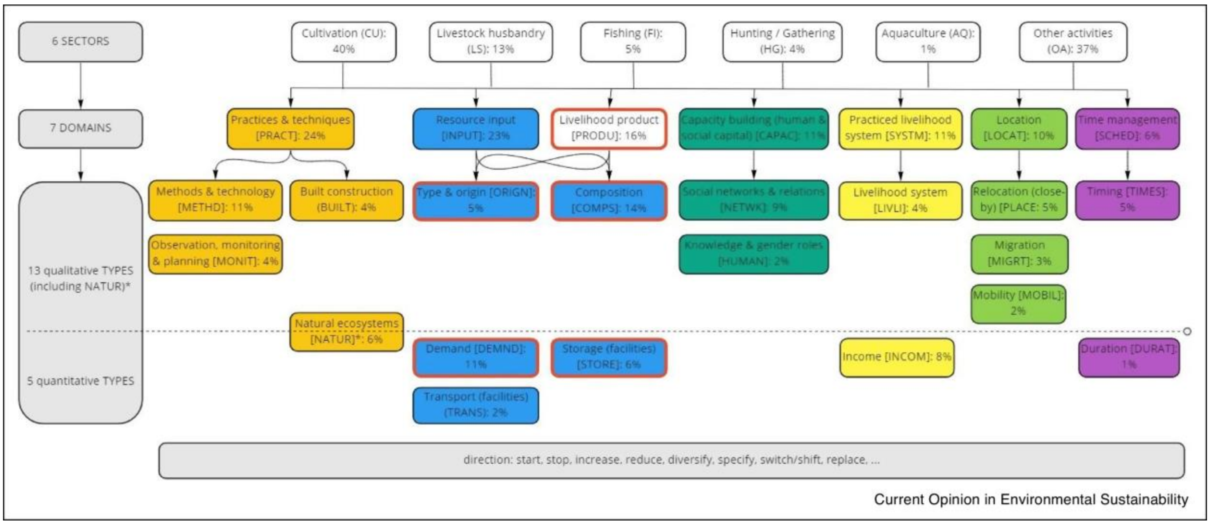

Figure 3-2. Diagram of the classification and coding system. Note that some strategies of the response type ‘Natural ecosystems (including biodiversity conservation)’ are qualitative, and some are quantitative. For the definitions of each response sector, domain, and type see Table SM2-4.1.

With respect to domains, as much as one-quarter (24%) of local responses involved changes in practices (e.g., methods applied, weather forecast, biodiversity conservation), and almost one-quarter (22%) involved changes in productive resource inputs (e.g., water, fertilizer). Changes in location and time management corresponded to less than 10% of reported responses each (Figure 3-2, domains). Finally, 68% of the responses represented qualitative changes, while only 32% accounted for quantifiable changes (Figure 3-2, types).

Some of the responses reported draw from ILK, such as indigenous seasonal climate forecasts and farming practices (Iticha & Husen, 2019; Tunde & Ajadi, 2018). Other responses, such as the use of GPS devices (Clark et al., 2016) or switching to early maturing hybrid varieties (Rahman & Alam, 2016), draw from scientific knowledge (see Table SM2-4.2).

The five most frequent response categories describe 33% of all reported local responses. These include ‘changes in the composition of cultivated crops and trees’ (CU.PRODU.COMPS = 10%), ‘changes in applied methods and techniques in cultivation’ (CU.PRACT.METHD = 7%), ‘changes in general social relationships & networks among community members’ (OA.CAPAC.NETWK = 6%), ‘changes in finances and incomes not derived from natural resource-dependent livelihoods’ (OA.SYST.INCOM = 6%), and ‘changes in the protection of natural ecosystems (including biodiversity conservation)’ (OA.PRACT.NATUR = 4%).

Comparing adaptation strategies across climates

Documented responses are similar across climate zones, with larger diversity within each climate zone than across zones (Figure 3-3). With the exception of snow regions, the most reported sector-based responses in all climate regions relate to cultivation (30–50%) and other activities (23–42%). In the snow regions, most responses refer to changes in livestock rearing (42%) and other activities (24%). The few responses reported for the fishery sector are limited to the equatorial, arid and polar regions (Figure 3-3b).

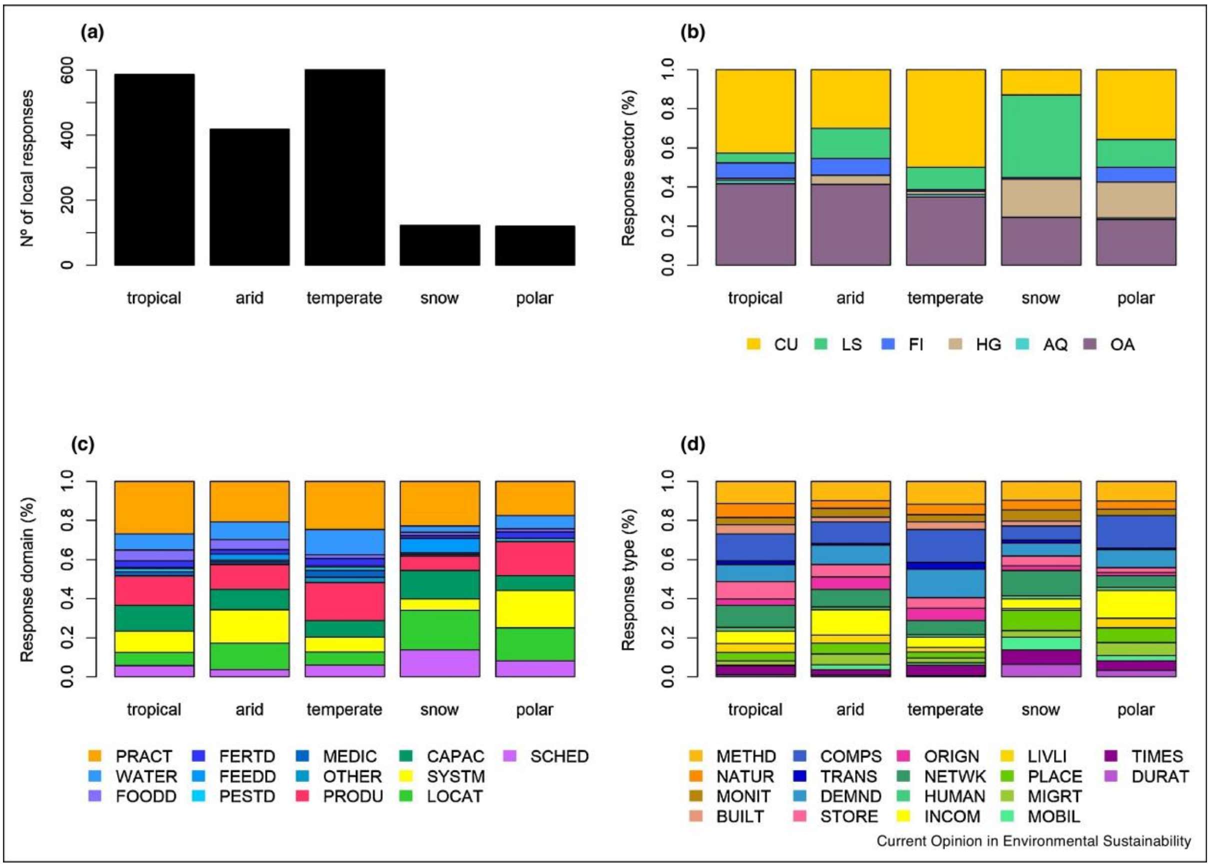

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Figure 3-3. Frequency of local climate change responses across climate zones (a), according to the response sector (b), the response domain (c), and the response type (d).

Changes in practices are the most frequently identified local response domain (21–27%) (Figure 3-3c), except in the polar regions, where a shift in the main livelihood system and income sources is more frequently reported (19%) than changes in practices (18%). In the snow region, changes in location are the second most common response domain (20%), probably due to common livestock rearing in higher mountain regions, such as the Andes and the Himalayas. In the other climate regions, responses related to changes in productive resource inputs (13–20%), such as water and food, were more often reported than changes in locations (7–17%). Nuanced differences exist regarding livelihood products, including changes in crop composition, which are more frequent in the temperate zones (20%), and changes in income generation activities, which are more frequent in the arid (13%) and polar regions (14%) (Figure 3-3d).

Comparing local adaptation strategies across sectors

Local responses to climate change impacts largely vary across sectors (Figure 3-4). The largest number of local responses was documented within the cultivation sector (n = 736) (Figure 3-4a). The most common local responses in the cultivation sector involve changes in the livelihood products (30%) — mainly changes in crop composition — followed by changes in cultivation practices (21%), for example, soil conservation methods, and changes in the application of productive resources, such as irrigation (13%) and fertilizer use (8%) (Figure 3-4b). Responses in the livestock sector were dominated by changes in grazing location (21%) and changes in animal species and herd size (21%). Adjustments in feeding practices accounted for 13% of the responses in the livestock sector. In the fishing sector, the most common responses correspond to the adoption of new fishing techniques (31%), especially the use of improved methods and gear (20%), followed by changes in the location of fishing spots (19%) and the duration and timing of fishing activities (14%) (Figure 3-4b, c). Responses in 'other activities' focus on intensifying social relationships and networks (16%), income generation through wage labor or small businesses (16%), and biodiversity conservation (10%) (Figure 3-4c).

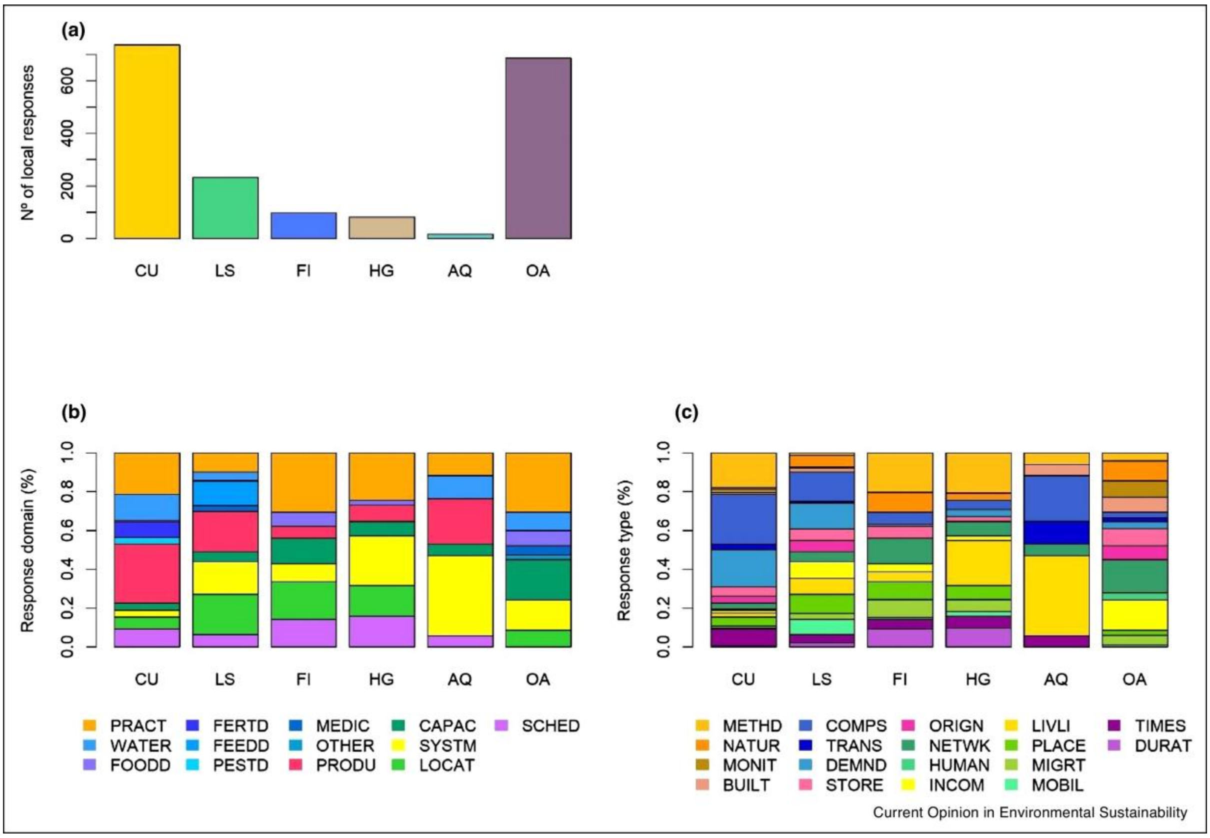

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Figure 3-4: Frequency of local climate change responses across different response sectors (a), according to the response domain (b) and the response type (c). Sectors: cultivation (CU), livestock husbandry (LS), fishing (FI), hunting/gathering (HG), aquaculture (AQ), and other activities (OA).

Comparing local adaptation strategies across world regions

To understand macro-regional patterns, we compared the local responses documented in regions with more data, namely Sub-Saharan Africa (AFR, n = 776), South Asia (SAS, n = 448), Latin America (LAM, n = 223) and the Asia-Pacific region (PAS, n = 203) (Figure 3-5a).

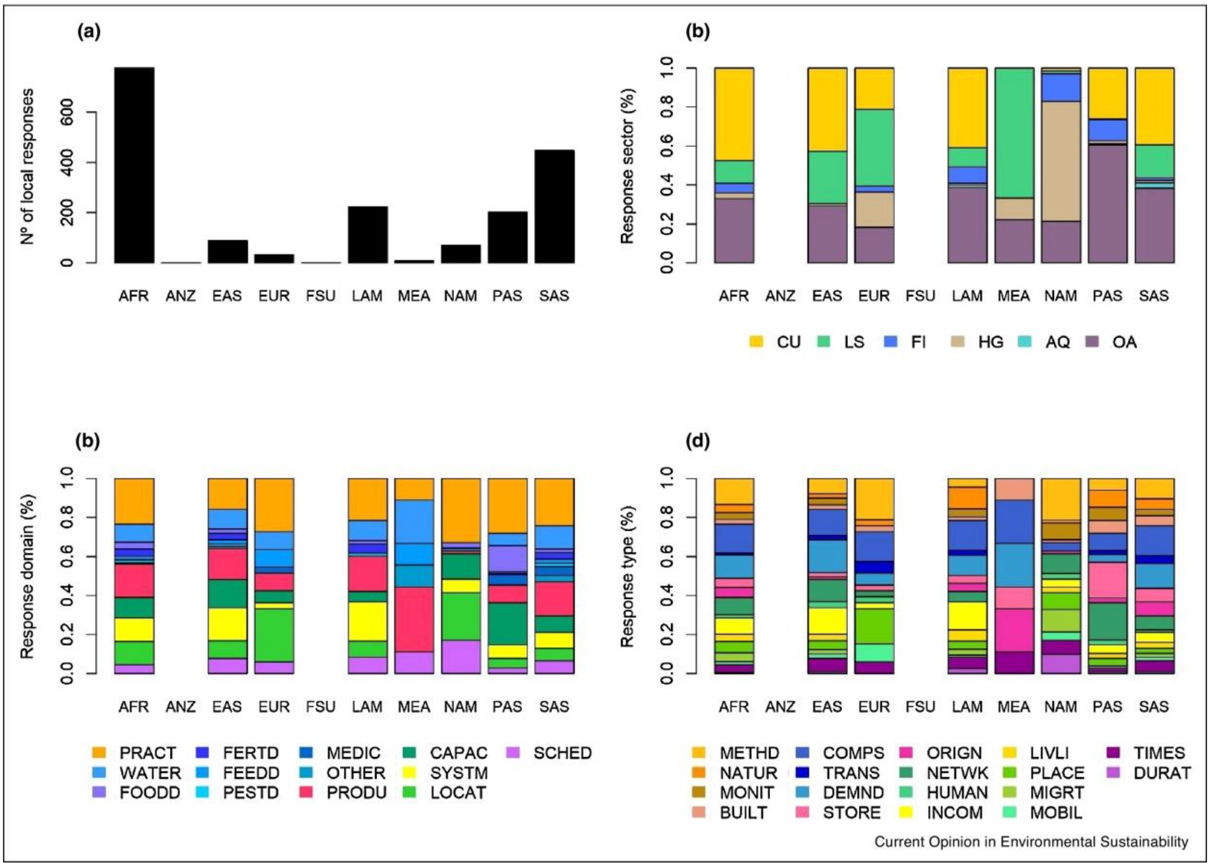

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Figure 3-5. Frequency of local climate change responses across world regions (a), according to the response sector (b), the response domain (c), and the response type (d). For the definitions of each world region see Table SM2-2.

Sub-Saharan Africa and South Asia show similarities regarding the frequency of responses for the cultivation sector, 48% and 40%, and other activities, 33% and 38%, respectively (Figure 3-5b). Latin America and the Asia-Pacific region show different patterns. For example, in Latin America and the Asia-Pacific region, the share of local responses directly related to the fishing sector are higher than in other regions, 9% and 11% respectively. No responses related to livestock keeping are reported for the Asia-Pacific region.

Although Sub-Saharan Africa and South Asia show similar response patterns regarding the cultivation sector, differences exist with respect to the response domain and type (Figure 3-5c,d). For example, while the demand for productive resource input, including water, fertilizer, pesticides and medicine is higher in South Asia (29%), more responses relate to relocation, including mobility, (12%) and income generation (9%) in Sub-Saharan Africa. Income generation is also a common response strategy in Latin America, while in the Asia-Pacific region a more common response is to strengthen social networks (19%) and rely on food storage (11%).

Discussion

IPLC across the world rely on a diverse portfolio of responses to face climate change impacts. While many responses involve changing natural-resources-based livelihood practices, about one-third of responses involve other activities (e.g., networking, off-farm labor, or biodiversity conservation). Globally, IPLC responses to climate change are more often shaped by livelihood activities than by the climate zone in which respondents live. We identified a geographic bias in the selected cases, which may be due to the uneven global distribution of research — also reported in other reviews on related topics (David-Chavez & Gavin, 2018; Petzold et al., 2020; Reyes-García et al., 2019; Savo et al., 2016) — the exclusion of gray literature (Piggott-McKellar et al., 2019) and non-English publications (Forero et al., 2014), and research investment patterns (d’Armengol et al., 2018).

Consistent with previous work (Lebel, 2013; Savo et al., 2017), we found a large number and diversity of local responses to climate change impacts. In absolute terms, we have identified more responses than any previous systematic review and described a larger number of response categories (Lebel, 2013; Nyong et al., 2007; Savo et al., 2017). Our 3-level approach is more comprehensive and detailed than previous classification systems (Paterson & Charles, 2019; Petzold et al., 2020; Smit & Skinner, 2002), thereby contributing to an improved understanding of local response strategies. Our classification system also allows manifold analysis by disentangling local responses into elementary units, that is, sector, domain and type. We found that IPLC generally respond to climate change impacts by changing aspects of their natural resource dependent livelihood system (63%), with cultivation being the most represented sector in the sample. While this predominance can be partially explained by the relative global importance of small-scale agriculture (Herrero et al., 2017; Ricciardi et al., 2018; Samberg et al., 2016), the share of responses in other livelihood sectors is disproportionately low compared to the number of communities that engage in other livelihoods in our sample. The apparent predominance of responses in the cultivation sector may also be due to the direct and strong impacts of changing rainfall patterns on cultivation and the resulting urgent need to adapt (IPCC, 2014a).

Similar to previous work (Biagini et al., 2014; Klöck & Nunn, 2019; Petzold et al., 2020), our findings show a high proportion of local responses related to behavioral changes, especially in the methods and techniques applied. However, contrary to previous work (e.g., Biagini et al. (2014)), we did not find that management, planning and knowledge transfer are important local adaptation strategies, probably because our review captures more spontaneous and reactive activities such as coping, adjusting or securing (Berrang-Ford et al., 2011).

As much as 36% of the documented responses do not directly relate to natural resource dependent livelihoods but to other household and community assets, for example, social networks, spirituality or biodiversity conservation (Granderson, 2017; Hiwasaki et al., 2015; Makondo & Thomas, 2018). A strong link between ILK and social capital and biodiversity conservation has also been reported in other studies (Ford, Smit, Wandel, et al., 2006; Joa et al., 2018). The importance of social relations in adaptation derives largely from its interaction and cascading benefits with other forms of capital (e.g., Adger (2003); Petzold & Ratter (2015)). For example, social institutions such as customary laws support coastal forest protection as adaptation measures to climate change impacts (Hiwasaki et al., 2015).

Although our search specifically targeted responses to climate change impacts by IPLC, not all reported responses could be unequivocally described as Indigenous or local (Hill, Adem, et al., 2020), indeed some were externally driven and/or scientifically based. For example, the use of chemical fertilizers and pesticides, the adoption of hybrid varieties or the shift towards off-farm work (Dedeurwaerdere & Hannachi, 2019; Emmanuel et al., 2016) were common responses. This finding shows that IPLC respond to climate challenges by using information from different knowledge systems (Granderson, 2017; Naess, 2013), but it also raises questions about the long-term viability of some responses, due to their financial capital requirements (Baloch & Thapa, 2018; Rotz & Fraser, 2015) or potential negative ecological impacts (Antwi-

Agyei et al., 2018). Other responses are more transformative and imply the potential loss of culture, tradition and social bonding (Adger et al., 2013). In that sense, it is important to note that responses cannot be considered successful ‘adaptation strategies’ until their long-term viability, effectiveness, sustainability and potential impacts have been examined (Adger et al., 2005).

Our results on global patterns of local responses to climate change impacts show that ILK is relevant and transferable beyond the local context and scale of communities (Forsyth, 2013). While the similarities in response strategies across climates may seem surprising, we argue that the patterns reflect the fact that people use similar strategies, rather than identical responses. For example, in different climates, changes in the cropping patterns and the adoption of irrigation might be a common response to climate change impacts in the cultivation sector. However, the selected species and varieties and the amount of required irrigation likely differ (Seo & Mendelsohn, 2008). Thus, applying our findings at the local level requires accounting for local conditions and peculiarities.

Our classification system of local responses to climate change impacts provides a new tool for future analyses on the topic. For future work, we have the following recommendations: the consideration of additional literature, including gray literature, could further improve the classification system and our understanding of local responses to climate change. Future research could also apply this classification system to related topics such as assessments of adaptation drivers, adaptation enablers and barriers, evaluations of adaptation feasibility, success, future viability, long-term sustainability and potential socio-cultural impacts of local responses to climate change impacts. Those are relevant topics for which our classification system presents a supportive tool for in-depth understanding.

Conclusion

Our systematic literature review constitutes a first attempt to consolidate and structure the scattered findings from many case studies on IPLC local responses to climate change impacts. The classification framework presented permits manifold analysis and comparisons of local responses within and between communities from different climates, world regions and with different natural resource dependent livelihoods, at local, regional and global levels. Our study shows that IPLC local responses to climate change are diverse, covering social, ecological and economic adjustments. Synthesizing such a wide range of local responses can help researchers, governments and other decision makers to understand the diversity of activities undertaken by IPLC, which could be used as a platform for informing future policies that support bottom-up approaches.

Chapter 4

The sustainability assessment of Indigenous and local knowledge-based climate adaptation responses in agricultural and aquatic food systems

Galappaththi, E. K., & Schlingmann, A. (2023). The sustainability assessment of Indigenous and local knowledge-based climate adaptation responses in agricultural and aquatic food systems. Current Opinion in Environmental Sustainability, 62, 101276.

Abstract

We examine common Indigenous and local knowledge-based adaptive responses to climate change from the sustainability perspective among Indigenous and local communities globally. We draw upon an assessment of 98 peer-reviewed articles to assess how local-level responses interact with the broader sustainability dimensions of social, economic, and environmental. We focus on five adaptive responses: 1) community-based adaptation, 2) diversification, 3) local governance and conflict resolution schemes, 4) land, soil, and water management, and 5) traditional weather forecast. Using sustainability framing, we illustrate how these adaptive responses can be both resilient and vulnerable. We argue that long-term successful adaptation to climate change should aim to avoid any increase in, and instead should decrease, vulnerability related to the social (e.g., loss of social bonds and mutual support), economic (e.g., insecure income), and environmental (e.g., soil contamination) dimensions. There is an urgent need to discuss successful adaptation to climate change from a holistic approach that includes long-term social, economic, and environmental sustainability aspects.

Introduction

Climate change is creating an unprecedented challenge for humanity, undermining progress toward achieving the Sustainable Development Goals (SDGs) and exacerbating ongoing difficulties facing the world's most disadvantaged communities (Fuso Nerini et al., 2019; Yap & Watene, 2019). In particular, climate change poses a high risk for Indigenous and local people (ILP) (Ford et al., 2020; Shaffril et al., 2020). This reflects the interaction of a combination of factors, including colonization, discrimination, and social exclusion, and directly results in conditions such as a high burden of food insecurity, ill health, and poverty (Comberti et al., 2019; Huang, 2018; Leite et al., 2020). Many of the risks that climate change poses stem from interactions with food systems (Lemke & Delormier, 2017). Indigenous and local communities typically have 'mixed' food systems, deriving significant nutrition from subsistence-based agriculture, hunting, fishing, and foraging, alongside small-scale farming, while also engaging in market activities to sell and obtain food (FAO, 2021; Galappaththi et al., 2021). While these food systems have historically been resilient, the compounding nature of climate risks and, in many cases, government policies has created significant vulnerabilities. At the same time, Indigenous communities are not ‘agent-less’ and helpless; they display a certain resilience to climate change, derived from their profound local and contextualized knowledge and their capacity to adapt to the climate variabilities they have faced over generations (Ford et al., 2020).

Indigenous and local knowledge (ILK) are an explicit characteristic of ILPs’ adaptive responses associated with their food systems. We understand ILK as an integrated body of knowledge transmitted orally and derived from the accumulation of long-term observations, experiences, and history in the collective memory with communal understanding (Berkes, 2018). Some threads of these knowledge systems are woven into various aspects of the lives of ILPs, whose diverse cultures and traditions helped develop the knowledge required to adapt to a remote environment (Maldonado et al., 2016). ILK is considered a process rather than content, as it coevolves through an adaptive process and is handed down by cultural transmission from one generation to the next (Kitolelei et al., 2021). This knowledge system also faces the serious threat of weakening, as it has been lost, is not learned by the current generation, or remains undocumented (Kitolelei et al., 2021). In this context, this body of knowledge has been fundamental to the environmental, cultural, and livelihood sustainability of ILPs (Berkes, 2018).

Previous studies have emphasized the intertwined nature of social–ecological systems and the dependency of economic and social well-being on an entire biosphere (Folke et al., 2016) as well as the importance of better understanding the nexus between effective adaptation, resilience, and sustainable development (Fuso Nerini et al., 2019; C. Singh et al., 2022). Eriksen et al. (2011) identify the integration of local knowledge as one of four key principles for sustainable adaptation, which, per definition, heightens social justice and environmental integrity across spatial and temporal scales while increasing resilience to climate change.

From this perspective, through the sustainability perspective, we identify and examine common ILK-based adaptive responses to climate change among ILPs globally. We draw upon an assessment of 98 peer-reviewed articles published over the last three years (2019–2021) to assess how local-level responses interact with the broader sustainability dimensions (e.g., social, economic, and environmental). In structuring our analysis by using sustainability framing, we also illustrate how ILK-based adaptations can be both resilient and vulnerable. We define resilience as the capacity of individuals, communities, and systems to survive, adapt, and self-organize in the face of stress and shocks and even transform when conditions require it (K. Brown, 2016). Vulnerability is susceptibility to harm (Arora-Jonsson, 2011). In writing this paper, we acknowledge that we are non-Indigenous academics who work within the epistemic community of global-change research. This positionality affects our analysis and interpretation of the literature.

Methods

Semi-systematic literature review

This article presents results from a semi-systematic literature review (Snyder, 2019), conducted in June 2021, to detect common patterns of ILK-based adaptation to climate change in small-scale agricultural and fishery communities. The underlying work contributed to chapter 5, 'Food systems,' in the Sixth Intergovernmental Panel on Climate Change (IPCC) report (IPCC, AR6, WG II, chapter 5, 2022) (Bezner Kerr, Hasegawa, et al., 2022)(Bezner Kerr, Hasegawa, et al., 2022) and focused on scientific literature published between 2019 and June 2021 to capture the most recent research evidence in line with the journal's publication guidelines.

We applied a two-phase search approach by using the web-based databases Web of Science and Scopus to identify English peer-reviewed publications (Figure 4-1). In the first phase, we used key search strings based on three subtopics: 1) ILK, 2) climate change, and 3) adaptation (see Table SM3-1 for specific search terms). This resulted in a list of 402 articles in Web of Science and 316 articles in Scopus. Duplicated articles (n = 243) that appeared in both databases were removed. The remaining 475 articles were screened for titles and abstracts. The purpose of this initial screening was to identify major ILK-based adaptation topics for the second phase. The themes were selected based on the number of articles published under each theme, and the depth and breadth of each study. The major adaptation themes were identified for small-scale fisheries (i.e. community-based adaptation, livelihood diversification, and local governance and conflict resolution) and smallholder farmers (i.e. crop diversification, traditional weather forecast, and soil and water management).

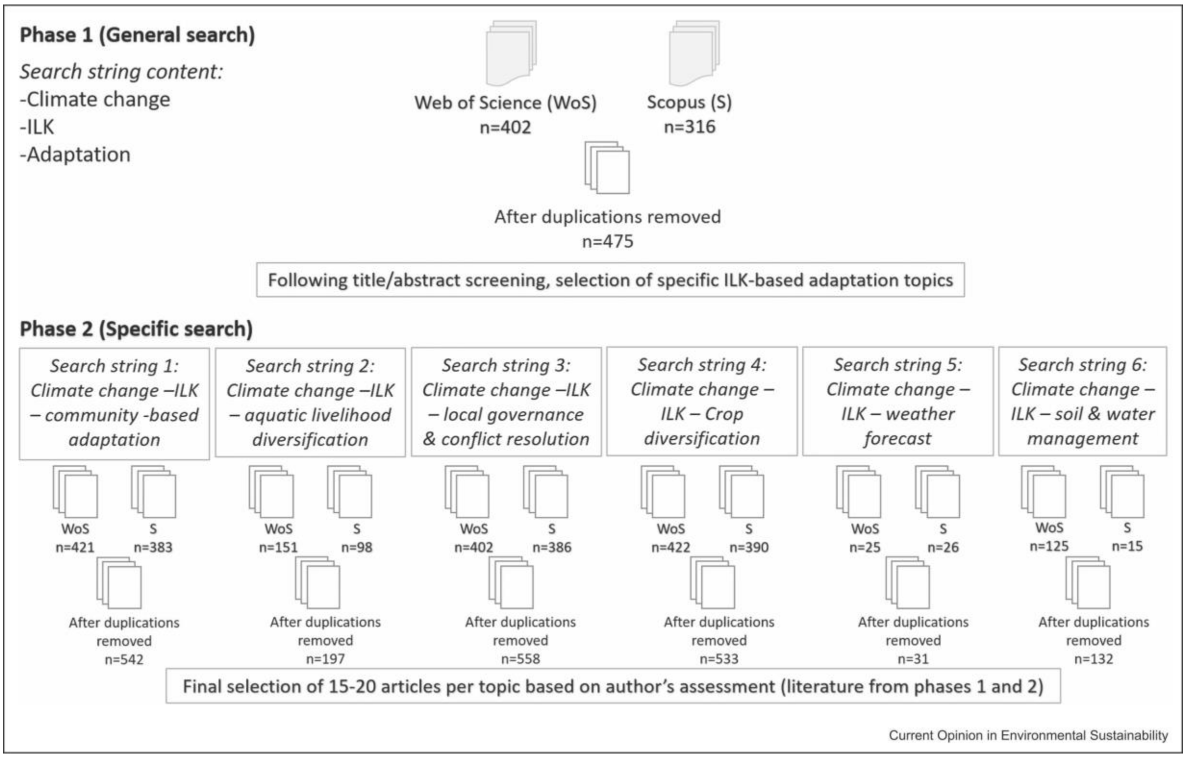

Figure 4-1: The two-phase search approach.

In the second phase, we repeated the search with specific key terms corresponding to each of the identified major ILK-based adaptation strategies to find the most study-relevant articles (see Table SM3-1 for specific search terms). From the total list of articles derived from phases 1 and 2, we selected approximately 15 articles per theme (or adaptation strategy) that best met the following criteria based on the authors' assessment of 1) topic relevance, 2) quality criteria, 3) level of details of results, and 4) diversity in the geographic distribution of case studies.

We also added nine articles that subject experts recommended but that did not appear in our search list. For the included articles and each adaptation theme, we conducted a qualitative analysis by assessing common patterns of benefits, costs, and trade-offs regarding the three sustainability dimensions (social, economic, and environmental), in line with social, economic, and environmental feasibility indicators developed by C. Singh et al. (2020). The supplementary materials contain a list of documents reviewed and a data sheet (seeTable SM3-2).

Adaptive responses and sustainability

We focus specifically on five adaptive responses in the context of ILK: 1) community-based adaptation, 2) diversification, 3) local governance and conflict resolution schemes, 4) land, soil, and water management, and 5) traditional weather forecast. Community-based adaptation refers to adaptive responses emerging from the local level (individual, household, and community) to address climate-related risk (Ensor et al., 2018). Diversification can take various forms, including diversification of livelihood activities and assets such as crop species and varieties and fisheries to minimize climate vulnerability by increasing the range of options available (Asfaw et al., 2018). Local governance and conflict resolution schemes refer to community-level resource governance partnerships occurring at multiple levels (community to government) in managing food systems to deal with climate risk. This can include community-based management and co-management approaches for natural resources (Plummer & Baird, 2013). Soil management includes (no-)tillage, plowing, mulching, ridge and furrow, and terrace cultivation with the general goal of increasing soil quality and water retention capacity (Rivera-Ferre et al., 2021). Water management refers to different types of irrigation and water conservation practices. Traditional weather forecasts use the ILK of biophysical indicators such as animals, plants, weather phenomena, and celestial bodies to predict upcoming weather and thereby plan daily and seasonal livelihood activities (e.g., Iticha & Husen, 2019).

Adaptive responses are key to the sustainability of Indigenous and local food systems. We understand sustainability in a climate change adaptation context as the combined result of the long-term dynamics of the resilience and vulnerability of human–environmental systems (Bhatasara & Nyamwanza, 2018; Eriksen et al., 2011). Social, economic, and environmental dimensions are various archetypical pathways of sustainability shaped by various adaptive responses. Specifically, the social dimension of sustainability refers to social equality and justice, including food, health, education, and gender aspects; the economic dimension to economic equality, including decent work, economic growth, and responsible production; and the environmental dimension to the integrity of terrestrial and aquatic systems, including the climate (Folke et al., 2016). Adaptive responses can generate mixed positive and negative impacts along the social, economic, and environmental dimensions of sustainability. When adaptive responses show evidence of generating more resilience than vulnerability (along the three dimensions of sustainability), they are identified as having a positive impact. On the other hand, high economic, social, or environmental costs constitute maladaptation (Barnett & O'Neill, 2010; Juhola et al., 2016) Table 4-1.

Table 4-1: Three dimensions and indicators of sustainability to assess adaptation in Indigenous and local contexts (adapted from Singh et al. (2020)).

Sustainability dimensions	Indicators	Questions asked with adaptation indicators	References
Social	Social benefits	Does the option offer health and education benefits? Does the option minimize negative trade-offs with other development policy goals and identify positive synergies with other policy goals?	Jordan et al. (2015)
	Sociocultural acceptability	Is there public resistance to the option? Does the option typically find acceptance within existing sociocultural norms and utilize diverse knowledge systems, including ILK?	Pearce et al. (2015), Singh et al. (2018), Tschakert et al. (2017)
	Social and regional inclusiveness	Does the option include different social groups and remote regions? Does the adaptation option adversely affect vulnerable groups or other areas?	Ford et al., (2017), Shi et al. (2016), Sovacool et al. (2015)
Economic	Microeconomic and macroeconomic viability, including employment and productivity enhancement potential	What are the economic costs and trade-offs of the option? (high costs correspond to low feasibility) Would the option lead to higher economic productivity? Does the option employ many people or does the system's productivity increase under the option?	Chakrabarty et al. (2013), Dalton et al. (2015)
Environmental	Adaptive capacity/ resilience-building potential	Does the option enhance the ability of ecosystems or relevant decision-makers to adjust to potential damage to the environment, take advantage of	Berbés-Blázquez et al. (2017)

		opportunities, or respond to consequences, or does the option contribute to building resilience (the environment's ability to cope with stressors and reorganize to maintain structures and functions and retain the capacity to transform)?	
	Ecological capacity	Does the option enhance supporting, regulating, or provisioning ecosystem services in any way?	Berbés-Blázquez et al. (2017)

Results

Social sustainability

We found records of diverse ILK-based adaptive responses leading to social sustainability Table 4-2. Community-based adaptation has a widely documented ability to positively impact social sustainability. For example, based on two case studies from the Solomon Islands, Basel et al. (2020) found that the community-based adaptation approach could address key climate change vulnerabilities (e.g., climate variability, extreme events), additional drivers of social vulnerability (e.g., limited equity and inclusion, education), and adaptive capacity (e.g., leadership, youth capacity-building). However, from the same islands, van der Ploeg et al. (2020) found that several other interconnected social and political problems such as youth unemployment, poor healthcare and education, gender-based violence, land tenure disputes, corruption, alcoholism, urbanization, and expectations of modernity could lead to food insecurity and health problems.

Table 4-2: Examples of ILK-based adaptation responses and their impacts on sustainability.

Adaptive responses	Examples	(+/–) Impacts on sustainability	Sustainability dimensions	References
Community-based adaptation	Participatory adaptation planning (Langalanga people from the Solomon Islands)	(+) Support community cohesion, local resource management (forest, water, and fisheries), and disaster risk reduction (-) Increased settlement along the coast leads to conflicts over access to fishing grounds	Social, environmental	Basel et al. (2020), van der Ploeg et al. (2020)

	Inclusion of women in fisheries (Alaskan native people, United States)	(+) Inclusion of women's knowledge in fisheries' decision-making (Alaskan native people, United States) (-) Limited research considering the knowledge and perspectives of fisherwomen in Alaska (Alaskan native people, United States)	Social	Lavoie et al. (2019)
Diversification	Livelihood diversification (Indigenous people in the Asia Pacific region)	(+) Diverse skills give them opportunities to maximize the flexible use of all available capital to sustain their livelihood and reduce climate risks and vulnerability (-) Limited specialization in one livelihood activity (expert knowledge and learning)	Economic, social	Galappaththi et al. (2020), Shaffril et al. (2020)
	Crop diversification (Bangladesh, Milpa farmers in Mexico,various ethnic groups in northern Vietnam,and Yi people in China)	(+) Contribution to agrobiodiversity, improved soil quality, reduced pest infestation, and health and nutritional intake diversity (-) Although mixed cropping increases yield, indigenous crops generally display lower yields and lower market prices, resulting in generally lower income generation potential compared with improved varieties	Environmental, economic, and social	Assefa et al. (2021), Novotny et al. (2021), Son et al. (2020), Song et al. (2020)
Local governance and conflict resolution schemes	Co-management (small-scale fishers in Timor-Leste and Bangladesh)	(+) Empowered communities are more likely to meet both socioeconomic and biological goals being involved in decision-making (-) Inequities reinforced by the customary power hierarchies reduce incomes and access rights of poor fishers	Social, economic, and environmental	Islam et al. (2020), Tilley et al. (2019)
	Community-based management (Laos PDR, Resex Pirajubaé fishers of Brazil)	(+) Foster capacity- building (-) Degradation of coastal–marine ecosystems and a severe impact on traditional fishery did not prevent due to urban growth over the reserve	Social, environmental	Casagrande et al. (2021), Suasi & Koya (2019)
Land, soil, and water management	Soil management (Thai farmers in Vietnam, smallholder farmers in Northern Ghana, and Khasi and Jaintia people in Northern India)	(+) Improves soil quality, including soil fertility and water retention potential (-) Labor work-intensive, which is addressed through collective actions and a culture of reciprocity	Environmental, economic, and social	Nguyen & Hens (2021), Upadhaya et al. (2020)
	Water management (Sri Lanka, Peruvian Andean Indigenous pastoralists,Northern Pakistan)	(+) A good water management system guarantees sustainable and fair water use among community members (-) Excessive water usage in the dry season might exhaust natural water sources	Social, economic, and environmental	Abeywardana et al. (2019), Ahmad et al. (2020), Postigo (2020)

Traditional weather observation and forecast	Traditional weather forecast (Alfa pastoralists in Ethiopia, Mayan milpa farmers in Mexico)	(+) High cultural acceptance. Information sharing to inform all community members (-) The higher unpredictability, especially of rainfall, makes traditional weather forecast less reliable and decision-making more difficult	Social, economic	Balehegn et al. (2019), Camacho-Villa et al. (2021)

Local governance and co-management arrangements are recorded among the Indigenous fisheries systems of northern Canada and Sri Lanka as a way of building the resilience of social–ecological systems and fostering adaptation to climate change. For example, both the Department of Fisheries and Oceans and the Hunters and Trappers Association, along with the Nunavut Wildlife Management Board and other designated Inuit organizations, are co-managers of the fisheries in Nunavut, Canada as outlined in the Nunavut Agreement Article 5 (Galappaththi et al., 2019). Some community fisheries such as Cambridge Bay and Pangnirtung have been using co-management for the last three decades (Galappaththi et al., 2022). These co-managers use the best-available ILK and science for decision-making related to annual fish quotas and fishing places. For instance, transformative changes such as food system changes (e.g., from land-based to ocean-based) recorded in Pangnirtung were fostered by the local perception of environmental change, sustained monitoring programs, shared narratives, and the interaction between knowledge systems, facilitated by a bridging organization within a broader process of governance transformation (Galappaththi et al., 2022). Similar co-management characteristics have been documented in Sri Lankan Coastal–Vedda culture-based fisheries (Galappaththi et al., 2020). Co-management is not an easy adaptive response but is the best-available collaborative management solution for Indigenous and local resource systems (Berkes, 2021).

Across the globe, Indigenous and local crops and varieties are an integral part of local cultures and therefore play an important role in customary traditions and local diets; they are often associated with a better taste and, consequently, are culturally highly accepted (Adhikari et al., 2019; B. Dhakal & Kattel, 2019; Dutta et al., 2020; Ndalilo et al., 2020; Ravera et al., 2019; Song et al., 2020). A mixed cropping system and the complementation of cultivated crops with medicinal plants has additional social benefits for health such as the potential to diversify the food and nutritional intake of ILPs and the supply of low-cost medical treatments (Adhikari et al., 2019; Chaudhary et al., 2021; B. Dhakal & Kattel, 2019; Novotny et al., 2021; R. K. Singh et al., 2020; H. N. Son et al., 2020). Social structures such as traditional seed networks and communal labor are important factors in preserving local seeds, crop diversity, and crop quality (Ravera et al., 2019; Song et al., 2020), pooling labor in times of intensive farming activities, and supporting each other in times of climate emergency, as practiced by the Lun Bawang, Sa'ban, and Penan people on the island of Borneo (Hosen et al., 2020).

The strong link between ILK-based adaptive strategies and customary institutions is also evident in the context of traditional weather forecasts. Information and knowledge-sharing through customary institutions are crucial for the collection and interpretation of weather indicators and the evaluation, correction, and dissemination of the final forecasts (Balehegn et al., 2019; Mogomotsi et al., 2020; Radeny et al., 2019). Similar to Indigenous crops, traditional weather forecasts have been transmitted through generations and therefore display high cultural acceptance and trust (e.g., Camacho-Villa et al. (2021) Nkuba et al. (2020), Radeny et al. (2019)).

Indigenous institutions are also crucial for controlling, regulating, and guaranteeing the balanced, equal, and sustainable use of water, an often-limited good (Ahmad et al., 2020). Additionally, social capital in the form of collective actions is visible in work-intensive soil and water management practices such as community-based pasture management in the Andes (Postigo, 2020) and chena cultivation and large-scale water tank systems in Sri Lanka (Abeywardana et al., 2019).

However, evidence indicates that local culture and customary institutions are weakening, which threatens social cohesion and resilience to climate change. For example, studies report declines in the cultivation of Indigenous and local crop varieties (Adhikari et al., 2019; Ndalilo et al., 2020), the application of Indigenous cropping systems, seed exchange between farmers (Ndalilo et al., 2020), and the application of customary water control systems and governance (Abeywardana et al., 2019).

Economic sustainability

The economic dimension of sustainability addresses uncertainties associated with Indigenous and local food systems. This includes various diversification responses as well as the application of traditional weather forecasts. Crop diversification is documented for microeconomic viability. A shift from subsistence to market integration is highly correlated with a shift toward cash crops (e.g., fruits, vegetables, wheat, and coffee) and improved and hybrid varieties (Adhikari et al., 2019; B. Dhakal & Kattel, 2019; Maikhuri et al., 2019; Ravera et al., 2019). This trend is strongly driven by certain economic benefits such as higher yields, shorter growing cycles, lower labor demand, and higher market values, which potentially increase income and food security (Adhikari et al., 2019; Aniah et al., 2019; B. Dhakal & Kattel, 2019; Ndalilo et al., 2020; R. K. Singh et al., 2020; Song et al., 2020); the exception is (Assefa et al., 2021). The economic trade-offs of improved and hybrid varieties are often neglected. For example, direct costs arise because hybrid varieties cannot be self-saved but must be purchased for each season (B. Dhakal & Kattel, 2019; Ndalilo et al., 2020; Ravera et al., 2019; H. N. Son et al., 2020). Indirect costs arise because improved varieties and cash crops often require more chemical fertilizer and pesticides as well as a cost-intensive irrigation infrastructure (B. Dhakal & Kattel, 2019; Ndalilo et al., 2020; Ravera et al., 2019). These economic downsides imply two consequences: 1) Indigenous crops have a higher energy use efficiency ratio as shown in a case study involving Nepalese and Bangladeshi farmers (Adhikari et al., 2019) and 2) Indigenous crops imply lower economic risks in a high-climate-risk year, due mainly to their lower investment costs (B. Dhakal & Kattel, 2019; Van Huynh et al., 2020). Furthermore, Indigenous cropping practices such as intercropping or relay cropping have the potential to increase yield per area compared with monocropping systems (Aniah et al., 2019; Novotny et al., 2021; Van Huynh et al., 2020). Economic value also arises through the incorporation of Indigenous medicinal plants and the generally better straw quality of Indigenous crops (B. Dhakal & Kattel, 2019; Ravera et al., 2019; R. K. Singh et al., 2020; H. N. Son et al., 2020).

Livelihood diversification is recorded in different forms as an adaptive response allowing rural populations to be involved in a range of activities that reduce their economic vulnerability.

For example, Inuit of the Canadian Arctic are involved in co-existing fisheries (commercial and subsistence; Arctic Char — Salvelinus alpinus and Turbot — Reinhardtius hippoglossoides) that create more economic opportunities (Galappaththi et al., 2019). In the Global South, Sri Lankan Coastal–Vedda are involved in multiple casual livelihood activities allowing them to shift between different livelihood options (e.g., culture-based fisheries, rice farming, and home gardening) (Galappaththi et al., 2020). However, in the context of economic diversification (as a main adaptive strategy), a peri-urban lake system in Zimbabwe records that males dominate the leadership of fishing cooperatives and that women (who are often low-paid or unpaid, with an unofficial status) are not recognized for their roles (e.g., net making, fish gutting, cleaning, and gleaning) (Utete et al., 2019).

Adequate weather forecasts are crucial for stabilizing yields, avoiding yield losses, and maximizing crop revenues. Compared with state-led weather forecasts, traditional weather forecasts display certain economic and technological advantages, that is, they are low-cost and low-tech, though additional costs and required technological infrastructure and understanding of state institutional weather forecasts are significant access impediments, especially for remote communities (Camacho-Villa et al., 2021; Chaudhary et al., 2021; Grey, 2019; Iticha & Husen, 2019; Radeny et al., 2019; H. N. Son et al., 2020; Ubisi et al., 2020). For example, based on evidence from studies in Zimbabwe, Mexico, Uganda, and Botswana, the scarcity of weather stations in remote regions, which results in a low spatial resolution of institutional weather forecasts, often presented at the regional level or even state level, is criticized as being too broad in its application and use at the local level and misaligned with farmers' needs (Camacho-Villa et al., 2021; Grey, 2019; Mogomotsi et al., 2020; M. R. Nkuba et al., 2020). Additionally, temporal delays in state forecast dissemination place a burden on its local applicability (Grey, 2019; Radeny et al., 2019).

Environmental sustainability and climate resilience

Many Indigenous crops, such as millet, buckwheat, quinoa and qañawa, yam and cocoyam, and cassava and their wild relatives, have adapted to harsh environmental conditions, including extreme cold droughts and floods (Adhikari et al., 2019; Dutta et al., 2020; Ndalilo et al., 2020; H. N. Son et al., 2020; Theodory, 2021; Van Huynh et al., 2020), and are less susceptible to pests and diseases (B. Dhakal & Kattel, 2019; Ndalilo et al., 2020; H. N. Son et al., 2020; Van Huynh et al., 2020). Therefore, the general demand for external inputs, such as pesticides, fertilizer, and irrigation, and, consequently, the environmental impacts, especially on soil and water, is generally lower for Indigenous crops (Chaudhary et al., 2021; B. Dhakal & Kattel, 2019). Instead, traditional crop cultivation depends on natural fertilizers and pesticides (Maikhuri et al., 2019; Ndalilo et al., 2020; H. N. Son et al., 2020) or dung from (free-range) livestock (B. Dhakal & Kattel, 2019). An example from Sri Lanka shows that chena cultivation systems use less artificial fertilizer and pesticides, depending instead on natural soil fertility (Abeywardana et al., 2019). We therefore argue that many Indigenous and local crops and varieties combine general climate resilience and environmental sustainability. However, the short maturation cycles of crops such as maize, groundnut, and cowpea and the improved short-cycle varieties increase their drought resistance by advancing their flowering and harvest dates compared with those of Indigenous crop varieties such as guinea corn and late millet; this results in a decline in the cultivation of Indigenous crops (Aniah et al., 2019; Chaudhary et al., 2021). On the other hand, traditional mixed cropping systems decrease the risk of complete crop failure and contribute to agrobiodiversity and increased soil quality (Chaudhary et al., 2021; Dutta et al., 2020; Maikhuri et al., 2019; Rivera-Ferre et al., 2021; Song et al., 2020). Similarly, soil conservation based on ILK is generally environmentally sustainable because of its low demand for energy and chemical products with the aim of increasing soil fertility and water retention capacity in an environmentally sustainable manner.

Local governance involves community-based efforts to face common challenges using collective action and local institutions, sometimes with the support of the government. Records from Sri Lanka show how small-scale shrimp farmers collectively use their local knowledge of shrimp disease spreading patterns across the inter-connected lagoon waterbody to implement a zonal crop calendar system by managing water withdrawal and discharge (Galappaththi et al., 2019). Also, in the Pacific Islands, Pearson et al. (2020) recorded how local governance of iTaukei (Indigenous Fijian) communities sustainably managed mangrove ecosystems over time and how this knowledge and these experiences can produce more sustainable and effective ecosystem-based adaptation options in the future. iTaukei indicates that mangrove plantations can prevent soil from washing away and can act as natural barriers to protect the coastline from sea-level rise, storm surges, and coral damage. However, there is not enough scientific data to facilitate sustainable environment management practices, for example, in the context of Arctic fisheries experiencing rapid environmental and climate change (Divine et al., 2021).

Traditional weather forecast methods are used to determine seasonal activities such as the timing of crop planting and harvesting and the seasonal selection of crop species and varieties (e.g., Mogomotsi et al. (2020), Pauli et al. (2021), Ubisi et al. (2020), Van Huynh et al. (2020)) and livestock activities (Radeny et al., 2019) to prepare for expected climate emergencies such as drought and flooding (Grey, 2019; Iticha & Husen, 2019; M. R. Nkuba et al., 2020; Pauli et al., 2021; Ubisi et al., 2020) as well as for adapting to long-term changes in local climates (M. R. Nkuba et al., 2020; Ubisi et al., 2020). However, nowadays, traditional weather forecast practices are threatened not only by cultural loss but also by the unprecedented speed of anthropogenic climate change itself, as shown in case studies from Malaysian Borneo (Hosen et al., 2020) and Ethiopia (Iticha & Husen, 2019). Several communities lament a decrease in the reliability and accuracy of traditional weather forecasts, as weather is more variable and rainfall more erratic nowadays and the relationships between biophysical indicators and weather phenomena are weakening (Camacho-Villa et al., 2021; Hosen et al., 2020). Nonetheless, the question of whether relying on institutional or traditional weather forecast methods is more accurate and implies fewer risks of error is not a trivial one, as (Ebhuoma, 2020) exemplified in a case study in Nigeria.

Discussion

We have investigated the most recently recorded evidence covering diverse regions and people to understand how these ILK-based adaptive responses can generate mixed positive and negative impacts along the social, economic, and environmental dimensions of sustainability. Across the examples we review, ILK provide the context for adaptive responses to foster the resilience and sustainability of agricultural and aquatic food systems. However, we have also seen that performance in the different domains of sustainability varies. While the reviewed strategies show specifically high potential to increase social and environmental sustainability, there are reported trade-offs in the economic sustainability domain. Therefore, strengthening ILK-based adaptation can enrich climate change resilience while contributing to the social and environmental SDG, for which low achievements have been reported thus far (Halkos & Gkampoura, 2021; Moyer & Hedden, 2020).

We find numerous records of adaptation in Indigenous food systems across diverse regions that are resilient to climate change and sustainable in many aspects. For example, the zaï cultivation system improves soil qualities, increases yields, and reduces climate impacts (Nyantakyi-Frimpong, 2020). However, we also find examples of sustainable trade-offs, especially regarding the economic domain, and argue that populations can be both resilient and vulnerable. For example, the high landrace diversity of buckwheat of the Yi people in China makes them resilient to climate variability but vulnerable to market conditions (Song et al., 2020). Furthermore, some of the adaptive responses that we document are being undermined or challenged to varying degrees, differing by (and within) populations; an example is the lack of capacity among Indigenous people on the Cook Islands to practically integrate and apply ILK in climate change adaptation planning (de Scally & Doberstein, 2022).

We argue that long-term successful adaptation to climate change should aim to avoid any increase in, and instead should reduce, social (e.g., loss of social bonds and mutual support), economic (e.g., food insecurity due to poverty), and environmental (e.g., soil contamination) vulnerability (Barnett & O’Neill, 2010; Juhola et al., 2016; Magnan et al., 2016). However, due to the complexity of climate change and adaptation in a sociopolitical context, trade-offs and maladaptive outcomes are omnipresent, even when the best intentions exist (Akinyi et al., 2021; Schipper, 2020). There is consequently an urgent need to discuss successful adaptation to climate change through a holistic approach that includes inter alia, long-term social, economic, and environmental sustainability aspects and to consider ILK (Magnan et al., 2016). This is especially important because 1) Indigenous and local food systems are undergoing rapid change due to environmental and climate change (Ford et al., 2020) and 2) these changes are not experienced in isolation but in a context of various socioeconomic, cultural, and political stressors (FAO, 2021). In other words, these various place-based conditions shape the way people respond to climate change impacts and determine the long-term and system-wide efficiency and sustainability of adaptation and, thus, the resilience and vulnerability of human–environmental systems (Ford et al., 2020).

Many ILK systems are rooted in a deep understanding and represent a process of social–ecological memory accumulated over several generations (Nykvist & von Heland, 2014). Also, these ILK systems are connected to specific environments (e.g., food systems) and social processes (e.g., livelihood) shaped by shocks and stressors over the long term (Ford et al., 2020). Additionally, as shown in our and other studies, ILPs are characterized by the high importance of social capital through the practice of collective action and collaboration (e.g., food sharing), local institutions (e.g., farmers' associations), human agency (e.g., assets), and learning (e.g., learning-by-doing) (Ford et al., 2020; Galappaththi et al., 2019, 2021). These characteristics can shape adaptive responses in the ILK setting and provide evidence for building the resilience and sustainability of food systems. Furthermore, culture, beliefs, and a high connection with and respect for nature foster sustainable resource use and impede any other harm to the natural environment, implemented and controlled through customary institutions and codes of ethics (Tengö & von Heland, 2011).

In our study, we find that some ILK systems are experiencing a weakening of knowledge systems and that this has the potential to result in the failure of sustainable adaptive capacity or increase exposure and sensitivity to climate impacts and other impacts (Galappaththi et al., 2021; Pearce et al., 2015). The weakening of ILK could stem from distractions in a process of social–ecological memory accumulation, for example, the loss of language and cultural and livelihood practices (e.g., toward off-farm activities), relocation, and increasing external influences, such as extension services and schooling (Sri Lankan Coastal–Vedda believe that aspects of their ILK system are weakening, due partly to three decades of ethnic conflict and social modernization) (Galappaththi et al., 2020, 2021). In the Canadian Arctic, some aspects of Inuit knowledge systems are weakening, as many elders possess knowledge but do not practice it themselves. For example, some young Inuit have not had to use survival skills on the ice, nor have they handled dog teams, read the sky, or sewn seal skin (Galappaththi et al., 2019, 2021). Thus, while ILK systems could result in resilience, their weakening could lead to vulnerability. Such weakening could lead to, for example, more environmental degradation (e.g., through the increased application of chemical fertilizers and pesticides as promoted by many extension services, a loss of local resources, and unconstrained overexploitation of water resources for the irrigation of cash crops) (B. Dhakal & Kattel, 2019) and a decrease in social bounds and the ethics of reciprocity. Therefore, several studies support the application of hybrid knowledge that combines ILK and scientific knowledge (Armitage et al., 2011). This can be a promising tool based on the premise of a decolonized and respectful exchange with a common understanding that both knowledge systems are equally valid, without any temptation to outperform each other, and guaranteeing the preservation of local culture and beliefs. Some examples of the successful application of such ‘hybrid knowledge’ are reported for natural resource management, including water, fisheries, and mountainous ecosystems (e.g., Armitage et al. (2011), Chaudhary et al. (2021), Song et al. (2020)).

Given the multiple policy challenges demanding joint solutions that seek to bring together sustainable development, climate change action, and disaster risk reduction, this assessment is conceptualized as an initial step toward building a broad understanding of sustainable climate adaptation responses in the context of ILK and their food systems. The five ILK-based adaptive responses are community-based adaptation; diversification; local governance and conflict resolution schemes; land, soil, and water management; and traditional weather forecast. These adaptive responses have significant potential for social and environmental sustainability, but ILK remains challenged and disadvantaged under economic aspects. ILK-based adaptive strategies can show trade-offs in fostering resilience regarding one dimension of sustainability while increasing vulnerability regarding another. The weakening of ILK systems can potentially fail and be maladaptive in terms of sustainable climate adaptation. The policy focusing on successful adaptation should aim at sustainability's social, economic, and environmental dimensions. Our assessment serves as a learning platform to anticipate urgent adaptation policies and envisions sustainable solutions to a wide range of fast-warming, small-scale agricultural, and aquatic food systems worldwide.

Part III: The challenges for adaptation

Chapter 5

Disentangling the complexity of local adaptation - A multi-site comparison study of adaptation constraints and opportunities among Indigenous Peoples and local communities

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Co-authors:Waha, K., Álvarez-Fernández, S., Attoh, E. M.N.A.N., Chakauya, R., Carmona, R., Fernández-Llamazares, Á., Izquierdo, A.E., Junqueira, A.B., Lanker, M., Porcuna-Ferrer, A., Torrents-Ticó, M., & Reyes-García, V.

Abstract

Globally, Indigenous Peoples and local communities that directly depend on nature-based livelihoods, such as small-scale agriculture, pastoralism, fishing, and hunting/gathering, are under pressure from climate change impacts. While applying adaptation measures is urgently needed, constraints often hamper implementation. Understanding such constraints is of highest relevance to foster climate change adaptation and minimize negative impacts. In this work, we assess adaptation determinants, i.e., constraints and opportunities, in rural Indigenous Peoples and local communities using empirical data from ten sites distributed across the globe. The study is based on a mixed-method approach, including semi-structured interviews, focus group discussions, and a total of 1,045 household surveys, and 1,349 individual surveys.

We found a significant positive but weak correlation between locally experienced climate change impacts and household's adaptation implementations, suggesting that cognitive factors promote adaptation, while other factors constrain its implementation. While our findings show that adaptation is a highly complex process, challenged by diverse and often context-specific adaptation constraints, they also point at common socio-economic patterns that, across sites, explain differences in experienced climate change impacts and adaptation implementation. Households who report above-average climate change impact levels but show below-average adaptation implementation rates are characterized by significantly lower access to households' capitals, such as social capital and asset ownership. Our results also show that those households are also at higher risk of low food and freshwater sovereignty than households that have adapted more and feel less affected.

We conclude that adaptation planning and implementation need to 1) consider both common patterns and local occurrences of adaptation constraints, and 2) improve information flow between communities and different institutional levels to address adaptation constraints most efficiently at the appropriate scale.

Introduction

Climate change is one of the biggest challenges that humanity is facing and will continue to face in the upcoming decades as it directly affects the safety, livelihood, and food and water security of societies (Caretta et al., 2022; Lenton et al., 2019; Mbow et al., 2022; B. O’Neill et al., 2022). Risks associated with climate change impacts are especially acute for Indigenous Peoples and local communities with nature-dependent livelihoods, such as small-scale agriculture, pastoralism, fishing, and hunting/gathering activities (Birkmann et al., 2022; Reyes-García, 2024; Reyes-García, García-del-Amo, Álvarez-Fernández, et al., 2024). To minimize adverse climate change impacts in these communities, the implementation of timely, effective, just, and sustainable adaptation strategies is needed (Adger & Barnett, 2009; Reyes-García, García-del-Amo, Porcuna-Ferrer, et al., 2024). However, responding to climate change impacts is seldom straight-forward. Rather, it is a complex process, steered and simultaneously influenced by multiple factors beyond climate change itself, for which it requires resources at various scales, from the local to the global (Orlove, 2022). Scientific literature suggests that two key aspects play a major role in people’s adoption of adaptive measures: 1) adaptation motivation (i.e., the recognition of the need and benefits of adaptation) and 2) adaptive capacity (i.e., the feasibility of adaptation) (Thomas et al., 2021; van Valkengoed & Steg, 2019).

Adaptation motivation arises from people's recognition of the need to adapt to experienced or expected climate change risks and impacts (i.e., people’s climate change risk and impact appraisal) and from peoples’ beliefs in and understanding of the benefits arising from the adaptation process (i.e., people’s appraisal of the adaptation efficacy) (Grothmann & Patt, 2005; van Valkengoed & Steg, 2019). Climate change risk and impact appraisals are shaped by cognitive factors (Grothmann & Patt, 2005), but also highly determined by people's place of residence and direct dependence on nature (Birkmann et al., 2022; Morton, 2007). A growing number of studies have assessed the relevance of cognitive factors, such as previous experiences with climate hazards and impacts, climate change risk awareness, and adaptation appraisal, for adaptation motivation (Burnham & Ma, 2017; Dang et al., 2018; Khanal et al., 2018; Yegbemey et al., 2014). For example, people who have had first-hand experiences of extreme events and who consider an adaptive measure effective are more likely to take action than people who do not (Wilson et al., 2020).

In addition to adaptation motivation, people's adaptive capacity plays a major role in the adaptation process. Adaptive capacity is defined by the prevalence of adaptation opportunities, constraints (also referred to as barriers), and limits. In other words, adaptive capacity is defined by the factors that facilitate, hamper, or impede the adaptation process (Klein et al., 2014). Thus, experiencing or expecting adverse climate change impacts and acknowledging the need for and benefits from adaptation does not automatically lead to adaptive responses, as constraints and limits affect people's adaptive capacities (Piggott-McKellar et al., 2019; Shackleton et al., 2015; Spires et al., 2014). On the contrary, adaptation opportunities foster people's adaptive capacities, facilitate the planning and implementation of adaptation, and promote co-benefits (Klein et al., 2014). Adaptation constraints and opportunities are complementary concepts, so studying the former helps detect and support the later (Biesbroek et al., 2013). In this work, and following the definitions proposed by Biesbroek and colleagues (2013, p. 1127) and Eisenack and colleagues (2014, p. 686), we understand adaptation constraints as the "subjective interpretation or collective understanding of sequential or simultaneously operating factors and conditions [...] which the actor values as having a negative influence on the process and reduce the chances of successful outputs, but that are manageable and can be overcome with concerted efforts" and as "impediment[s] to specified adaptations for specified actors in their given context [...]". An adaptation limit exists when no adaptation options are available to secure valued objectives from intolerable risks (Dow et al., 2013). In theory, adaptation constraints can be overcome with certain efforts, whereas adaptation limits cannot (Moser & Ekstrom, 2010). In practice, the distinction between adaptation constraints and limits is not always clear, and in certain contexts, constraints might actually turn into limits (Barnett et al., 2015; Shackleton et al., 2015).

To assess a household's adaptive capacity, most studies refer to the sustainable rural livelihood approach and use access to different household capitals as a proxy for adaptive capacity (Morse & McNamara, 2013). Indeed, several studies have found a positive association between households' adaptive behavior and households' access to capitals, including financial and economic (e.g., income), physical (e.g., agricultural equipment), human (e.g., education, age, access to information), natural (e.g., secured land tenure, soil fertility), and social capital (e.g., access to agricultural extension, membership in social groups) (e.g., Antwi-Agyei et al.

(2015, 2021), Below et al. (2012), P. R. Brown et al. (2019)). For example, in a study with farmers in Ethiopia, access to information on temperature and precipitation (human capital) increased the likelihood of planting different crop varieties by almost 18%, and access to farmer-to-farmer extension (social capital) increased the likelihood of using different crop varieties by 11% and of planting trees by 12% (Deressa et al., 2009).

However, adaptive capacity assessments based on financial, technical, and institutional factors, but that neglect cultural, cognitive, and psychological aspects in decision-making on adaptation fall too short in explaining adaptive behavior (Dang et al., 2019). Understanding the complexity of adaptation determinants requires paying attention to both adaptation motivation (e.g., cognitive and psychological factors) and adaptive capacity (e.g., socio-economic factors) (Shackleton et al., 2015; Thomas et al., 2021; van Valkengoed & Steg, 2019).

By assessing the complex nature of adaptation constraints and opportunities in specific biophysical, economic, political, and socio-cultural environments, previous case studies have shown that adaptation determinants can vary over small distances, even between neighboring villages (Dang et al., 2018). Paying attention to such context-specific differences is crucial when designing and implementing local adaptation plans. However, while providing multifaceted evidence, research on adaptation constraints and adaptive capacity remains fragmented, disconnected, and lacks a consistent application of concepts and methods (Berkhout & Dow, 2023; Siders, 2019). Specifically, case studies do not support the identification of common patterns of adaptation constraints beyond the local context. Therefore, they do not allow for the type of generalizations that help policy makers in orienting regional and global policies. To make insights from place-specific experiences transferable to other places, multi-site assessments are needed (Berkhout & Dow, 2023; Lam et al., 2020; Piggott-McKellar et al., 2019; Siders, 2019). Such types of assessments, however, are largely lacking in the literature (but see Berman et al. (2020) for exception).

This study contributes to filling this research gap by assessing common patterns and context-specific particularities of cognitive and socio-economic factors that result in adaptation constraints and opportunities among Indigenous Peoples and local communities. Specifically, our research draws on empirical evidence from ten rural and nature-dependent Indigenous Peoples and local communities across the world to target three questions: 1. How important is experience of climate change impacts to triggering adaptation action? 2. What are locally-relevant and context-specific adaptation constraints encountered by Indigenous Peoples and local communities? 3. What role do socio-economic factors play in determining the implementation of adaptive responses beyond the local context?

Methods

This study is part of a bigger research project that assesses common patterns of local indicators of climate change impacts and adaptive responses in rural Indigenous Peoples and local communities with the goal to bring Indigenous and local knowledge to the forefront of climate change research and policies (Reyes-García, 2024; Reyes-García, García-del-Amo, Porcuna-Ferrer, et al., 2024). Primary data collection was carried out by a global network of researchers (Reyes-García et al., 2019, 2023).

Study sites

In this work, we used data from ten field sites located in sub-Saharan Africa, Latin America, and Central Asia that differ in climate-geographic and socio-cultural conditions (see Table 5-1). The field sites cover tropical (four sites), arid (three sites), and temperate (three sites) climate zones. Predominant livelihoods in the study sites are agriculture and agropastoralism (three field sites, respectively), pastoralism (two field sites), and fishery and hunting/gathering activities (one field site, respectively).

Table 5-1: Overview of the socio-economic and climate-geographic characteristics of the ten field sites and data collection.

People	Main livelihood	Site name	Country	Climate	Topography	vegetation	Household surveys	Individual surveys
Kolla-Atacameños	pastoralism	Puna	Argentina	arid (Bwk)	high mountains	gras- & shrubland	114	151
Ribeirinhos	fishing	Juruá River	Brazil	tropical (Af)	low land	rainforest	98	127
Mapuche	agro-pastoralism	Lonquimay	Chile	temperate (Cfb)	mid-mountains	broadleaf & mixed forest	74	75
Tibetan	agro-pastoralism	Shangri-la county	China	temperate (Cwb)	high mountains	coniferous forest	123	141
Dagomba-Gur	agri-culture	Kumbungu district	Ghana	tropical (Aw)	low land	savanna	116	175
Mam	agro-pastoralism	Western highlands	Guatemala	temperate (Cwb)	high mountains	coniferous forest	63	63
Daasanach	agropastoralism	Ileret Ward	Kenya	arid (BWh)	low land	savanna	162	255
Betsimisaraka	hunting/ gathering	Vavatenina district	Madagascar	tropical (Af)	low land	rainforest	37	40
Bassari	agri-culture	Bassari Country	Senegal	tropical (Aw)	low land	savanna	138	177
Farmers	agri-culture	Chiredzi district	Zimbabwe	arid (BSh)	low land	savanna	120	145
Total:							1,045	1,349

Note: low land: <1.000 meters above sea level (masl), mid-mountains: 1.000-2.500, high mountains: >2.500 masl

Data collection

Primary data collection followed a standardized protocol that allows for cross-site comparison (Reyes-García et al., 2023). In each field site, data collection took place in 3-8 villages with relatively homogeneous environmental and socio-cultural conditions. Data collection comprised a two-step mixed-method approach, including semi-structured interviews and focus group discussions to collect qualitative data and subsequent household and individual surveys to collect quantitative data (Table 5-1). Information from the semi-structured interviews and focus group discussions were used to design the surveys.

For the semi-structured interviews and focus group discussions, we selected participants based on convenience sampling to ensure a balanced distribution across age groups, gender[3], and main nature-based livelihood activities performed in the area. We only interviewed community members with a long-lasting relationship with the place (i.e., adults who have grown up in the community without spending major periods outside). We conducted semi-structured interviews to assess local indicators of climate change impacts and local adaptive responses. Specifically, we asked respondents for observed changes in the local environment occurring between the informant's young adulthood and the time of the interview. Reported local observations which respondents related to climatic drivers were categorized as 'local indicators of climate change impacts' according to the classification system developed by (Reyes-García et al., 2016, 2019). For example, the local observations 'summers are now warmer' and 'temperatures during the dry seasons are higher' were both coded into the category 'Changes in the mean temperature in a given season'. For each local indicator of climate change impacts, we asked for local adaptive measures that were implemented by community members in response to them (i.e., local adaptive responses). A saturation of information was normally achieved after 20-30 semi-structured interviews. In each field site, we organized focus group discussions with 4 to 18 participants to assess the level of group consensus for controversial climate-related observations. We considered a climate-related observation as controversial i) if less than three interviewees reported the observation, ii) if there were disagreements regarding the existence or the direction of the reported observation, or iii) if an observation's association with climatic drivers was unclear. As the outcome of the semi-structured interviews and the focus group discussions, for each site, we obtained a group-

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[3] We identified interviewees as men or women according to the socio-cultural expression of their gender. We acknowledge that our binary gender variable does not necessarily reflect the gender identities of our interviewees (Cameron & Stinson, 2019).

validated list of reported local indicators of climate change impacts and local adaptive responses.

Finally, a survey was used to quantitatively assess differences in the adaptation implementation by households and their underlying factors (i.e., adaptation determinants). Some survey questions referred to household characteristics and some to individual information. We applied random sampling to select households and convenience sampling to select individuals within a household, aiming for gender balance. We only targeted the male or the female household heads. Our total sample includes 1,045 household surveys and 1,349 individual surveys, as two household heads were interviewed in some households. Besides socio-economic data (i.e., age, gender, practiced livelihoods, and households' capitals), the survey included questions on climate change impacts observed by the person interviewed and questions on adaptive responses implemented by the households. Specifically, from the site-specific and group-validated lists of climate change impacts and adaptation reports, we randomly selected 15 local indicators of climate change impacts and 10 local adaptive responses to be included in the survey. For each of the 15 local indicators of climate change impacts, we asked household heads if they had observed the specific change and, if so, how this change had impacted their lives and livelihood. We distinguished between three levels: "does not affect me at all", "affects me a little", and "affects me a lot". Similarly, we asked whether the household had implemented any of the 10 randomly selected local adaptive responses. For each adaptive response that a household had not implemented, we asked for the reasons why they had not done so (i.e., reported adaptation constraints).

Data transformation

To identify common patterns and context-specific singularities of adaptive behavior and adaptation determinants, our multi-site comparison study required the transformation of site-specific data into cross-site comparable information (Reyes-García et al., 2023). To assess if and how experienced climate change impacts translate into adaptation action, we developed indices capturing household heads' climate change impact appraisal levels and households' adaptation implementation rates. To compare context-specific adaptation determinants across sites, we coded reported adaptation constraints into categories. To analyze how people's access to capital determines their adaptive behavior, we developed socio-economic indices for interviewed household heads and households. A short description of each of the indices is provided below (see supplementary materials for a full description).

Defining climate change impact and adaptation indices

For the analysis of how people's experiences with climate change impact translates into adaptation behavior, we categorized household heads' climate change impact appraisal levels and households' adaptation implementation rates. Specifically, for each interviewed household head we developed a Climate Change Impact index (CC_{idx}) that represents individually experienced climate change impacts based on observation and the assigned severity level (i.e., impact appraisal) for each of the 15 local indicators of climate change impact. To create individual CCI_{idx}, we multiplied the reported observation of each of the 15 local indicators of climate change impacts by the perceived severity of the respective impact. Then, we calculated the total sum over all 15 local indicators of climate change impacts and transformed the values into standard scores (i.e., z-score). The standardization allows the comparison across sites, although climate change impact levels were estimated based on site-specific indicators of climate change impacts. Positive z-scores describe experienced climate change impact levels above the sample mean, while negative z-scores describe experienced climate change impact levels below the sample mean.

(1) $$iCCI_{idx} = \frac{\sum_{k=1}^{15}(O_k \cdot S_k)}{15}, \qquad O_k \in \{0,1\}, S_k \in \{0,0.5,1\}$$

(2) $$CCI_{idx} = \frac{iCC\,I_{idx} - \overline{iCCI_{idx}}}{\sigma_{iCCI_{idx}}}$$

where O_k is the observation of the climate change impact k (0 - "not observed", 1 - "observed") and S_k is the severity level reported for the climate change impact k (0 - "does not affect me at all", 0.5 - "affects me a little", 1 - "affects me a lot").

Household heads with an above-average CCI_{idx} (>0) were considered *major impacted* (MI) and those with an average or below–average CCI_{idx} (≤0) *minor impacted* (mI).

For each household, we developed a Climate Change Adaptation index (CCA_{idx}) describing the household's adaptation implementation rate based on the relative frequency of applied adaptive responses. To create the CCA_{idx}, we transformed the total number of local adaptive responses that have been applied by a household in standard z-scores:

$$(1) \qquad hCCA_{idx} = \frac{\sum_{k=1}^{10} A_k}{10}, \quad A_k \in \{0,1\}$$

$$(2) \qquad CCA_{idx} = \frac{hCCA_{idx} - \overline{hCCA_{idx}}}{\sigma_{hCCA_{idx}}},$$

where Ak is the implementation of the adaptation measure k.

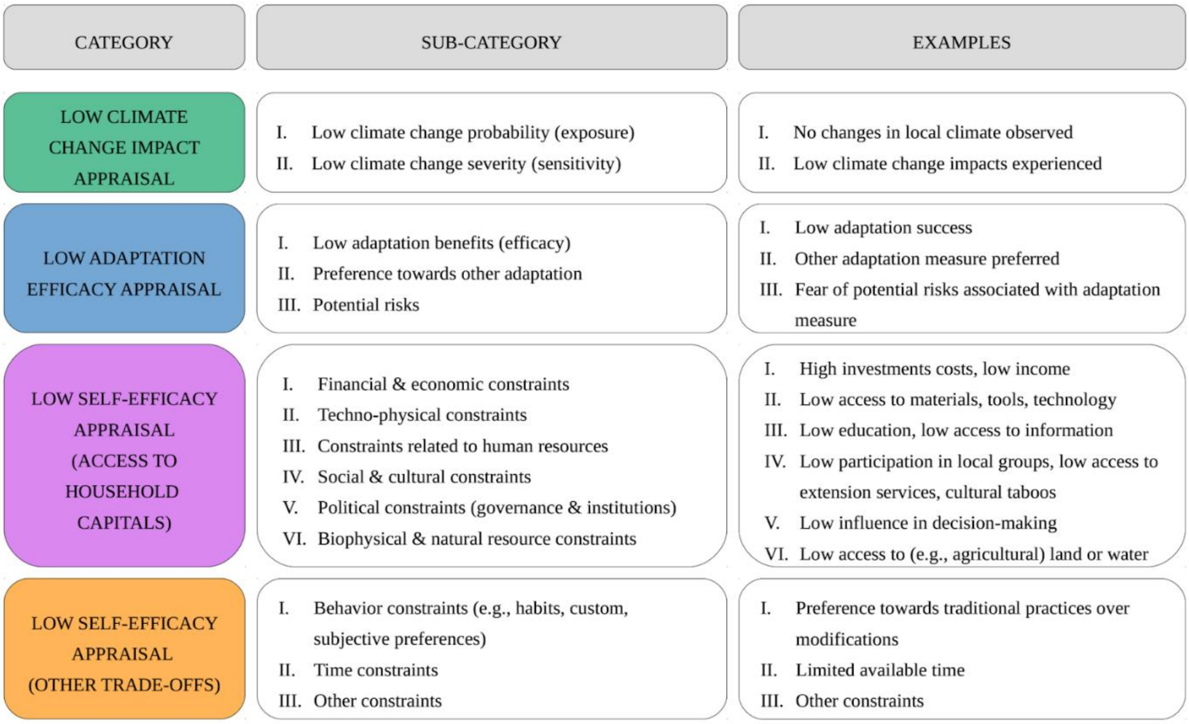
Households with an above-average CCA_{idx} (>0) were considered *(major) adapters* (MA) and those with an average or below-average CCA_{idx} (≤0) *minor adapters* (mA).

For each interviewed household head, we assigned the respective CCI_{idx} and CCA_{idx}, resulting in a total of four *climate change impact - adaptation* (CCI_{idx} - CCA_{idx}) groups: *major impacted adapters* (MI-MA), *major impacted minor adapters* (MI-mA), *minor impacted adapters* (mI-MA), and *minor impacted minor adapters* (mI-mA).

Classifying adaptive responses and adaptation constraints

We coded reported adaptive responses into 'local adaptation to climate change impacts' categories, following the classification system proposed by Schlingmann et al. (2021) (see also Figure SM4-1). Scaling up local adaptive responses into broader categories allows the comparisons of adaptation constraints for similar adaptive strategies across sites. For example, the reported context-specific adaptive responses 'planting new crops', 'diversifying crops', and 'shifting to maize cultivation' were all coded into the adaptation category 'Changes in composition' of agricultural products. Similarly, local activities related to social networks and resource sharing, such as ‘community-based fire brigades’, ‘local farmers organization’, or ‘seed sharing networks’ were coded under the category ‘Social networks & relations’.

We also developed a comprehensive classification system of adaptation constraints. The classification system - inspired by the MPPACC model by (Grothmann & Patt (2005) - distinguishes four main categories: 1) low climate change risk and impact appraisal, including low adaptation need appraisal, 2) low adaptation efficacy appraisal, 3) low self-efficacy appraisal with respect to access to capitals, and 4) low self-efficacy appraisal with respect to other trade-offs and inconveniences (Figure 5-1). We refer to climate change risk appraisal when we consider people' perception of and belief in climate change occurrence and intensity, while we refer to climate change impact appraisal when we consider people’s experiences with realized climate change risks, thus impacts. Adaptation efficacy appraisal refers to people’s belief in the efficacy of an adaptive response, while the self-efficacy appraisal refers to people’s perception of their ability to carry out the respective adaptive response (Grothmann & Patt, 2005). We further differentiate into subcategories inspired by the sustainable rural livelihood approach and slightly modified according to the terminology used by the IPCC (Klein et al., 2014; Morse & McNamara, 2013). For example, for the category ‘*low self-efficacy appraisal with respect to access to household capitals*’, we distinguish six sub-categories (i.e., financial and economic constraints; techno-physical constraints; human resources constraints; biophysical and natural resource constraints; social and cultural constraints; political constraints).



CATEGORY	SUB-CATEGORY	EXAMPLES
LOW CLIMATE CHANGE IMPACT APPRAISAL	I. Low climate change probability (exposure) II. Low climate change severity (sensitivity)	I. No changes in local climate observed II. Low climate change impacts experienced
LOW ADAPTATION EFFICACY APPRAISAL	I. Low adaptation benefits (efficacy) II. Preference towards other adaptation III. Potential risks	I. Low adaptation success II. Other adaptation measure preferred III. Fear of potential risks associated with adaptation measure
LOW SELF-EFFICACY APPRAISAL (ACCESS TO HOUSEHOLD CAPITALS)	I. Financial & economic constraints II. Techno-physical constraints III. Constraints related to human resources IV. Social & cultural constraints V. Political constraints (governance & institutions) VI. Biophysical & natural resource constraints	I. High investments costs, low income II. Low access to materials, tools, technology III. Low education, low access to information IV. Low participation in local groups, low access to extension services, cultural taboos V. Low influence in decision-making VI. Low access to (e.g., agricultural) land or water
LOW SELF-EFFICACY APPRAISAL (OTHER TRADE-OFFS)	I. Behavior constraints (e.g., habits, custom, subjective preferences) II. Time constraints III. Other constraints	I. Preference towards traditional practices over modifications II. Limited available time III. Other constraints

Figure 5-1: Classification of adaptation constraints, modified from Grothmann & Patt (2005), Grothmann & Reusswig (2006), Klein et al. (2014), Morse & McNamara (2013), Siders (2019).

Socio-economic individual and household indices

For the subsequent analyses, we developed four composite indices: household head's human capital index, household's social capital index, asset ownership index, and food and freshwater sovereignty index, ranging between the values 0 (low access to capital) and 1 (high access to capital) (Table 5-2, Supplementary Materials SM4-2).

The *human capital index* describes the household head's level of schooling and language knowledge (national language and other non-local language). The *household social capital index* represents household members' participation in collective activities and organized groups, information on NGO support, and the number of adult family members living outside the community. The *household asset ownership index* is used to identify financially better off households, by estimating 'material wealth' based on ownership of assets with market value.

The *household's food and freshwater sovereignty index* describes households' access, use, and control over sufficient, high-quality, and preferred freshwater and food sources.

Data analysis

We conducted descriptive and statistical analysis for the ten sites to detect factors that determine adaptation implementation across sites. Data were analyzed and visualized using R, version 4.1.2 (R Core Team, 2021), and R studio, version 2021.9.0.351 (RStudio Team, 2021).

First, we applied a linear regression model to test for significant linear correlation between the climate change impact appraisal level by the interviewed household head, thus the CCI_{idx}, and the adaptation implementation rate of the respective household, thus the CCA_{idx}. To do so, we used the *lm* function of the *stats* package in R, version 4.1.2 (Chambers & Hastie, 1992; R Core Team, 2021). Allowing for interviews with two household heads from the same household resulted in some cases in repetitive CCA_{idx} that were assigned to different household heads, thus to different CCI_{idx} values. For descriptive analysis of household information (e.g., the implementation rate for specific adaptive response) duplicated information was removed.

Finally, we assessed socio-economic differences between the two climate change impact groups (i.e., *major impacted* vs. *minor impacted*), the two adaptation groups (i.e., *adapters* vs. *minor adapters*), and across the four *climate change impact - adaptation* (CCI_{idx} - CCA_{idx}) groups using non-parametric statistical analyses. We applied the non-parametric Wilcoxon sum rank test when comparing statistical differences between two groups, i.e., between the two impact groups and -separately- the two adaptation groups, and the non-parametric Kruskal-Wallis test for the comparison across the four *climate change impact - adaptation* (CCI_{idx} - CCA_{idx}) groups (Kruskal & Wallis, 1952; Wilcoxon et al., 1970). For the post-hoc procedure after the Kruskal-Wallis test, we used the Dunn tests, with adjusted p-values based on the Bonferroni method (Dunn, 1961, 1964). To perform the statistical analysis, we applied the *cor* function and the *kruskal.test* function of the *stats* package in R, version 4.1.2. and the *dunn.test* function in the *FSA* package in R, version 1.3.5 (Ogle et al., 2023; R Core Team, 2021).

Results

Sample description

The gender distribution of survey respondents was balanced (i.e., 53% women). Household heads were on average 46 years old and their human capital index showed a mean value of 0.48. The households' food and freshwater sovereignty index was highest with a mean value of 0.75, followed by the asset ownership index with a mean value of 0.45, and the social capital with a mean value of 0.37 (Table 5-2).

On average, household heads had observed 11 of the 15 local indicators of climate change impacts included in the survey. Across sites, 18% of the respondents mentioned having observed all the 15 local indicators of climate change impacts included in the survey. Only 6% of the respondents had observed five or less local indicators of climate change impacts. In most cases, household heads felt affected by climate change impacts in one way or another. In 45% of the responses about how respondents felt affected by a specific local indicator of climate change impact, household heads indicated that they felt strongly affected and in 15% of the responses that they felt somewhat affected. In the remaining 40% of the responses, they either did not feel affected (11%) or had not observed the specific indicator (29%).

Compared to the generally relatively high observation of local indicators of climate change impacts, the adaptation implementation rate by households was considerably lower. On average, households had implemented five local adaptive responses and less than 1% have implemented the 10 local adaptive responses included in the survey.

Table 5-2: Description of the socio-economic variables of household heads and households included in the non-parametric analyses of variance to test for significant differences in the value ranks across the four climate change impact - adaptation (CCI_{idx} - CCA_{idx}) groups.

Explanatory Variable	Description	Mean	Standard deviation
Household head (n = 1,349)			

Age	Age of household head, in years	46	16
Human capital	Human capital of the household head, including schooling and language knowledge [0-1]	0.48	0.18
Household (n = 1,045)			
Social capital	Household social capital index, including participation in group activities, support by NGOs, relatives outside the community [0-1]	0.37	0.25
Asset ownership	Household asset ownership index [0-1]	0.45	0.21
Food & freshwater sovereignty	Households food and freshwater sovereignty, including aspects of quantity, quality, access control and preferences [0-1]	0.75	0.17

Relationship between climate change impact appraisal and adaptation implementation

When assessing the relationships between the **C**limate **C**hange **I**mpact index (CCI_{idx}) and the Climate Change Adaptation index (CCI_{idx}), we find differences in the number of respondents in each of the four *climate change impact - adaptation* (CCI_{idx} - CCA_{idx}) groups. The group of *major impacted adapters* (MI-MA) is the largest group, with 33% of the respondents (n=443), followed by the group of *minor impacted minor adapters* (mI-mA) that account for 27% of the respondents (n=366). About 20% of respondents, respectively, belong to the group of *minor impacted adapters* (mI-MA) (n=276) and the group of *major impacted minor adapters* (mI-mA) (n=264).

In line with these findings, the results of the linear regression between the CCA_{idx} and the CCI_{idx} indicates a significant and positive, but very weak correlation (Spearman’s rho = 0.23, $p = 2.2*10^{-16}$, $R^2 = 0.05$), suggesting that a household's adaptation implementation rate is not steered alone by the climate change impact appraisal level of the household heads.

Reported context-specific adaptation constraints

The frequencies of implemented adaptive responses show that the implementation rates differ both across sites and for different adaptive responses (Figure SM4-3). Asking survey respondents about why their households have not implemented specific adaptive responses provides insights into context-specific adaptation constraints. Constraints include differences in climate change risk and impact appraisals (i.e., adaptation need), and adaptation appraisals (i.e., adaptation efficacy and self-efficacy). Across sites, reported adaptation constraints per adaptive responses correspond on average to 6.7 different categories (SD = ±2.9). In only 5% of the adaptive responses, reported reasons belonged to less than four different categories.

Across sites, in 27% of the provided responses, respondents mention a lack of need to adapt to a specific climate change impact because they did not feel impacted by it due to low climate change sensitivity (16% of the responses) or low direct exposure (11%). In another 15% of the responses, respondents referred to behavioral constraints such as (personal) preferences, customs, and habits that prevent them from applying adaptive measures. In 13% of the responses, respondents evaluated the measure as little effective and/or preferred another adaptive strategy. Other frequently reported constraints include limited access to different forms of capital, especially to natural (11%), financial (8%) and human capitals (6%).

Although the diversity of provided reasons remains generally high in all the sites, in a few of them, there are some dominant ones (Figure 5-2a). For example, in Kumbungu district (Ghana), Dagomba-Gur agriculturalists dominantly (55% of provided answers) refer to economic factors (e.g., lack of money, lack of job opportunities) as an adaptation constraint that impede households from complementing main livelihood activities with off-farm work, from harvesting rainwater, or from adjusting buildings to warmer temperatures.

In the Western highlands (Guatemala), for several adaptive responses Mam agropastoralists refer frequently (30%) to biophysical and natural resource constraints, especially lack of access to farmland and limited available water for irrigation (Figure 5-2b). Limited access to natural capital is a frequently reported constraint for forest preservation, fruit tree planting, crop cultivation during the dry season, use of greenhouses, cultivation of new crops, and crop diversification in general.

In Lonquimay (Chile), Mapuche report in 21% of their responses that lack of human capital, especially lack of access to information, is a factor that hinders the application of several adaptive responses, such as protecting water sources, working in the tourism sector, and participating in community-organized reforestation and fire protection activities (Figure 5-2c).

For Daasanach agropastoralists in Ileret Ward (Kenya), low adaptation implementation frequently relates to behavioral constraints related to habits and customs (37%), but also to differences in perceived adaptation needs (32%) (Figure 5-2d). For example, traditional customs and social taboos prevent Daasanach from switching to unfamiliar activities, such as fishing or camel rearing, and from using external information. Fishing has traditionally been despised by the Daasanach as a subsistence activity fit only for “poor people with no livestock” and associated with a low social status. Similarly, interviewed Daasanach people are largely reticent to the idea of modifying their diets towards alternative and unfamiliar food products during droughts. Furthermore, differences in practiced main livelihoods (i.e., farming, livestock rearing, fishing) define differences in climate change sensitivities, thus in the need to apply adaptive measures that relate to agricultural or fishing activities.

Ribeirinhos in the Juruá River region (Brazil) often indicate behavior constraints (26%), especially habits and customs, or relate to low experienced impacts, thus to low adaptation needs (32%) (Figure 5-2e). Typical answers in this site were that they perform their activities in the same way they have always done and that there is no need for adaptive measures.

In contrast to such examples, it is difficult to detect any dominant reasons for reduced adaptation implementation for other sites. Specifically, for Kolla-Atacameños in the Puna (Argentina), Tibetan in Shangri-la county (China), Betsimisaraka in Vavatenina district (Madagascar), Bassari in Bassari Country (Senegal), and local farmers in Chiredzi district (Zimbabwe) the reported reasons are so diverse that drawing general conclusions on site-specific adaptation determinants is not possible (Figure 5-2f-j).

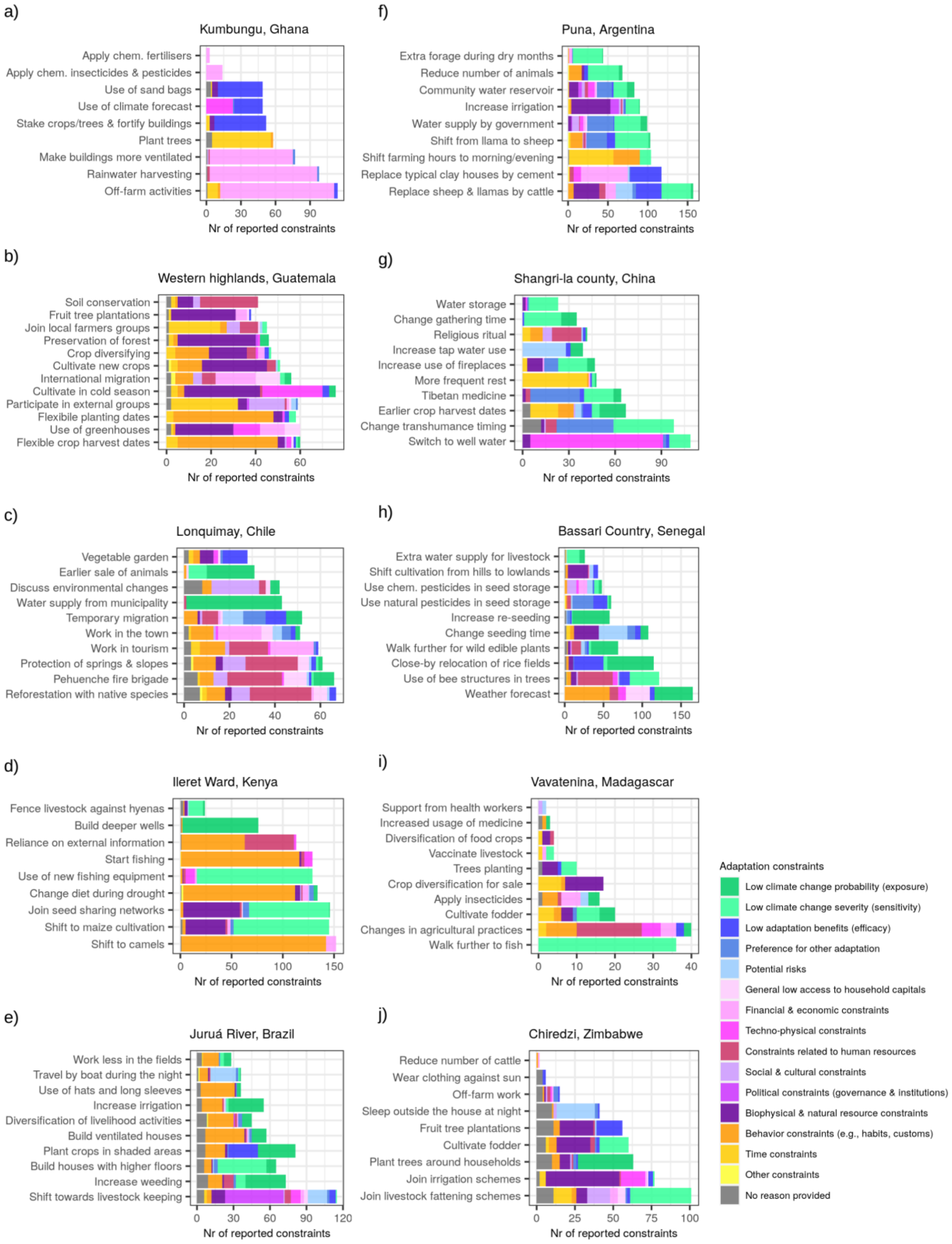


Figure 5-2: Context-specific adaptation constraints reported by Indigenous Peoples and local communities in the ten study sites. Data represents responses provided by households that did not implement a specific adaptive response (several reported constraints per household possible).

The high diversity in adaptation constraints within and across field sites is also obvious when comparing reported constraints for adaptive responses that belong to the same adaptation category. Reported adaptation constraints for adaptive responses related to *social networks and relations* have little in common in the different field sites (Figure 5-3a). For example, while Daasanach households generally lack access to natural resources (i.e., seeds) to participate in seed exchange networks and engage in small-scale floodplain agriculture, Mapuche often lack required information to participate in community-based fire brigades, and Mam agropastoralists in the Western highlands are often challenged in participating in social groups due to time constraints. Similar deviations exist for reported adaptation constraints in reforestation efforts between the field sites, with a lack of information as frequently reported constraint by Mapuche, lack of time as major constraints reported by Dagomba-Gur, and a lack of need to plant trees reported by local farmers in Chiredzi district (Figure 5-3b). The only two exceptions are the relevance of lacking access to or availability of water as dominant constraint for irrigation as reported both by Kolla-Atacameños in the Puna region and local farmers in Chiredzi district (Figure 5-3c), and a lack of access to (fertile) land as a frequently reported constraint for changes in crop composition for Mam agropastoralists in the Western highlands and Daasanach in Ileret Ward (Figure 5-3d).

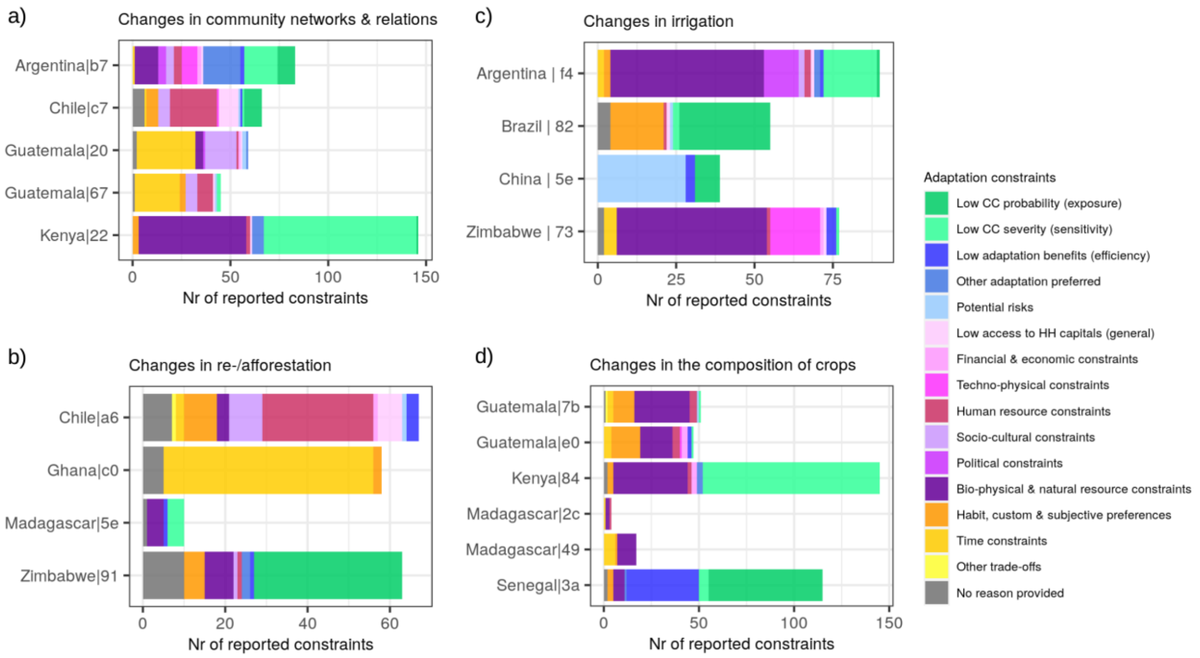


Figure 5-3: Comparison of reported adaptation constraints for selected adaptation categories across field sites. Data represents responses provided by households that did not implement a specific adaptive response (several reported constraints per household possible).

Common patterns between socio-economic factors, climate change impacts and adaptation

Comparing socio-economic characteristics between the two climate change impact groups (i.e., *major impacted* vs. *minor impacted*), the two climate change adaptation groups (i.e., *adapters* vs. *minor adapters*), and across the four *climate change impact* - *adaptation* groups (CCI_{idx} - CCA_{idx}) reveals that the groups differ significantly, but differently, with respect to age, human capital, social capital, asset ownership and food and freshwater sovereignty (Table 5-3, Figure SM4-4).

First, the two groups with different climate change impact levels differ significantly with respect to age and asset ownership, but not concerning human capital, social capital, and food and freshwater sovereignty. Specifically, household heads in the *major impacted* (MI) group are generally significantly older than households in the *minor impacted* (MI) group. They also show significantly lower asset ownerships. Second, households in the two adaptation groups differ significantly with respect to human and social capital, but not with respect to age, asset ownership, or food and freshwater sovereignty. In particular, the group of *minor adapters* (mA) show significantly lower access to human and social capital compared to the group of *adapters* (MA). Third, the four *climate change impact - adaptation* (CCI_{idx} - CCA_{idx}) groups differ significantly with respect to age, asset ownership, social capital, and food and freshwater sovereignty, but not with respect to human capital. In particular, household heads belonging to the group of *major impacted minor adapters* have significantly lower asset ownership and access to social capital than those belonging to the group of *major impacted adapters* (MI-MA). And the group of *minor impacted adapters* (mI-MA) show significantly higher asset ownership, social capital, and food and freshwater sovereignty than *major impacted minor adapters* (MI-mA).

Table 5-3: Parameter estimates of the analysis of variance according to the non-parametric Wilcoxon rank-sum test, Kruskal-Wallis test, and Dunn tests. Significance levels are indicated at 5% (*), 1% (**) and 0.1% (***) probability levels.

Response variables	Wilcoxon rank-sum test		Kruskal -Wallis test	Dunn test					
	MI-mI	MA-ma	all groups	MI-MA/MI -mA$^{1.1)}$	MI-MA/mI -MA$^{1.2)}$	MI-MA/mI -mA$^{1.3)}$	MI-mA/mI -MA$^{1.4)}$	MI-mA/mI -mA$^{1.5)}$	mI-MA/mI -mA$^{1.6)}$
	Coef. (W)	Coef. (W)	Coef (Chi²)	Coef. (z)	Coef. (z)	Coef. (z)	Coef. (z)	Coef. (z)	Coef. (z)
Household head									
Age	**255070*****	233654	**16.941*****	-0.227	**-2.830***	**-3.397****	-2.315	**-2.755***	-0.294
Human capital	225823	**240752***	7.2432	-	-	-	-	-	-
Household									
Asset ownership	**200692*****	231066	**25.774*****	**-3.344****	0.501	2.034	**3.467****	**4.997*****	1.322
Social capital	223694	**247603****	**10.612***	**-2.818***	0.187	-1.568	**2.712***	1.342	-1.569

Food & freshwater sovereignty	137926	155728	**8.8788·**	-1.673	1.714	-0.052	**2.973·**	1.583	-1.707

1.1)Comparison between *major impacted adapters* (MI-MA) and *major impacted minor adapters* (MI-mA);

1.2)Comparison between *major impacted adapters* (MI-MA) and *minor impacted adapters* (mI-MA);

1.3)Comparison between *major impacted adapters* (MI-MA) and *minor impacted minor adapters* (mI-mA);

1.4)Comparison between *major impacted minor adapters* (MI-mA) and *minor impacted adapters* (mI-MA);

1.5)Comparison between *major impacted minor adapters* (MI-mA) and *minor impacted minor adapters* (mI-mA);

1.6)Comparison between *minor impacted adapters* (mI-MA) and *minor impacted minor adapters* (mI-mA).

Discussion

This study has applied a multi-site comparative approach to assess the common patterns and local occurrences of adaptation determinants among Indigenous Peoples and local communities. It directly responds to two main research gaps: the need to upscale local insights and make them transferable to other contexts and the joint consideration of cognitive and socio-economic factors when assessing adaptation constraints and opportunities. We found that adaptation constraints are highly diverse and context-specific, but also that there are common patterns between socio-economic factors, experienced climate change impacts and adaptation implementation across sites. We organize the discussion around three main findings: 1) there is a positive but weak association between household heads' climate change impact appraisal levels and households' adaptation implementation rates; 2) locally reported adaptation constraints are largely context-specific and vary both within and across adaptive responses and sites; 3) those who show higher climate change impact appraisal levels but lower adaptation implementation rates generally dispose of significantly lower access to socio-economic capitals and higher risk of food and freshwater sovereignty than those who are characterized by lower climate change impact appraisal levels and higher adaptation implementation rates.

We acknowledge that many relevant aspects fell outside the scope of the study and might be subject to future research. First, this study does not systematically assess the efficacy of each adaptive response. Such information, for example people's (dis)satisfaction with implemented adaptation, would improve prioritization processes in adaptation planning by complementing feasibility aspects with efficacy aspects to define adaptation success (Adger et al., 2005; Dilling et al., 2019; C. Singh et al., 2020, 2022). Second, the study lacks a systematic assessment of the role of cultural and behavioral factors (i.e., customs, habits) across sites. While the study offers meaningful insights on how to systematically assess climate change impact appraisal levels, adaptation implementation rates and household's access to different socio-economic capitals, the development of a systematic approach for cultural and behavioral aspects would enrich the analysis of common patterns of adaptation determinants across sites. Third, this work does not assess how local adaptation constraints and opportunities, including vulnerability and resilience, link to and result from the broader socio-economic and political context they are embedded in (Porcuna-Ferrer, Calvet-Mir, et al., 2024; Ribot, 2014). A deeper understanding of such interrelations could improve the detection of structural vs. local adaptation determinants, thereby supporting the development of transformational solutions.

Our first important finding is that there is a significant positive but weak association between climate change impact appraisal levels and adaptation implementation rates. This finding highlights both the importance of climate change experience as a driver for adaptation motivation and the relevance of adaptation constraints in explaining the difference between adaptation motivation and action (van Valkengoed et al., 2023; van Valkengoed & Steg, 2019). For example, respondents frequently referred to low adaptation needs as a reason for not adapting, particularly when they had not experienced climate change impacts. Our finding supports previous research highlighting the importance of considering cognitive factors, such as climate change risk awareness, when analyzing adaptation motivation and decision-making processes (e.g., Adger et al. (2009)). However, we also found that high climate change impact appraisal levels do not always lead to more adaptation, nor are adaptive measures only applied when climate change impact appraisal levels are high. Specifically, at least 40% of the households fall into groups that do not fit the assumed positive relation between climate change impact appraisal levels and adaptation implementation rates. 20% of respondents are *minor impacted adapters*, thus belonging to households with a high adaptation implementation rate despite a low climate change impact appraisal level. We can think of three possible explanations for the relatively high share of households in this group. First, adaptation normally occurs in a context of multiple stressors, so many adaptive measures might, in fact, respond to changes other than climate change, e.g., socio-economic ones (Ensor et al., 2019; J. Z. McDowell & Hess, 2012; Nyantakyi-Frimpong & Bezner-Kerr, 2015; Porcuna-Ferrer, Guillerminet, et al., 2024). A second possible explanation for the relatively large group of *minor impacted adapters* is that the successful implementation of adaptive measures has already reduced experienced climate change impacts. Finally, it is also possible that the mismatch in data collection affects results, as we assessed experienced climate change impacts at the individual (i.e., household head) and adaptation implementation at the household level. This might resulted in a lack of correspondence for households where adaptive decision-making is done by others rather than the interviewed household head (Niemann et al., 2024). Discerning the plausibility of these explanations would need further research that could provide additional insightful findings on adaptation efficacy, co-benefits beyond climate change resilience, and decision-making processes within households.

At the other end, 20% of the households fall in the group of the *major impacted minor adapters*, characterized by high climate change impact appraisal levels but low adaptation implementation rates. This group illustrates that a non-negligible number of households adopt few adaptation measures, although they feel strongly impacted by climate change. Previous work suggests that Indigenous Peoples and local communities are well aware of ongoing climatic changes and experienced impacts (Reyes-García et al., 2016; Savo et al., 2016, 2017). However, many of them are hampered in their adaptive responses by external and internal factors (e.g., Fayazi et al. (2020), McNamara et al. (2017)). In line with previous work (van Valkengoed & Steg, 2019), our finding provides nuance to the somehow simplified assumption that fostering climate change awareness results in increased adaptation actions (Marshall et al., 2013; McNamara, 2013). In other words, our findings suggest that for awareness raising to lead to adaptation, it should be thought of in conjunction with detecting, addressing, and overcoming existing adaptation constraints (Thomas et al., 2021).

However, addressing adaptation constraints is everything but easy, as suggested by the second main result of the study, which underscores that adaptation constraints are highly diverse, complex, and context specific. These results directly relate to the definition of adaptation constraints proposed by Biesbroek et al. (2013) and Eisenack et al. (2014), in which they highlight the subjectivity (subjective interpretation by a specific actor or group of actors), the complexity (simultaneous or sequential factors and conditions), and the context-specificity of adaptation. We derive two main implications for adaptation planning and implementation of this result. First, efforts to overcome adaptation constraints require diverse and holistic approaches that allow addressing multiple constraints simultaneously (Shackleton et al., 2015). Second, there is no ‘one-fits-all’ solution to overcome constraints. Rather, many adaptation constraints need to be addressed at the local scale and within the respective context. For example, reported adaptation constraints reveal the importance of habits and customs in adaptation decision-making, often linked to cultural and traditional bonds (Adger et al., 2009, 2013). In particular, our results indicate that Daasanach in Ileret Ward and ribeirinhos in the Juruá River region reject adaptive measures that are not aligned with traditional and/or personal customs and habits, such as changing diets and shifting to new livelihood activities. In the same line, in a study on adaptation constraints of successful community-based adaptation, Piggott-McKellar et al. (2019) found reluctance to implement unknown technologies and to development projects that contrasted community cultural and religious values among the most frequently reported constraints.

Complementing this result, our third finding reveals common patterns across sites between experienced climate change impacts, adaptation implementation, and socio-economic factors. Specifically, we found that above-average levels of climate change impact appraisal and below-average rates of adaptation implementation are associated with lower access to socio-economic capitals (i.e., asset ownership and social capital), while below-average climate change impacts and above-average adaptation implementation are generally associated with higher access to such capitals. The finding could be interpreted as low access to social capital and low asset ownership might (directly or indirectly) act as adaptation constraints, whereas high access to them might present an adaptation opportunity.

Our results dovetail with those of other studies which emphasize the importance of access to physical and financial capital to allow for climate change, and that limited access to those forms of capital hampers adaptation action (e.g., Williams et al. (2021), Below et al. (2012), Deressa et al. (2009)). Similarly, the relationship between access to social capital and adaptation implementation found in our data is well in line with previous research findings (Adger, 2003; McNamara & Buggy, 2017; Méndez-Lemus & Vieyra, 2017). Indeed, many traditional practices and adaptive responses based on Indigenous and local knowledge, such as seed exchange networks or community-based wildfire preparedness, build on social ties between family and community members (Fenzi et al., 2022; Galappaththi & Schlingmann, 2023; Labeyrie et al., 2021; Prior & Eriksen, 2013). Due to their potential to compensate for the lack of other required assets, social ties and networks can sometimes be even more relevant for adaptation than the direct access to financial assets (Barnes et al., 2020). Similarly, networks with external actors, for example with extension services and NGOs, can have positive effects and support adaptation (Comoé & Siegrist, 2015; Khanal et al., 2018), although research also shows that, in some contexts, external support also bears some risks such as reducing communities' autarky by increasing dependence on external factors beyond one’s control (Porcuna-Ferrer, Calvet-Mir, et al., 2024).

Our findings also demonstrate that households with higher levels of climate change impact appraisals and lower adaptation implementation rates experience significantly lower food and freshwater sovereignty. This is highly alarming, as it shows that households in this group are highly vulnerable due to a combination of high climate change impacts, low food and freshwater sovereignty, and low adaptive capacities (Otto et al., 2017). Overall, this suggests that adaptation can only be successful when it is understood and addressed in a broader context of sustainable development that targets the reduction of socio-economic inequalities between and within communities (Bhatasara & Nyamwanza, 2018; Eriksen & Brown, 2011; Fuso Nerini et al., 2019).

Our work makes important contributions to two aspects of adaptation planning. First, the identification of adaptation constraints and opportunities facilitates decision-making during planning and preparation because it helps to prioritize feasible adaptation options over those that are especially ‘costly’ (i.e., encounter more or more diverse adaptation constraints than others). Second, by assessing general, alongside context-specific constraints, our findings give clear indications on relevant impediments that need to be addressed urgently, an important prerequisite for solution-oriented approaches that develop hands-on strategies for adaptation (Haasnoot et al., 2020; Sietsma et al., 2021).

For future research, we recommend 1) a stronger situation of adaptation in the context of multiple drivers, 2) a focus on adaptation efficacy assessments, and 3) a critical reflection of the eligibility and explanatory power of adaptive capacity assessment based on socio-economic factors only. Therefore, we recommend systematic assessments of the role of cognitive and cultural factors for adaptation decision-making across sites.

Conclusions

This study explored common and site-specific adaptation constraints and opportunities among 10 Indigenous Peoples and local communities. Our results indicate that adaptation determinants are highly diverse and context-specific but framed by general patterns. In particular, household heads (and their households) experiencing stronger climate change impacts and implementing fewer adaptive responses display lower asset ownership and lower access to social capital, as well as lower food and freshwater sovereignty.

We draw three policy recommendations from our study. First, paying attention to the heterogeneous pattern of experienced climate change impacts and adaptive capacities within communities and detecting most vulnerable households must be a priority in local adaptation planning and implementation. Hence, to make adaptation successful it needs to be understood and conceptualized in a broader context of multiple stressors and vulnerabilities and in conjunction with sustainability goals that target the reduction of social and economic inequalities within and between communities. Related to the first recommendation, our second recommendation refers to the need of Indigenous Peoples and local communities' representation in adaptation planning, including regular consultation with different vulnerable groups within the same community. This is crucial to align adaptation planning and implementation with local concerns, needs, and worldviews in general, but also to detect and address the manifold and context-specific constraints that different vulnerable groups encounter. Finally, we conclude that effective adaptation planning requires close coordination between different institutional levels, from the local to the (inter)national. To inform, organize, and manage adaptation planning at different scales, a robust information flow between the different institutional levels is required to assess and define which adaptive constraints must be tackled at the local level, and which are most efficiently addressed at a higher level.

Chapter 6

Conclusion

Theoretical contribution

By assessing the need for as well as the opportunities and challenges of climate change adaptation among Indigenous Peoples and local communities, this thesis contributes to the small, but gradually growing, body of scientific literature on local climate change risks, adaptation, vulnerability, and resilience among communities with nature-dependent livelihoods (Ford et al., 2018, 2020; G. McDowell et al., 2016; Petzold et al., 2020; Shackleton et al., 2015; Siders, 2019).

More specifically, the thesis advances our knowledge on global vs. local patterns of climate change risks and adaptation regarding four main aspects. First, it reveals current and future needs for local adaptation by supporting the identification of climate change risk hotspots (Chapter 2). Second, it brings local adaptive responses, their diversity, and sustainable nature into focus by featuring global patterns of local adaptation strategies across regions, climates, and livelihood activities (Chapter 3) and by assessing the potential contribution of Indigenous and local knowledge-based adaptive responses for sustainable adaptation (Chapter 4). Finally, this work draws attention to persistent challenges in adaptation implementations by detecting common patterns and context-specific occurrences of adaptation constraints (Chapter 5).

The first main contribution of this work is to provide a culturally-attuned way of assessing where local adaptation is most needed (Chapter 2). The thesis shows that Indigenous Peoples and local communities differ considerably with respect to experienced climate change impacts, adaptation action, climate change sensitivity, and potential climate change risks they might face in future. By assessing local climate change sensitivities of social-ecological systems and putting such sensitivities in relation with projected temperature trends, this work contributes to our understanding of potential future climate change risk hotspots, thereby, drawing attention to communities and places that need highest priority in risk management. Moreover, by revealing that future climate change risk hotspots are not necessarily places that already experience high climate change impacts and respond through adaptive actions, the thesis fosters discussion on the importance of climate change preparedness and efforts towards proactive actions, i.e., anticipatory adaptation. Overall, the development of a new approach to identify local climate change risk hotspots which considers people’s severity appraisal of experienced impacts offers a holistic, value-based and people-centered understanding of hotspots, which contrasts prevailing biophysical and economic approaches (Byers et al., 2018; Diffenbaugh & Giorgi, 2012).

The second main contribution of this thesis is a comprehensive compilation of a large body of empirical evidence on local adaptation among Indigenous Peoples and local communities (Chapters 3 and 4). Thereby, the thesis substantiates the importance of Indigenous Peoples and local communities and their knowledge as an important resource to strengthen diverse, flexible, and sustainable adaptation. The analysis here shows that local adaptation among Indigenous Peoples and local communities draws on a rich, diverse, and extensive pool of practices and actions, often referring to reactive coping and incremental adaptive strategies, but also including transformational adaptation. The thesis reveals that adaptive responses are patterned by local livelihoods, with communities depending on similar livelihoods applying similar strategies across sites and that Indigenous Peoples and local communities draw on different sources of knowledge when adapting to climate change impacts. Hence, local adaptive responses build on the one hand on flexibility and openness towards external knowledge and information, and on the other hand on the preservation of traditional knowledge. The large and systematic compilation work conducted in this thesis emphasizes the high potential of Indigenous and local knowledge-based adaptive responses for sustainable adaptation, especially with respect to supporting social and environmental benefits, while identifying economic trade-offs. Overall, the analysis conducted in this thesis highlights not only the potential, but also the limitations of local adaptation, thereby indicating and guiding needs for actions such as improving economic benefits, preventing further weakening of Indigenous and local knowledge, and allowing Indigenous and local knowledge to adapt to rapidly changing climate conditions.

The third main contribution of the thesis is to draw attention to persisting challenges in the implementation of local adaptive responses faced by Indigenous Peoples and local communities (Chapter 5). Specifically, drawing on primary data, this thesis highlights that experiences with climate change impacts do not unconditionally lead to adaptation actions, nor that adaptive strategies are only applied when climate change risks are high, thereby indicating that additional factors strongly influence adaptive behavior. This thesis also shows that adaptation implementation rates differ across sites and across different adaptation strategies. Moreover, the thesis shows that across sites households that experience high climate change impacts but have implemented few adaptive responses display significantly lower access to social and human capital and own fewer assets. These households also face higher risks of food and freshwater insecurity. Thereby, the thesis provides substantial proof of existing associations between adaptive capacities and vulnerability of households, and their access to social-economic capitals. Despite these common patterns, this thesis also highlights context- and culture-specific factors that steer adaptation implementation rates. Altogether, by detecting differences in adaptation rates between and within communities and adaptive strategies, by identifying common and context-specific constraints and by highlighting socio-economic inequalities within communities, this work contributes to our understanding of how social-economic, cultural and cognitive factors steer the feasibility of adaptation and affect the resilience and vulnerability of households. Thereby, the thesis has the potential to inform adaptation planning and implementation and to guide prioritization by pointing to both structural constraints and locally manifested constraints.

In sum, this thesis provides new insights in current and near-future climate change risk hotspots and reveals the generally high potential of local adaptive responses for diverse and sustainability adaptation. By drawing attention towards common patterns and site-specific occurrences of local adaptation strategies and persistent adaptation constraints among Indigenous Peoples and local communities, insights from this thesis have the potential to improve adaptation planning and implementation from the local to the global scale.

Methodological contributions

The thesis addresses two main methodological challenges in current research on climate change impacts and adaptation. The first methodological contribution consists in creating new knowledge based on evidence from natural and social science and from Indigenous and local knowledge. The second methodological contribution consists in providing a method to detect common patterns based on multi-site comparison studies.

The first methodological contribution addresses complexity in climate change research by proposing to bring together expertise from various disciplines and knowledge systems. Acknowledging the many interlinked impacts of climate change on socio-ecological systems at different spatial and temporal scales has led to a rising number of interdisciplinary research and a growing interest in the topic of knowledge co-production (Hill, Walsh, et al., 2020; Klenk et al., 2017; Orlove et al., 2023; Tengö et al., 2014). This thesis offers a novel to generate new evidence based on joint interpretation of information from different knowledge systems, including natural and social science, and Indigenous and local knowledge. Specifically, the thesis looks at the relation between past and potential future temperature changes, experienced climate change impacts, and adaptation implementation in Indigenous Peoples and local communities to estimate people's climate change sensitivity and to identify climate change risk hotspots (Chapter 2). Redefining how to identify climate change risk hotspots based on measured and modeled temperature data and on people's lived experience is a relevant contribution to a more comprehensive, holistic, and value-based understanding of climate change risks in social-ecological systems as this measure reflects the severity of climate change impacts as experienced by local people. Despite a growing interest in the potential of knowledge co-production, empirical research on the topic is still little developed and limited (David-Chavez & Gavin, 2018; Klenk et al., 2017; Lam et al., 2020). For example, Indigenous and local knowledge is often, and against common recommendations, compared against other knowledge systems. In contrast, the approach used in this thesis equally values different knowledge systems and rather makes use of the different and complementing properties, qualities, and informative values of each information to create new and enriched insights that build on the combined explanatory power of various pieces of evidence (Tengö et al., 2014).

The second methodological contribution of this work responds to the need to upscale local findings and increase the transferability of insights from specific places and make them meaningful for other locations and societies beyond the local context. Upscaling local findings through global and multi-site comparison studies are therefore imperative to foster adaptation success and efficiency, but requires the development of adequate tools (Berkhout & Dow, 2023; Piggott-McKellar et al., 2019; Siders, 2019). This thesis directly contributes to this need by presenting systematic, structured, and standardized multi-site comparison approaches and by providing key tools that facilitate the synthesis, upscaling and comparison of local insights across sites. The two reviews of literature presented in this work (Chapter 3 & 4) extend the few existing systematic assessments with a focus on local adaptation to climate change (see Petzold et al. (2020) as exception). Importantly, the two literature reviews did not only compile, structure, and visualize the many scattered findings derived from case studies, they also provide new and concise insights on global patterns of local adaptation to climate change by Indigenous Peoples and local communities. This work also offers useful classification and coding tools that allow for multi-site comparisons. Particularly, in Chapter 3, I developed a classification system for local adaptive response (i.e., LACCI classification) and in Chapter 5 a classification system for adaptation constraints that could be used beyond this work. The strengths of such classification tools lie in their potential to detect common patterns at a broader scale based on generalizations that allow for comparisons across sites. Moreover, in Chapter 2 and 5, I developed climate change impact and adaptation indices that describe people's climate change impact appraisal and household's adaptation implementation in a way that is simultaneously place-specific and cross-culturally comparable. Such tools can be easily adopted, modified and applied in future multi-site assessments related topics on adaptation, for example, when studying adaptation success across sites.

Policy recommendations

This thesis has brought important insights on the need for adaptation, and the benefits arising from adaptation, as well as challenges of local adaptation by Indigenous Peoples and local communities that help to improve adaptation planning and implementation. Based on my findings, I derive five main policy recommendations for adaptation planning and implementation: 1) foster anticipative and proactive adaptation, 2) support long-term monitoring of local climate change risks and adaptation success, 3) recognize and adopt Indigenous and local knowledge-based adaptation strategies, 4) reduce inequalities and differences in climate change risks and vulnerability both within and between communities, and 5) develop strategies at different institutional levels to overcome common and context-specific adaptation constraints.

Foster anticipative and proactive adaptation

Anticipating risks and fostering proactive adaptation is urgently needed to prepare for increasing climate change risks in the near-, mid-, and long-term. This is important for several reasons. First, there is a real threat that even sites experiencing relatively low climate change impacts nowadays and showing low rates of implemented adaptation might turn into climate change risk hotspots in the near future (see Chapter 2). Second, in most cases local adaptation strategies have not yet translated sufficiently into the reduction of experienced impacts (Chapter 2 and 5). Considering drastic and abrupt climate-related changes within the realms of possibilities, proactive adaptations are urgently needed because they can address discrepancies between potential future risks and low preparedness, and –in contrast to reactive adaptation-compensate for potential time lags of adaptation measures between implementation and unfolding of positive effects.

Support long-term monitoring of local climate change risks and adaptation success

In addition, policies need better support long-term monitoring programs to improve our understanding on how climate change impacts and adaptation strategies -including adaptation effectiveness- evolve over time. On several occasions in the thesis (e.g., in Chapter 2 and 5), I have pointed out how these knowledge gaps limit our understanding of climate change risks and adaptation success, thereby hampering the identification of adaptation needs and priorities, and undermining effective adaptation planning and implementation. Therefore, climate change and adaptation policies need to support research and political institutions, practitioners, and concerned communities in their efforts to monitor and document local climate change impacts and adaptation success. Such support implies providing additional financial, institutional, and human resources, but also structural changes and paradigm shifts from policy and research programs that focus on short-term studies towards programs that additionally support long-term initiatives.

Recognize and adopt Indigenous and local knowledge-based adaptation strategies

Policy-makers need to officially recognize the value and potential of Indigenous and local knowledge for climate change adaptation to foster diversified and sustainable adaptation. This thesis provides multiple evidence on the diversity and potential benefits of local adaptive practices and strategies (Chapter 3 and 4). Therefore, I call for stronger adoption of Indigenous and local knowledge-based adaptation strategies into adaptation planning and implementation. This implies that Indigenous Peoples and local communities need to play a crucial role in adaptation policies by being involved in all steps from adaptation designing to implementation to guarantee that their knowledge is sufficiently reflected in adaptation planning and programs, including in countries' National Adaptation Plans (P. Singh et al., 2024). It also implies the official recognition of Indigenous rights, cultures, and their customary institutions, in which Indigenous knowledge is embedded (Carmona et al., 2024).

Address inequalities and differences in climate change risks and vulnerability both within and between communities

Adaptation policies must address inequalities between and within communities to foster successful adaptation and reduce vulnerabilities. My findings indicate that lower adaptation rates, higher climate change risks, as well as food and freshwater insecurity are associated with lower access to social-economic capitals (Chapter 5). Therefore, it is important that policy-makers consider and address these social-economic vulnerabilities in adaptation planning and implementation, including in National Adaptation Plans. This implies the active inclusion and participation of different social groups, and specifically the most vulnerable, in adaptation planning and implementation to guarantee that policy programs and initiatives develop and provide solutions to tackle their concerns and encountered challenges so that the most vulnerable benefit most.

Develop strategies at different institutional levels to overcome common and context-specific adaptation constraints

Related to the last aspect, and departing from the findings of this thesis that revealed both context-specific but also common patterns of adaptation constraints, I conclude that policy-makers need to develop and implement plans and strategies at different institutional levels to overcome both context-specific constraints and common constraints that are found globally across sites. This implies the need to foster information exchange and improve communication channels between communities and political institutions, as well between different institutional levels, from the local to the national and international, to develop and address constraints at the scale that most apply.

And finally, acknowledging high uncertainties and persistent knowledge gaps on future climate change risks on the one hand and adaptation success on the other hand, and being aware on persistent adaptation constraints and limits, I close my recommendations by highlighting that international and national climate policies still require persistent efforts towards upholding mitigation goals, hence the reduction of global greenhouse gas emissions at highest rates. Adaptation must be understood as accompanying but not compensating climate change mitigation.

Limitations

This section describes the limitations and caveats of this thesis as well as research-related challenges and approaches in response to them.

The first limitation of this work refers to the lack of an adaptation effectiveness assessment. Incorporating adaptation effectiveness appraisals by community members would have improved the results and conclusions of the thesis in various ways. For example, while the thesis identifies which households apply more adaptation strategies against those that apply fewer, it does not allow for a comprehensive conclusion on who is better prepared, i.e., more resilient, against climate change impacts based on qualitative criteria. Information on the appraisals of adaptation effectiveness would have brought more meaningful results to identify climate change risk hotspots (Chapter 2) and would allow prioritization towards removing constraints of adaptive measures that are highly effective over those that are less effective (Chapter 5).

A second limitation of this work is that results are based on a one-time assessment of experienced climate change impacts and implemented adaptation. The lack of repetitive measures over a longer time period through long-term studies affect the interpretation of results in two important ways. First, the study misses clear information on temporal impact-adaptation chronologies. For example, our results lack precision regarding time lags between noticing changes in temperature and precipitation, experiencing cascading impacts, and implementing adaptation measures, thereby missing evidence on proactive vs. reactive adaptation. Second, understanding the temporal evolution of experienced climate change impacts and how this experience relates to changes in temperature (e.g., if the relationship is rather linear, quadratic or exponential) would improve the identification of potential climate change risk hotspots and help detect socio-ecological tipping-points.

The third limitation of this thesis refers to the predefined focus on climate change, a focus that biases results and does not adequately reflect people's primary concerns, at least in some of the study sites. For example, some adaptive responses documented might have been misinterpreted as mainly addressing climate change concerns, while they might have been implemented to respond to other factors, such as changes in economic systems. Similarly, the thesis lacks in-depth assessments of the underlying causes of vulnerabilities that relate to the political and economic systems at different institutional levels in which Indigenous Peoples and local communities are embedded. In response to such gaps, additional publications have emerged in parallel to the thesis that recognize that multiple drivers (including stressors) simultaneously interact, steer and influence local (adaptive) responses and vulnerabilities (see Izquierdo & Schlingmann (2024), Porcuna-Ferrer, Guillerminet, et al. (2024)).

Future research

In recent years, the number of studies on adaptation to climate change has substantially increased, although certain research gaps persist, especially in relation to local adaptive responses in rural Indigenous Peoples and local communities. Although this PhD thesis has directly addressed some of the detected research gaps by providing new empirical evidence, further research is needed.

In the following, I discuss the five main recommendations for future research derived from this thesis. These recommendations concern enhanced research efforts on: 1) assessing and monitoring adaptation efficacy and success, 2) analyzing adaptation in the context of multiple drivers, 3) hands-on solution to overcome structural and context-specific adaptation constraints, 4) facilitating co-production of knowledge, and 5) fostering cross-site comparisons and transferability. While the first three recommendations contribute to epistemological concepts, the last two contribute to methodological approaches in research.

Future research is needed on the continuous monitoring and evaluation of people's appraisals of the effectiveness of adaptation measures, in combination with a steady assessment of sustainability and feasibility. Understanding the effectiveness, feasibility and sustainability of adaptation provides much more adequate indications of successful adaptation than the adaptation implementation rate alone. Such studies could help respond to whether adaptation can keep up with the unprecedented speed of anthropogenic climate change, and what type of adjustments will be required. Moreover, understanding adaptation effectiveness and success beyond biophysical parameters would help detect and understand superposing effects and the consequences of multiple interrelated and simultaneous factors, such as reinforcing positive co-benefits, negative or contrasting effects.

The second recommendation is to expand the focus of research on adaptation drivers in order to understand adaptation in a broader context of multiple drivers. Such research would help to better understand the relative importance of climate change among other stressors. Assessing the motivation behind adaptation, such as why and to what drivers rural Indigenous Peoples and local communities respond and adapt to, would provide additional insights into people’s priorities and main concerns. So far, ranking multiple local drivers has been rather neglected in research with few exceptions (e.g., Izquierda & Schlingmann, 2023). For timely adaptation planning, it is furthermore of high relevance to monitor how priority setting might shift over time.

Third, future research is also needed on practical advice and hands-on solutions on how to overcome persisting adaptation constraints. While many studies remain rather problem-oriented, for example, by describing adaptive capacities, we need more solution-oriented research that provides insights on how to best minimize existing constraints (Sietsma et al., 2021). My thesis has shown that some adaptation constraints are rather site-specific and thus need to be addressed at the local scale, while others appear in different sites and might need solutions at a higher institutional level, including at the national and international scale. This finding, however, requires more systematic assessments on how global, regional and local political and economical systems interact and how they construct and manifest together vulnerabilities on the ground. Understanding such interlinks are important entry points for strategies to break up pre-existing fragilities and inequalities (Ribot, 2014). While in the long-term the focus should be on practicable advice for overcoming and reducing structural and site-specific adaptation constraints, solution-oriented approaches could also help to detect adaptation measures for which existing constraints are easier to overcome, thereby supporting prioritization processes in adaptation planning in the short term.

The last two research recommendations refer to methodological approaches and should be considered in combination with the previous recommendations. Besides the need for more case studies in understudied regions (e.g., North African countries) and livelihoods (e.g., hunting/gathering) (see Chapter 3), there is further need for comparative studies to assess potential transferability of results beyond the local context. Specifically, detecting and distinguishing problems and solutions that are valid and applicable to a broader regional (or global) scale and easily transferable to other locations, from highly context-specific and non-transferable aspects is crucial for local, regional and global adaptation policy, planning and implementation. For example, future multi-site comparison studies could assess adaptation effectiveness and success at a higher scale to understand which adaptation can or should be promoted at larger scales and which require local approaches. Similarly, multi-site comparison studies on adaptation constraints in a context of multiple drivers and globalization could contribute to our understanding of drivers and constraints that are embedded in and derive from the global political-economic system, and these should be addressed as such.

Supplementary materials

SM1 Supplementary materials for Chapter 2

SM1-1 Additional information on the shared socioeconomic pathways (SSPs)

The SSPs describe different pathways of population, education, urbanization and GDP development, with implications for energy, land use, and emissions, but in the absence of climate change and climate policy (Riahi et al., 2017).

The **SSP2** pathway describes a “Middle of the Road" development, “in which social, economic, and technological trends do not shift markedly from historical patterns” and income inequalities persist, thereby challenging reductions in vulnerability to societal and environmental changes. The **SSP5** pathway describes a “fossil-fueled” development with an emission-intensive future where “the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world.” (B. C. O’Neill et al., 2017; Riahi et al., 2017).

SM1-2 Determination of site’s climate change sensitivity and risk

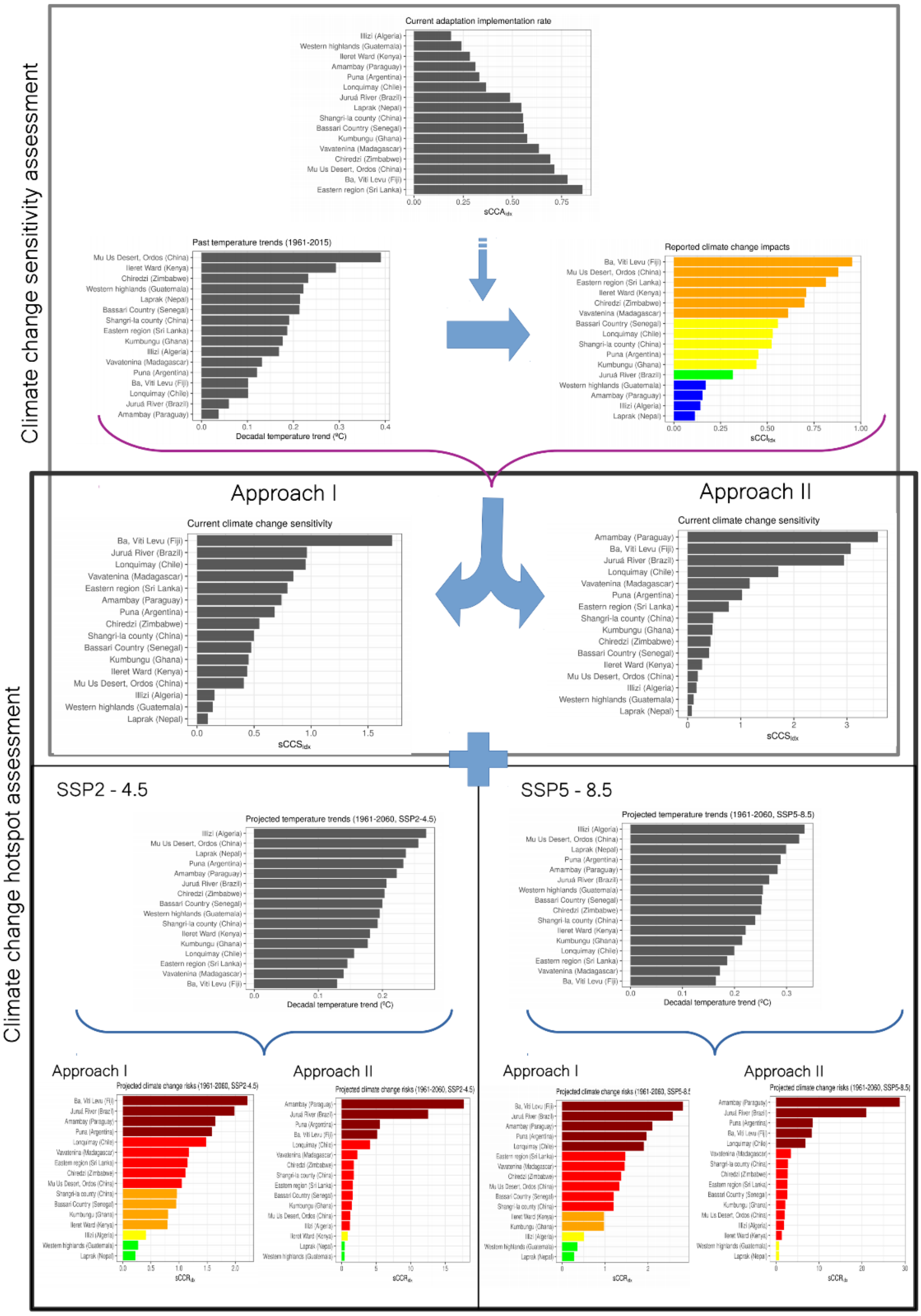


Figure SM1-2: Overview of the results for the site's climate change sensitivity and risks. Results are presented for the two socio-economic scenarios, SSP2-4.5 (left) and SSP5-8.5 (right), and for the two approaches to estimate climate change sensitivity, approach 1 (linear assumption) and approach 2 (quadratic assumption).

SM2 Supplementary materials for Chapter 3

SM2-1 The systematic literature review according to the ROSES pro forma principals

We conducted a systematic literature review in line with both, the PSASAR method (Mengist et al., 2020) and the ROSES pro forma criteria (RepOrting standards for Systematic Evidence Syntheses) (Haddaway et al., 2018), which constitute the most updated guidelines for conducting and presenting environmental systematic literature reviews.

Our review targets local responses to climate change impacts by IPLC and associated with their ILK. Specifically, with this review we aim at answering the following questions: What is the geographical extent of research on local responses to climate change impacts? What are frequently reported local response strategies? How do responses differ across climates, livelihoods and regions?

An overview of the framework and search process of this review is summarized in Table SM2-1.1 and Table SM2-1.2.

Table SM2-1.1: The PICo (population, interest, and context) framework for this review.

Population (P)	Interest (I)	Context (Co)
Indigenous Peoples and local communities with natural-resource-based livelihoods, such as small-holding agriculture, pastoralism, small-scale fishing, aquaculture or hunting/gathering	Documented human ground-based adaptation responses to climate change	First-hand case studies published between 2015 and 2019 on local adaptation responses to climate change across the globe

Table SM2-1.2: Outline of the literature review according to the STARLITE principal.

Sampling strategy	Selective: Studies relevant to local adaptation to climate change based on ILK
Type of study	Partially reported: Any first-hand qualitative, quantitative or mixed method study
Approaches	Electronic subject search only
Range of years	2015-2019
Limits	English

Inclusion and exclusion	Inclusion: case studies reporting implemented responses to climate change by IPLC
Terms used	“climate change” AND ("indigenous knowledge" OR "local knowledge" OR "traditional knowledge" OR "traditional ecological knowledge") AND (“adapt*” OR “coping” OR “cope”) appearing in titles, abstracts and keywords
Electronic sources	Scopus®, Web of Science®

Step 1 – Protocol development

We developed a protocol including the research goal, the search strategy, the coding guidelines and a glossary. The protocol guided article selection and coding, ensuring the application of homogenized inclusion and exclusion criteria among different coders. After receiving a personal training, all coders conducted a test coding before starting the systematic review. During the search and coding process, the protocol was regularly updated and new versions shared among co-authors and coders. The coding process of all supporting coders was double checked by the main author.

Step 2 - Search

We used two standard web-based search engines for scientific peer-reviewed publications in English, the Web of Science® (WOS) (http://science.thomsonreuters.com) and Scopus® (https://www.scopus.com). The search was conducted at the beginning of February 2020. We selected these databases and their search engines because of their large size (+70 million articles), multidisciplinary scope, and friendly search tools (18 and 79 field codes/limiters permitted, respectively), which allowed for a targeted, precise and replicable search (Gusenbauer & Haddaway, 2020) and minimized retrieval bias (Durach et al., 2017).

Information on the online search, including search string, online database, date and location of the conducted search and results are summarized in Table SM2-1.3.

Table SM2-1.3: Details on the online search.

	Scopus	Web of Science
Search string	TITLE-ABS-KEY(("climate change") AND ("indigenous knowledge" OR "local knowledge" OR "traditional knowledge" OR "traditional ecological knowledge") AND (“adapt*” OR “coping” OR “cope”))	TS=(("climate change") AND ("indigenous knowledge" OR "local knowledge" OR "traditional knowledge" OR "traditional ecological knowledge") AND (“adapt*” OR “coping” OR “cope”))
Date, Location	2020/02/03, Universitat Autònoma de Barcelona, Spain	2020/02/03, Universitat Autònoma de Barcelona, Spain
Nr of publications (all years)	681	709
	Total of both databases (without duplicates): 931	
Nr. of publications (2015-2019)	394	445
	Total of both databases (without duplicates): 580	

The search resulted in 931 records from both databases after the removal of duplicates and without any temporal limitations (Table SM3). The number of records was low before 2010 (< 30 records/year), but strongly increased after, surpassing 90 records/year in 2015. To reduce the number of records to a manageable amount while maintaining the depth of our review in a research field of high maturity (Kraus et al., 2020), we followed the suggestions by Okoli (Okoli, 2015) to limit the included timeline. We thus limited our search to the period after 2014. The decision was based on two reasons. First, in 2014, the IPCC report - a compilation of current climate change research - stated the need for more efforts towards the integration of ILK with existing practices for a higher effectiveness of adaptation (IPCC, 2014a), thereby promoting a new research focus towards local adaptation to climate change by IPLC. Second, in 2015, the number of annual records surpassed 90 records/year, a promising number for solid data analysis.

Limitations:

We acknowledge that our review is not comprehensive as i) we cover a short timeframe, ii) we did not conduct manual searches to identify additional sources of evidence, in English or any other language (Cooper et al., 2018), and iii) we did not seek advice from bibliometric experts to reduce any inherent publication bias (Durach et al., 2017). Furthermore, we are aware that our keyword string does not capture all relevant publications on local responses to climate change in subsistence-oriented IPLC and could be improved by specifically including different livelihoods (e.g., 'small-scale fishing') in the search keywords, and in so doing potentially reduce the above-mentioned retrieval and publication bias (Durach et al., 2017). However, we suggest that this would have resulted in an inoperable amount of publications with an undesirable lower representation of traditional and indigenous strategies and a higher proportion of externally-driven measures, two consequences that contradict our interest. The bias in the quantity of available publications on different livelihoods might have resulted in an underdevelopment of our classification system for fishing and hunting / gathering livelihoods.

Step 3 - Appraisal (inclusion/exclusion criteria and quality appraisal)

I. Inclusions/exclusion criteria:

Articles were selected if they reported first-hand data on implemented and currently practiced responses to climate change and variability (including coping, adaptation, transformation and capacity building) by IPLC. Articles were excluded if they (1) did not report any relationship between adaptation and climate change, i.e., adaptation to non-climatic drivers, (2) referred to a community whose main livelihoods did not depend on natural resources, (3) described only potential but not actual and realized adaptation or coping strategies, (4) provided only assessments of vulnerability, resilience or adaptive capacity but no response actions, (5) discussed theoretical frameworks, concepts or modeling exercises, or (6) were secondary studies such as reviews (see Table SM2-1.4 for the complete list of inclusion / exclusion criteria).

Table SM2-1.4: Description of the inclusion and exclusion criteria.

INCLUDED

Topic:

Local responses to climate change in Indigenous Peoples and local communities:

The title and/or abstract of the study explicitly indicates that currently practiced adaptive strategies are reported/mentioned/assessed/discussed in the paper. Local climate change adaptation is among the research objectives of the paper and the full text reports results and a subsequent discussion on the topic. The local responses to climate change must be set in place.

Timeline:

Studies published between 2015 and 2019

Population:

Indigenous Peoples and local communities – mainly rural - with natural resource dependent livelihood such as smallholding agriculture, small-scale fishing, aquaculture and livestock rearing, hunting-gathering.

Data:

Primary studies based on first-hand empirical data.

Publication type:

Peer-review articles and book chapters with a thorough and comprehensive description of the data collection procedure.

EXCLUDED

Topic:

Biological adaptation:

Any study focusing on adaptation in the biological system (flora, fauna, fungi and other microorganisms).

Adaptation to non-climatic drivers:

Studies on adaptation to non-climatic drivers only, e.g., deforestation, technology transfer.

Natural climate variability and extreme events:

Studies on responses to long-existing climate variability and extreme events if no change in such variability or extreme events is mentioned in relation to climate change.

Past adaptation to natural (non-anthropogenic) climate change:

All articles about past adaptation to non-anthropogenic but natural climate change and climate variability (e.g., during the Pleistocene/Holocene transition)

Future or potential adaptation:

Studies on unrealized adaptation to climate change, e.g., suggestions or recommendations for future or potential adaptation, including adaptation planning.

Planned/Institutional/Governmental adaptation:

We excluded studies that did not focus on local (autonomous) adaptation. For example, we excluded reported adaptation at the institutional (e.g., industry), governmental, and (inter-)national level. We also excluded studies with a focus on adaptation purely driven and implemented by external agents, e.g., NGOs, extension services, or researchers.

Impact/risk/uncertainty assessments only:

Studies with a main focus on climate change impacts, e.g., in the biological, physical or human system, including impact perception and observation and/or risk awareness with respect to climate change.

Mitigation:

All studies that focused on mitigation strategies only, e.g., the reduction of greenhouse gas emissions, and increase in carbon sinks.

Sustainable development only:

Articles documenting or assessing sustainable development programs, processes and ideas without an explicit focus on adaptation to climate change.

Vulnerability/resilience/adaptive capacity assessments:

Articles assessing vulnerability of a particular group/system to climate change based on environmental/social factors (e.g. geographical location, poverty level) but without including actual adaptive actions set in place to improve resilience or adaptive capacity.

Timeline:

Studies published before 2015 (<2015) and after 2019 when the data analysis was performed (>2019).

Population:

Studies that did not focus on IPLC with natural resource dependent. For example, studies in metropolitan regions were excluded and studies on populations that mainly depend on work in the service sector or industry, or similar labor work (e.g., small businesses). **Data:** We excluded secondary studies such as reviews, reports and other studies based on secondary data, pure conceptual and theoretical frameworks, and theoretical (e.g., scenario-based) modelling work. We also excluded studies that present results that were already published in previous work of the same author(s). Article quality: Non-peer-revied publications or publications of very low quality.

II. Critical appraisal:

Since our systematic literature review only includes peer-reviewed literature, the case studies have all been through one quality-control process. Nonetheless, we applied some measures to ensure quality. For each publication, we checked the Journal Citation Report (JCR) Impact Factor (IF) for the year 2019. For publications in journals that were scored equal or higher than 1.5, we automatically assumed an acceptable quality (score=1; included) of the publication. For publications in journals with either an impact factor <1.5 (Kraus et al., 2020) or without an impact factor, as well as for all book chapters, we assessed the quality by revising the respective publication with special focus on the method description. Book chapters and studies published in journals with low or no impact factor but which provided basic information on the research approach (i.e., research objective, data collection methods, and a specification of the study site), were accepted for the subsequent data coding and analysis process (score=0.5; included). Publications that did not provide such fundamental information were excluded (score=0; excluded) (see Table SM2-1.5). Only one book chapter did not meet the minimum quality requirements.

Table SM2-1.5: Considered journals and their JCR Impact Factors for the year 2019.

JCR Impact Factor	Journal names (number of publications in the database).
>1.5: included	n=64; Acta Tropica (n=1), Agricultural Systems (n=1), Ambio (n=2), Anthropocene (n=1), Climate and Development (n=7), Climate Research (n=1), Climate Risk Management (n=2), Climatic Change (n=4), Current Opinion in Environmental Sustainability (n=1), Ecological Indicators (n=1), Ecological Processes (n=1), Environment, Development and Sustainability (n=4), Environmental Management (n=1), Environmental Science & Policy (n=3), Experimental Agriculture (n=1), Frontiers in Earth Science (n=1), Frontiers in Marine Science (n=2), GAIA-Ecological Perspectives for Science and Society (n=1), Geoforum (n=1), Global Environmental Change-Human and Policy Dimension (n=1), Human and Ecological Risk Assessment (n=1), International Journal of Biodiversity Science, Ecosystem Services and Management (n=1), International Journal of Disaster Risk Reduction (n=1), International Journal of Sustainable Build Environment (n=1), Journal of Arid Environments (n=1), Journal of Environmental Management (n=2), Journal of Marine Systems (n=1), Land Degradation & Development (n=1), Land Use Policy (n=1), Local Environment: The International Journal of Justice and Sustainability (n=1), Natural Hazards (n=1), Regional Environmental Change (n=2), Scientifica (n=1), Social Science & Medicine (n=1), Society & Natural Resources (n=1), Sustainability (n=4), Sustainability Science (n=1), Theoretical and Applied Climatology (n=1), Water (n=1), Weather, Climate and Society (n=3),
< 1.5 or NA: included after reviewing	n=55 African Geographical Review (n=2), Agenda-Empowering Women for Gender Equity (n=1), Arctic Science (n=1), Asian Geographer (n=1), Climate (n=5), Cogent Social Sciences (n=1), Environment and Natural Resources Journal (n=1), Environmental Hazards-Human and Policy Dimensions (n=2), Environmental Justice (n=1), Genetic Resources and Crop Evolution (n=1), Geography, Environment, Sustainability (n=1), Human Ecology (n=1), Human Organization (n=1), Indian Journal of Traditional Knowledge (n=2), Interdisciplinary Description of Complex Systems (n=1), International Journal of Climate Change Strategies and Management (n=4), International Journal of Social Economics (n=1), Iranian Journal of Science and Technology, Transaction A: Science (n=1), Jamba-Journal of Disaster Risk Studies (n=2), Journal of Agricultural Extension (n=2), Journal of Asian and African Studies (n=1), Journal of Environmental Science and Management (n=2), Journal of Environmental Studies and Sciences (n=1), Journal of Mountain Science (n=2); Journal of Social Sciences (n=1), Mountain Research and Development (n=3), Norsk Geografisk Tidsskrift-Norwegian Journal of Geography (n=1), Pacific Journalism Review (n=1), Pastoralism-Research, Policy and Practice (n=1), Sarhad Journal of Agriculture (n=1), South African Review of Sociology (n=1), The Rangeland Journal (n=1), Book chapters (n=7)
< 1.5 or NA: excluded after reviewing	n=1; Book chapter (n=1)

Final article selection:

The key word search resulted in a total of 582 records published between 2015 and 2019, from which 271 were immediately excluded by reading the title and abstracts, including eight conference proceedings and two non-English publications. Twelve other documents were excluded because they were not findable or accessible. 299 were retrieved for full text reading. 179 articles were excluded because they did not match the topic and one publication was excluded after critical appraisal due to low quality. This resulted in a final list of 119 articles included in the analysis (see Figure SM2-1.1 and Supplementary Materials 2-5 (SM2-5)).

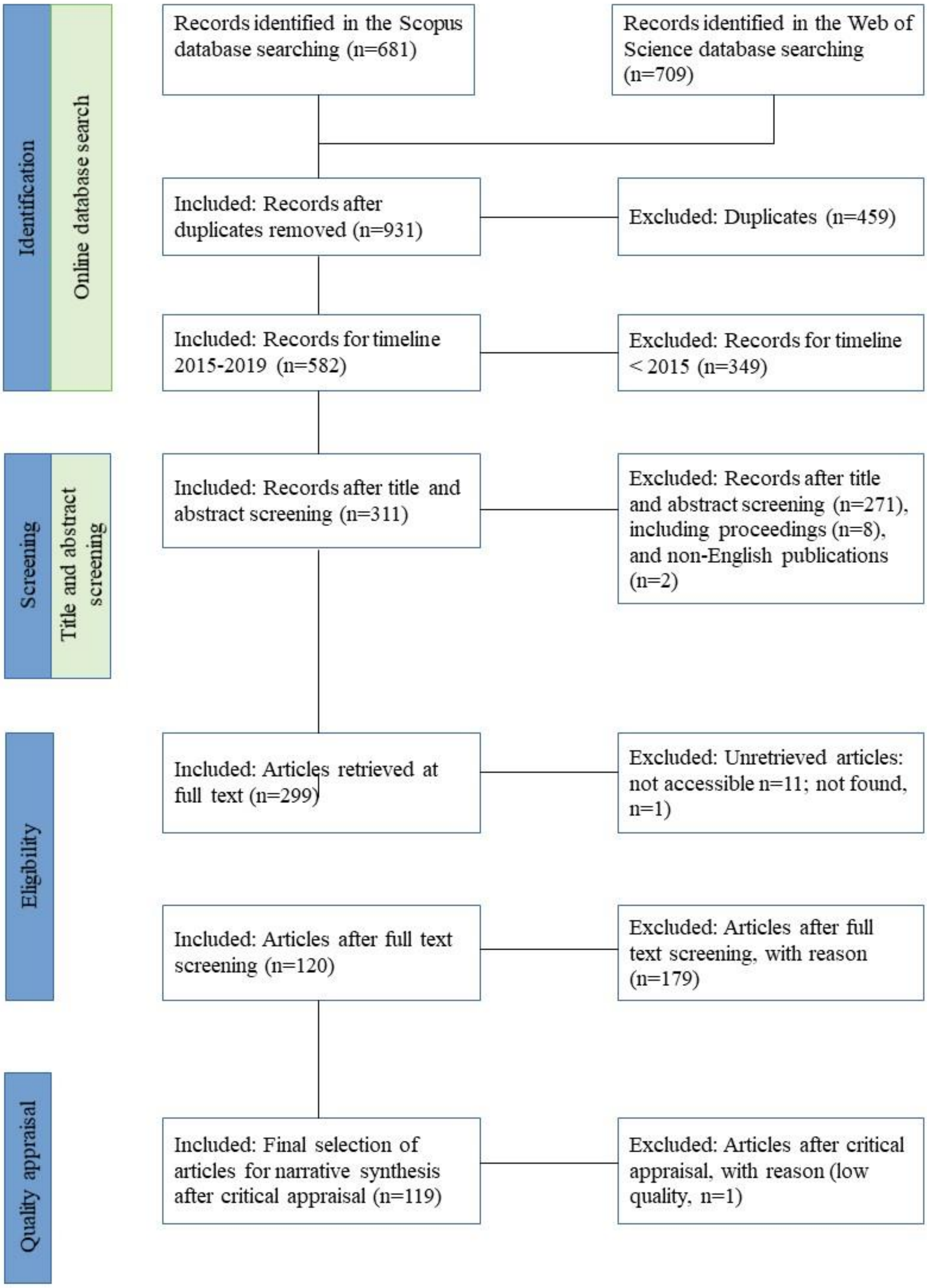


Figure SM2-1.1. Summary of document selection according to the ROSES pro forma standard.

Step 4 – Synthesis (data extraction):

From each case study documenting local responses to climate change impacts, we recorded: 1) bibliographic information (e.g., title, authors, publication year, journal), 2) georeferenced location and geographic characteristics (e.g., coordinates, main climate, altitude range), 3) studied group and attributes (e.g., livelihoods), and 4) the list of local responses to climate change (Table SM2-1.6. We only coded local responses for which the authors explicitly provided a link to climate change and its impacts. The coded entries of each article were double-checked by the lead author.

Table SM2-1.6. Data extracted and analyzed for the purpose of this study.

Variable	Data entry options	Data type
Bibliographic information	Author(s)	text
	Title	text
	Publication year	numeric
	Journal/Book	text
	Language	text
	DOI	character string
Study site information	X-latitude, Y-longitude	numeric (6 decimal)
	Continent	text
	World region	category
	Country	text
	Location name	text
	Altitude range	category
	main climate according to the Köppen-Geiger classification	category
Study group information	name of study group (e.g., ethnic group)	text
	the three main livelihoods	category
Information on reported local adaptation to climate change	descriptions of local responses to climate change	text
	classification of local responses to climate change	category
	direction of change	category

Information for the georeferenced location and altitude were taken directly from the article, if provided, otherwise from secondary data, such as Wikipedia GeoHack (https://tools.wmflabs.org/geohack/) or Google Maps (https://www.google.com/maps) for the location and Enetplanet (http://www.enetplanet.com/) or Daft Logic Google Maps Finds Altitude (https://www.daftlogic.com/sandbox-google-maps-find-altitude.htm) for the altitude.

Since our analysis is a global assessment, possible discrepancies arising from the quality of the secondary data are considered minor, with negligible impacts on the quality of our results. For the estimation of the main climate we used the freely available raster layer of the Köppen-Geiger climates, provided by Kottek et al. (Kottek et al., 2006). We estimated the climate zone of the study sites based on the GPS locations.

Step 5 - Data Analysis

The global map of the locations of case studies reviewed in this article was drawn with the open-source geographic information system Quantum GIS (QGIS, version 3.4.14-Madeira) (QGIS Development Team, 2018).

We performed the descriptive and statistical data analysis with RStudio (version 1.2.5033) (R Studio Team, 2019) based on the R language (version 3.6.2) (R Core Team, 2019).

SM2-2 World regions

Table SM2-2. Definitions of the world regions and included countries.

World region	Countries
AFR (Sub-Saharan Africa)	Angola, Botswana, Ethiopia, Ghana, Kenya, Lesotho, Malawi, Namibia, Nigeria, Rwanda, South Africa, Tanzania, Uganda, Zambia, Zimbabwe,
MEA (Middle East/North Africa)	Iran
SAS (South Asia)	Bangladesh, India, Myanmar, Nepal, Pakistan
EAS (Eastern Asia)	China (including Tibet), Vietnam
PAS (Asia-Pacific)	East Timor, Indonesia, Malaysia, Papua New Guinea, Philippines, Solomon Islands, Thailand, Vanuatu
LAM (Latin America and the Caribbean)	Bolivia, Brazil, Colombia, Ecuador, Jamaica, Mexico, Peru, Venezuela
NAM (North America)	USA (Alaska), Canada
EUR (Europe)	Finland, Greenland, Norway

SM2-3 Overview of sites

Table SM2-3. Spatial distribution and livelihood characteristics of study sites. nonNRD = non- or low-natural resource dependent; a: The category ‘Total’ for the number of case studies for the livelihoods differ from the number of case studies per continent and altitude since the livelihoods of a given community may be classified into several non-exclusive categories.

	climate zone					
	equatorial	**arid**	**temperate**	**snow**	**polar**	**Total**
Continents, Total	54	30	53	23	21	181
Africa	17	26	15	0	0	58
Asia	30	2	28	6	2	68
North & Central America, excl. Arctic	0	0	1	15	9	25
Oceania	0	0	0	0	0	0
Latin America & the Caribbean	7	2	9	0	9	27
Europe	0	0	0	2	1	3
Altitude, Total	54	30	53	23	21	181
coast	32	8	2	15	10	67
low-/midlands (=< 1,500 masl)	19	18	23	2	0	62
high altitudes (1,500 - 2,000 m)	2	2	17	1	0	22
very high altitudes (> 2,500 masl)	1	2	11	5	11	30
Livelihoods, Total[a]	114	53	109	43	41	360
Cultivation	52	19	59	4	11	145
Fishing & Aquaculture	32	9	2	15	10	68
Livestock husbandry	16	19	31	8	7	81
Hunting / Gathering	6	3	6	15	10	40
nonNRD* livelihood	8	3	3	1	2	26

SM2-4 Response sectors, domains, and types

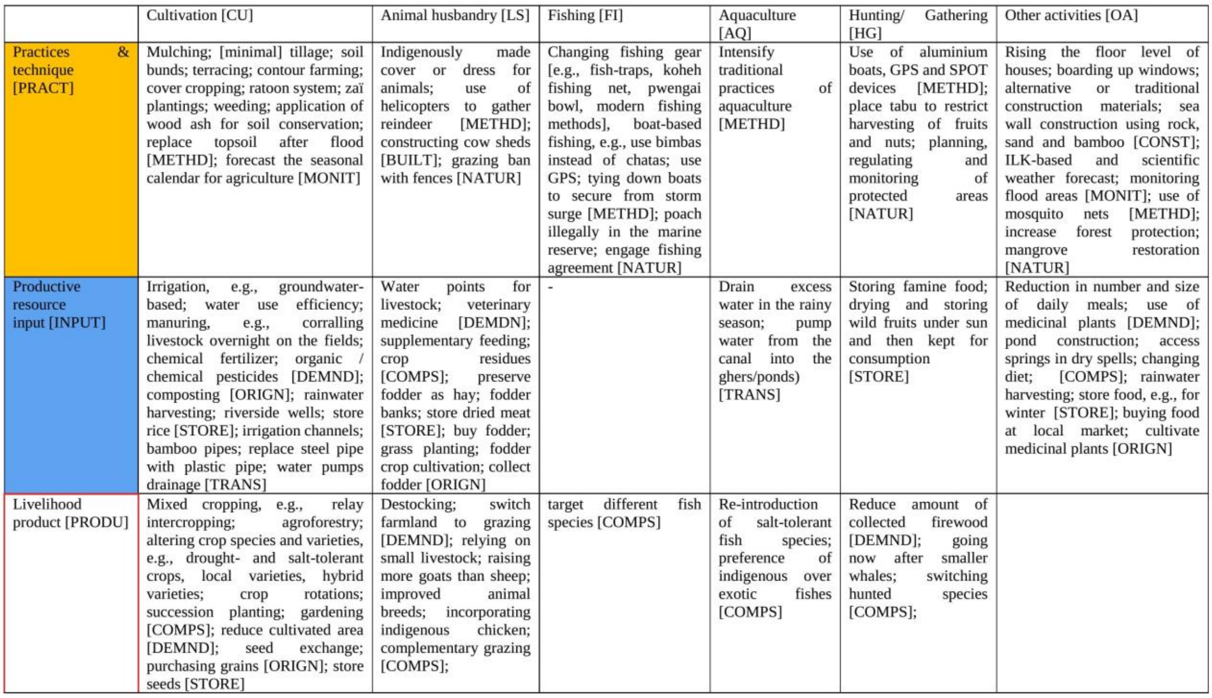
Readers are able to access interactive data visualization of the classification of local responses to climate change by Indigenous Peoples and local communities, presented in Figure 3-2, Table SM2-4.1, Table SM2-4.2 and https://licci.eu/local-responses-to-climate-change-classification.

Table SM2-4.1. Definition of the response sectors, domains and types (in alphabetic order).

Response level	Definition
Response sector	AQ: Changes in the aquaculture sector; CU: Changes in the cultivation sector; FI: Changes in the fishery sector; LS: Changes in the livestock sector; OA: Changes in ‘other activities’

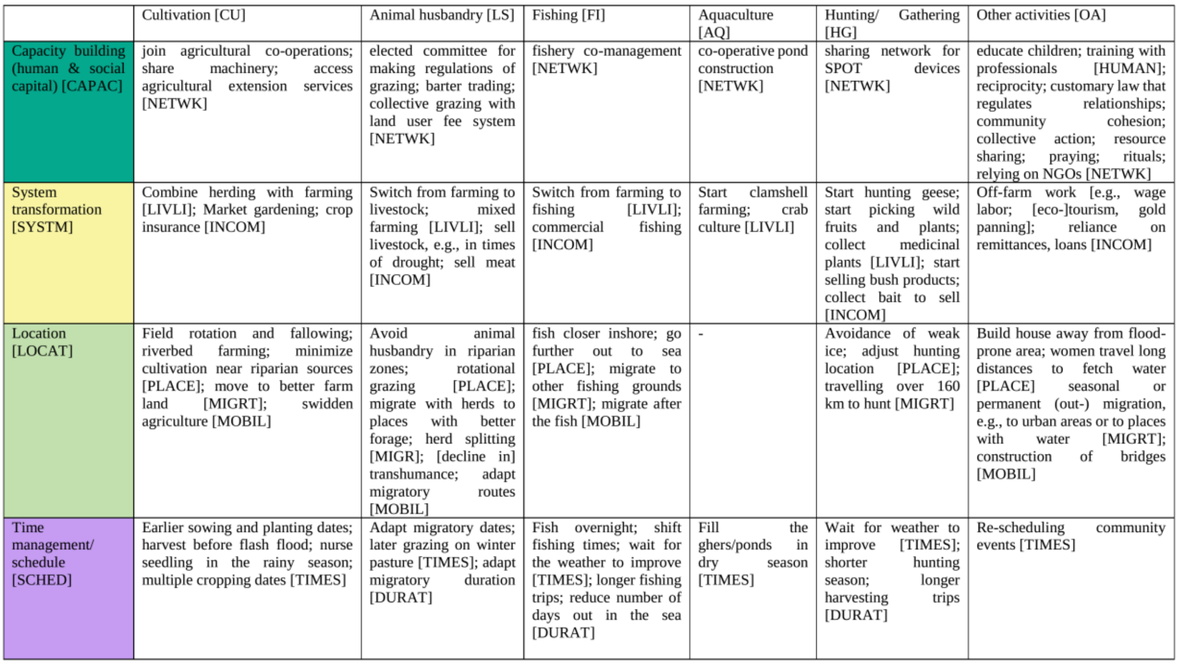
Response domain	CAPAC: Changes in the capacity building related to the human and social capital; INPUT: Changes in the input of productive resources (FERTD: fertiliser; FOODD: food; MEDIC: medicine/antibiotics; PESTD: pesticides; WATER: water); LOCAT: Changes in locations; PRACT: Changes in practices; PRODU: Changes in livelihood products; SCHED: Changes in time management; SYSTM: Changes in the livelihood system
Response type	COMPS: Changes in the composition of resource input and livelihood products; BUILT: Changes in built construction; DEMND: Changes in the demand of resource input and livelihood products; DURAT: Changes in duration; HUMAN: Changes in human capacities; INCOM: Changes in income generation; LIVLI: Changes in the natural-resource-based livelihood system; METHD: Changes in methods and techniques; MOBIL: Changes in mobility; MONIT: Changes in observation and monitoring; NETWK; Changes in social relation and networks; MIGRT: Changes in migration; NATUR: Biodiversity conservation; ORIGN: Changes in the provenance of resource input and livelihood products; PLACE: Changes in nearby places (close-by relocation); STORE: Changes in storage and storage facilities; TIMES: Changes in timing; TRANS: Changes in (water) transport facilities;

Table SM2-4.2. Examples of the classification of documented local responses to climate change impacts. The columns refer to the response sector, while the rows refer to the response domain. Examples refer to different response types belonging to the respective response sector and domain.



	Cultivation [CU]	Animal husbandry [LS]	Fishing [FI]	Aquaculture [AQ]	Hunting/ Gathering [HG]	Other activities [OA]
Practices & technique [PRACT]	Mulching; [minimal] tillage; soil bunds; terracing; contour farming; cover cropping; ratoon system; zaï plantings; weeding; application of wood ash for soil conservation; replace topsoil after flood [METHD]; forecast the seasonal calendar for agriculture [MONIT]	Indigenously made cover or dress for animals; use of helicopters to gather reindeer [METHD]; constructing cow sheds [BUILT]; grazing ban with fences [NATUR]	Changing fishing gear [e.g., fish-traps, koheh fishing net, pwengai bowl, modern fishing methods], boat-based fishing, e.g., use bimbas instead of chatas; use GPS; tying down boats to secure from storm surge [METHD]; poach illegally in the marine reserve; engage fishing agreement [NATUR]	Intensify traditional practices of aquaculture [METHD]	Use of aluminium boats, GPS and SPOT devices [METHD]; place tabu to restrict harvesting of fruits and nuts; planning, regulating and monitoring of protected areas [NATUR]	Rising the floor level of houses; boarding up windows; alternative or traditional construction materials; sea wall construction using rock, sand and bamboo [CONST]; ILK-based and scientific weather forecast; monitoring flood areas [MONIT]; use of mosquito nets [METHD]; increase forest protection; mangrove restoration [NATUR]
Productive resource input [INPUT]	Irrigation, e.g., groundwater-based; water use efficiency; manuring, e.g., corralling livestock overnight on the fields; chemical fertilizer; organic / chemical pesticides [DEMND]; composting [ORIGN]; rainwater harvesting; riverside wells; store rice [STORE]; irrigation channels; bamboo pipes; replace steel pipe with plastic pipe; water pumps drainage [TRANS]	Water points for livestock; veterinary medicine [DEMDN]; supplementary feeding; crop residues [COMPS]; preserve fodder as hay; fodder banks; store dried meat [STORE]; buy fodder; grass planting; fodder crop cultivation; collect fodder [ORIGN]	-	Drain excess water in the rainy season; pump water from the canal into the ghers/ponds) [TRANS]	Storing famine food; drying and storing wild fruits under sun and then kept for consumption [STORE]	Reduction in number and size of daily meals; use of medicinal plants [DEMND]; pond construction; access springs in dry spells; changing diet; [COMPS]; rainwater harvesting; store food, e.g., for winter [STORE]; buying food at local market; cultivate medicinal plants [ORIGN]
Livelihood product [PRODU]	Mixed cropping, e.g., relay intercropping; agroforestry; altering crop species and varieties, e.g., drought- and salt-tolerant crops, local varieties, hybrid varieties; crop rotations; succession planting; gardening [COMPS]; reduce cultivated area [DEMND]; seed exchange; purchasing grains [ORIGN]; store seeds [STORE]	Destocking; switch farmland to grazing [DEMND]; relying on small livestock; raising more goats than sheep; improved animal breeds; incorporating indigenous chicken; complementary grazing [COMPS];	target different fish species [COMPS]	Re-introduction of salt-tolerant fish species; preference of indigenous over exotic fishes [COMPS]	Reduce amount of collected firewood [DEMND]; going now after smaller whales; switching hunted species [COMPS];	

Continued table SM2-4.2. Examples of the classification of documented local responses to climate change impacts. The columns refer to the response sector, while the rows refer to the response domain. Examples refer to different response types belonging to the respective response sector and domain.



	Cultivation [CU]	Animal husbandry [LS]	Fishing [FI]	Aquaculture [AQ]	Hunting/ Gathering [HG]	Other activities [OA]
Capacity building (human & social capital) [CAPAC]	join agricultural co-operations; share machinery; access agricultural extension services [NETWK]	elected committee for making regulations of grazing; barter trading; collective grazing with land user fee system [NETWK]	fishery co-management [NETWK]	co-operative pond construction [NETWK]	sharing network for SPOT devices [NETWK]	educate children; training with professionals [HUMAN]; reciprocity; customary law that regulates relationships; community cohesion; collective action; resource sharing; praying; rituals; relying on NGOs [NETWK]
System transformation [SYSTM]	Combine herding with farming [LIVLI]; Market gardening; crop insurance [INCOM]	Switch from farming to livestock; mixed farming [LIVLI]; sell livestock, e.g., in times of drought; sell meat [INCOM]	Switch from farming to fishing [LIVLI]; commercial fishing [INCOM]	Start clamshell farming; crab culture [LIVLI]	Start hunting geese; start picking wild fruits and plants; collect medicinal plants [LIVLI]; start selling bush products; collect bait to sell [INCOM]	Off-farm work [e.g., wage labor; [eco-]tourism, gold panning]; reliance on remittances, loans [INCOM]
Location [LOCAT]	Field rotation and fallowing; riverbed farming; minimize cultivation near riparian sources [PLACE]; move to better farm land [MIGRT]; swidden agriculture [MOBIL]	Avoid animal husbandry in riparian zones; rotational grazing [PLACE]; migrate with herds to places with better forage; herd splitting [MIGR]; [decline in] transhumance; adapt migratory routes [MOBIL]	fish closer inshore; go further out to sea [PLACE]; migrate to other fishing grounds [MIGRT]; migrate after the fish [MOBIL]	-	Avoidance of weak ice; adjust hunting location [PLACE]; travelling over 160 km to hunt [MIGRT]	Build house away from flood-prone area; women travel long distances to fetch water [PLACE] seasonal or permanent (out-) migration, e.g., to urban areas or to places with water [MIGRT]; construction of bridges [MOBIL]
Time management/ schedule [SCHED]	Earlier sowing and planting dates; harvest before flash flood; nurse seedling in the rainy season; multiple cropping dates [TIMES]	Adapt migratory dates; later grazing on winter pasture [TIMES]; adapt migratory duration [DURAT]	Fish overnight; shift fishing times; wait for the weather to improve [TIMES]; longer fishing trips; reduce number of days out in the sea [DURAT]	Fill the ghers/ponds in dry season [TIMES]	Wait for weather to improve [TIMES]; shorter hunting season; longer harvesting trips [DURAT]	Re-scheduling community events [TIMES]

SM 2-5 Included references

Table SM2-5. List of documents that were coded and analyzed in this review.

Country	Climate_code	LACCIpublication_ID	Reference
Alaska / USA	C	601	(Wyllie de Echeverria & Thornton, 2019)
	D	90 112 637	(Rosales & Chapman, 2015), (Chapin et al., 2016) (Huntington et al., 2017)
	E	90 637	(Huntington et al., 2017) (Rosales & Chapman, 2015)
Angola	B	680	(Sowman & Raemaekers, 2018)
Bangladesh	A	125 144 226 634 656	(Sultana & Thompson, 2017) (Momtaj Bintay Khalil et al., 2019) (Rakib et al., 2019) (Alam et al., 2017) (M.B. Khalil et al., 2016)
	C	125	(Sultana & Thompson, 2017)
		170	(M. N. Q. Ahmed & Atiqul Haq, 2019)
		290	(Rahman & Alam, 2016)
Bolivia	B	164	(Meldrum et al., 2018)
	C	164	(Meldrum et al., 2018)

		648	(Taboada et al., 2017)
	E	164	(Meldrum et al., 2018)
		648	(Taboada et al., 2017)
Botswana	B	298	(Kolawole et al., 2016)
		633	(Akinyemi, 2017)
		646	(Ngwenya et al., 2017)
Brazil	A	106	(Vogt et al., 2016)
		658	(Oviedo et al., 2016)
		667	(Pinho et al., 2015)
Canada	C	601	(Wyllie de Echeverria & Thornton, 2019)
	D	670	(Clark et al., 2016)
		676	(Panikkar et al., 2018)
		683	(Waugh et al., 2018)
	E	603	(Galappaththi et al., 2019)
		670	(Clark et al., 2016)
		676	(Panikkar et al., 2018)
China	C	278	(Shijin & Dahe, 2015)
		684	(Zhang et al., 2018)
		897	(Song et al., 2020)
	D	291	(Wu et al., 2015)
		672	(Dong, 2017)
	E	278	(Shijin & Dahe, 2015)
Colombia	C	608	(Leroy, 2019)
East Timor	A	666	(Hiwasaki et al., 2015)
Ecuador	B	606	(Kieslinger et al., 2019)
	C	904	(López et al., 2017)
	E	904	(López et al., 2017)
Ethiopia	A	604	(Gebru et al., 2019)
	B	600	(M. E. Ahmed & Bihi, 2019)
		649	(Tilahun et al., 2017)
		688	(Balehegn et al., 2019)
	C	115	(Iticha & Husen, 2019)
		604	(Gebru et al., 2019)
		625	(Amare, 2018)
		643	(Mekuriaw, 2017)
Finland	D	138	(Turunen et al., 2016)
Ghana	A	143	(Gyasi & Gyekye Awere, 2018)
		619	(Yamba et al., 2019)
		627	(Freduah et al., 2018)
		629	(Kwoyiga & Stefan, 2018)
		664	(Antwi-Agyei et al., 2015)
		690	(Nyantakyi-Frimpong & Bezner-Kerr, 2015)
Greenland / Denmark	E	681	(Tejsner & Veldhuis, 2018)
India	A	623	(P. K. Singh et al., 2019)
		628	(Kodirekkala, 2018)
	B	669	(Sarkar et al., 2015)
	C	157	(Pandey et al., 2018)
		289	(Shukla et al., 2016)
		605	(Inaotombi & Mahanta, 2019)
		645	(Negi et al., 2017)
		654	(Hazarika et al., 2016)
		669	(Sarkar et al., 2015)

		672	(Dong, 2017)
		863	(Maikhuri et al., 2018)
	D	095	(Ingty, 2017)
		672	(Dong, 2017)
Indonesia	A	632	(Utami et al., 2018)
		666	(Hiwasaki et al., 2015)
Iran	C	615	(Saboohi et al., 2019)
Jamaica	A	626	(Baptiste, 2018)
Kenya	B	614	(Omolo & Mafongoya, 2019)
	C	810	(Ombati, 2019)
Lesotho	C	147	(Palframan, 2015)
Malawi	A	137	(Trogrlić et al., 2019)
		630	(Limuwa et al., 2018)
		674	(Hockett & Richardson, 2018)
		682	(Trogrlić et al., 2018)
	B	137	(Trogrlić et al., 2019)
		682	(Trogrlić et al., 2018)
	C	674	(Hockett & Richardson, 2018)
Mexico	A	004	(Audefroy & Sánchez, 2017)
		602	(Frawley et al., 2019)
Myanmar	A	279	(Swe et al., 2015)
	B	620	(Zin et al., 2019)
Namibia	B	655	(Hooli, 2016)
		680	(Sowman & Raemaekers, 2018)
Nepal	C	100	(T.K. Baul & McDonald, 2015)
		113	(S. Devkota & Lal, 2016)
		142	(Gentle & Thwaites, 2016)
		609	(Maharjan & Maharjan, 2020)
		621	(Cieslik et al., 2019)
		635	(R. P. Devkota et al., 2017)
		672	(Dong, 2017)
Nigeria	A	631	(Tunde & Ajadi, 2018)
		636	(Ebhuoma & Simatele, 2017)
		638	(Ifeanyi-Obi et al., 2017)
Norway	D	653	(Gundersen et al., 2016)
Pakistan	C	686	(Nasir et al., 2018)
Papua New Guinea	A	639	(Inamara & Thomas, 2017)
Peru	C	678	(Saylor et al., 2017)
	E	127	(Walshe & Argumedo, 2016)
		678	(Saylor et al., 2017)
Philippines	A	611	(G. L. M. Nelson et al., 2019)
		640	(Lirag & Estrella, 2017)
		647	(Soriano et al., 2017)
		657	(Landicho et al., 2016)
		666	(Hiwasaki et al., 2015)
		920	(Molina & Neef, 2016)
Rwanda	C	662	(Taremwa et al., 2016)
Solomon Islands	A	285	(S. Aswani et al., 2015)
South Africa	B	119	(Ubisi et al., 2020)
		292	(Rankoana, 2016b)
		680	(Sowman & Raemaekers, 2018)

		687	(Vilakazi et al., 2019)
	C	171	(Apraku et al., 2018)
		659	(Rankoana, 2016a)
		687	(Vilakazi et al., 2019)
Tanzania	A	058	(Ojoyi & Mwenge Kahinda, 2015)
		149	(Wang et al., 2013)
		286	(Velempini et al., 2018)
		661	(Smucker & Wangui, 2016)
	B	058	(Ojoyi & Mwenge Kahinda, 2015)
		661	(Smucker & Wangui, 2016)
Thailand	A	616	(Sereenonchai & Arunrat, 2019)
Tibet	D	613	(Nyima & Hopping, 2019)
Uganda	A	612	(M. Nkuba et al., 2019)
Vanuatu	A	133	(Granderson, 2017)
Venezuela	C	608	(Leroy, 2019)
Vietnam	A	660	(Thi Hoa Sen & Bond, 2017)
	C	617	(H. Son & Kingsbury, 2020)
		618	(H. N. Son et al., 2019)
Zambia	B	010	(Makondo & Thomas, 2018)
	C	010	(Makondo & Thomas, 2018)
Zimbabwe	B	607	(Kupika et al., 2019)
		644	(Mubaya & Mafongoya, 2017)
		679	(Siambombe et al., 2018)
	C	104	(Mugambiwa, 2018)
		176	(Mutandwa et al., 2019)
		610	(Mashizha, 2019)
		622	(Mugambiwa & Rukema, 2019)
		882	(Mapfumo et al., 2016)

SM3 Supplementary materials for Chapter 4

SM3-1 Literature review process – search strings

Table SM3-1: Summary of applied key search strings during the different phases of the literature review.

	Key search string
Phase 1	((“climate change” OR “global warming” OR “climate variability” OR “climate risk”) AND
	(“indigenous knowledge” OR “local knowledge” OR “traditional knowledge” OR “traditional ecological knowledge” OR “ILK” OR “TEK”) AND
	(“adapt*” OR “coping” OR “cope”))
	WOS: 402; Scopus: approx.316
Phase 2	((“climate change” OR “global warming” OR “climate variability" OR "climate risk") AND (“indigenous knowledge” OR “local knowledge” OR “traditional knowledge” OR “traditional ecological knowledge” OR “ILK” OR “TEK”) AND
	Topic ‘community-based adaptation’: ((fish*) OR (Aqua*)) AND (adapt*) AND ((Village) OR (communit*) OR (Hamlet) OR (municipal*)) [WOS: 421; Scopus: 383]
	Topic ‘livelihood diversification’: ((fish*) OR (Aqua*)) AND (adapt*) AND (diversif*) [WOS: 151; Scopus: 98]
	Topic ‘Local governance and conflict resolutions schemes’: ((fish*) OR(Aqua*)) AND (adapt*) AND ((co-manag*) OR (communit*) OR (collaborat*) OR (self*)) [WOS: 402; Scopus: 386]
	Topic ‘traditional crops and crop diversification’: ("traditional crop*" OR "indigenous crop*" OR "traditional food crop*" OR "indigenous food crop*" OR "traditional variet*" OR “indigenous variet*” OR "traditional crop variet*" OR “indigenous crop variet*” OR "crop diversit*" OR "agrobiodiversity" OR “multiple crop*” OR “intercrop*” OR “inter-crop*” OR “mixed crop*” OR “companion crop*” OR “relay crop*” OR “sequential crop*”)) [WOS: 422; Scopus: 390]

	Topic ‘traditional weather forecast’: ("indigenous knowledge" OR "local knowledge" OR "traditional knowledge" OR "traditional ecological knowledge" OR “ILK” OR “TEK”) AND ("climate forecast*" OR "weather forecast*" OR "weather predict*" OR "drought predict*" OR "flood predict*" OR "climate indicator*" OR "weather indicator*" OR "bioindicat*" OR "bio-indicator*"OR "cropping schedule" OR "seasonal calendar" OR "agricultur* calendar" OR "seasonal activit*")) [WOS: approx. 25; Scopus: approx. 26]
	Topic ‘traditional soil and water management’: (("indigenous knowledge" OR "local knowledge" OR "traditional knowledge" OR "traditional ecological knowledge" OR "traditional" or "indigenous" or "ILK" or "TEK") AND ("water conservation" OR "water management" OR “water restor*” OR “soil conservat*” OR “soil restor*” OR "soil management" OR “mulch* OR “tillag* OR “zai” OR “zaï” OR “bun shift*”)))[WOS:approx. 125; Scopus: 15]

SM3-2 Literature review process – included publications

Table SM3-2: List of the 98 articles

Authors	Year	Title	Journal
Fisheries food systems			
Galappaththi, E.K., Ford, J., Bennett, E., Berkes, F.	2019	Climate change and community fisheries in the Arctic: A case study from Pangnirtung, Canada.	Journal of Environmental Management
Galappaththi, E.K., Ford, D.J., Bennett, E.M.	2020	Climate change and adaptation to social-ecological change: The case of Indigenous people and culture-based fisheries in Sri Lanka.	Climatic Change
Galappaththi, E.K., Ford, J., Bennett, E., Berkes	2021	Adapting to climate change in small-scale fisheries: Insights from Indigenous communities in the global north and south	Environmental Science and Policy
Galappaththi, E.K., Berkes, F., Ford, J.	2019	Climate change adaptation in coastal shrimp aquaculture: a case from northwestern Sri Lanka	FAO
Stephan Schott, James Qitsualik, Peter Van Coeverden de Groot, Simon Okpakok, Jacqueline M. Chapman, Stephen Lougheed, and Virginia K. Walker	2020	Operationalizing knowledge coevolution: towards a sustainable fishery for Nunavummiut	Arctic Science

Roux, M.J., Tallman, R.F., Martin, Z.A.	2019	Small-scale fisheries in Canada's Arctic: Combining science and fishers knowledge towards sustainable management	Marine Policy
Lavoie, Anna, Lee, Jean, Sparks, Kim, Hoseth, Gayla, Wise, Sarah	2019	Engaging with women's knowledge in Bristol Bay Fisheries through oral history and participatory ethnography	Fisheries
Berkes, Fikret	2021	Toward a new social contract: community-based resource management and small-scale fisheries	e-book
Bronen, Robin, Pollock, Denise, Overbeck, Jacquelyn, Stevens, Susan Natali, Maio, Chris	2020	Usteq: integrating indigenous knowledge and social and physical sciences to coproduce knowledge and support community-based adaptation	Polar Geography
Chen, Tzu-Ling, Cheng, Hung-Wen	2020	Applying traditional knowledge to resilience in coastal rural villages	International Journal of Disaster Risk Reduction
Barua, P., & Rahman, S. H.	2019	Indigenous knowledge and sustainable value chain approach to climate change adaptation in the fisheries sector of coastal Bangladesh	IUP Journal of Knowledge Management
Basel, Britt Goby, Gillian Johnson, Johanna	2020	Community-based adaptation to climate change in villages of Western Province, Solomon Islands	Marine Pollution Bulletin
van der Ploeg, Jan Sukulu, Meshach Govan, Hugh Minter, Tessa Eriksson, Hampus	2020	Sinking islands, drowned logic; climate change and community-based adaptation discourses in Solomon Islands	Sustainability
Sowman, Merle	2020	Participatory and rapid vulnerability assessments to support adaptation planning in small-scale fishing communities of the Benguela Current Large Marine Ecosystem	Environmental Development
Salas S., Huchim-Lara O., Guevara-Cruz C., Chin W.	2019	Cooperation, competition, and attitude toward risk of small-scale fishers as adaptive strategies: The case of Yucatán, Mexico	Springer Nature 2019
Diamir de Scally & Brent Doberstein	2021	Local knowledge in climate change adaptation in the Cook Islands	Climate and Development
Pearson, Jasmine McNamara, Karen E. Nunn, Patrick D.	2020	iTaukei ways of knowing and managing mangroves for ecosystem-based adaptation	Springer International Publishing
Mohamed Shaffril, Hayrol Azril, Ahmad, Nobaya, Samsuddin, Samsul Farid,	2020	Systematic literature review on adaptation towards climate change impacts among indigenous people in the Asia Pacific regions	Journal of Cleaner Production

Samah, Asnarulkhadi Abu, Hamdan, Mas Ernawati			
Galappaththi, E.K., Ford, J., Bennett, E., Berkes, F.	2019	Climate change and community fisheries in the Arctic: A case study from Pangnirtung, Canada.	Journal of Environmental Management
Pinsky, ML, Fenichel, E, Fogarty, M, et al.	2021	Fish and fisheries in hot water: What is happening and how do we adapt?	Population Ecology
Oyebola, O.O., Efitre, J., Musinguzi, L. et al.	2021	Potential adaptation strategies for climate change impact among flood-prone fish farmers in climate hotspot Uganda	Environ Dev Sustain
Martins, Ivan Machado Gasalla, Maria A.	2020	Adaptive Capacity Level Shapes Social Vulnerability to Climate Change of Fishing Communities in the South Brazil Bight	Frontiers in Marine Science
Utete, Beaven Phiri, Crispen Mlambo, Sibonani S. Muboko, Never Fregene, Bernadette T.	2019	Vulnerability of fisherfolks and their perceptions towards climate change and its impacts on their livelihoods in a peri-urban lake system in Zimbabwe	Environment, Development and Sustainability
Mulyasari, G. Irham, Waluyati, L. R. Suryantini, A.	2021	Understanding and adaptation to climate change of fishermen in the northern coastal of Central Java, Indonesia	IOP Conference Series: Earth and Environmental Science
Islam MA, Shamsuzzoha M, Rasheduzzaman M, Ghosh RC, and Faisal M.	2019	Assessment on climate change adaptation: a study on coastal area of Khulna district in Bangladesh	Aust. J. Eng. Innov. Technol.
Melissa Nursey-Bray, R. Palmer, T. F. Smith & P. Rist	2019	Old ways for new days: Australian Indigenous peoples and climate change	Local Environment
von Seggern, Janne	2021	Understandings, practices and human-environment relationships—A weta-ethnographic analysis of local and Indigenous climate change adaptation and mitigation strategies in selected Pacific Island States	Sustainability
Dutta, S., Maiti, S., Garai, S. et al.	2020	Analyzing adaptation strategies to climate change followed by the farming community of the Indian Sunderbans using Analytical Hierarchy Process	Journal of Coastal Conservation
Whitney, C. K., A. Frid, B. K. Edgar, J. Walkus, P. Siwallace, I. L. Siwallace, and N. C. Ban	2020	“Like the plains people losing the buffalo”: perceptions of climate change impacts, fisheries management, and adaptation actions by Indigenous peoples in coastal British Columbia, Canada.	Ecology and Society

Mohamed Shaffril, Hayrol Azril Samah, Asnarulkhadi Abu Samsuddin, Samsul Farid Ali, Zuraina	2019	Mirror-mirror on the wall, what climate change adaptation strategies are practiced by the Asian's fishermen of all?	Journal of Cleaner Production
Schlingmann, Anna Graham, Sonia Benyei, Petra Corbera, Esteve Martinez Sanesteban, Irene Marelle, Andrea Soleymani-Fard, Ramin Reyes-García, Victoria	2021	Global patterns of adaptation to climate change by Indigenous Peoples and local communities. A systematic review	Current Opinion in Environmental Sustainability
Mbah, Marcellus Ajaps, Sandra Molthan-Hill, Petra	2021	A systematic review of the deployment of Indigenous knowledge systems towards climate change adaptation in Developing World contexts: Implications for climate change education	Sustainability
Millin, Amanda	2020	Indigenous aquaculture: A tool to support food security.	UC San Diego: Center for Marine Biodiversity and Conservation.
Gianelli, Ignacio Ortega, Leonardo Pittman, Jeremy Vasconcellos, Marcelo Defeo, Omar	2021	Harnessing scientific and local knowledge to face climate change in small-scale fisheries	Global Environmental Change
Casagrande, Alana Salvatore, Rita Rover, Oscar José Chiodo, Emilio Fantini, Andrea	2021	Artisanal mollusc fisheries co-management in Brazil and Italy: Institutional innovations to address environmental crisis	Journal of Environmental Management
Tilley, Alexander Hunnam, Kimberley J. Mills, David J. Steenbergen, Dirk J. Govan, Hugh Alonso-oblacion, Enrique Roscher, Matthew Pereira, Mario Rodrigues, Pedro Amador, Teresa Duarte, Agustinha Gomes, Mario Cohen, Philippa J. Fujita, Rod	2019	Evaluating the fit of co-management for small-scale fisheries governance in Timor-Leste	Frontiers in Marine Science
Burden, Merrick Fujita, Rod	2019	Better fisheries management can help reduce conflict, improve food security, and increase economic productivity in the face of climate change	Marine Policy
Tran, Thong Anh Pittock, JamesTuan, Le Anh	2019	Adaptive co-management in the Vietnamese Mekong Delta: examining the interface between flood management and adaptation	International Journal of Water

			Resources Development
Martins, Ivan Machado Gasalla, Maria A.	2020	Adaptive capacity level shapes social vulnerability to climate change of fishing communities in the South Brazil Bight	Frontiers in Marine Science
Islam, Mohammad Mahmudul Nahiduzzaman, Md Wahab, Md Abdul	2020	Fisheries co-management in hilsa shad sanctuaries of Bangladesh: Early experiences and implementation challenges	Marine Policy
Stephan Schott, James Qitsualik, PeterVan Coeverden de root, Simon Okpakok, Jacqueline M. Chapman, Stephen Lougheed, and Virginia K. Walker	2020	Operationalizing knowledge coevolution: towards a sustainable fishery for Nunavummiut	Arctic Science
Chan, Bunyeth Ngor, Peng Bun Hogan, Zeb S. So, Nam Brosse, Sébastien Lek, Sovan	2020	Temporal dynamics of fish assemblages as a reflection of policy shift from fishing concession to co-Management in one of the world's largest tropical flood pulse fisheries	Water
Kyvelou, Stella Ierapetritis, Dimitris	2020	Fisheries sustainability through soft multi-use maritime spatial planning and local development co-management: Potentials and challenges in Greece	Sustainability
Suasi, Thanyalak, Koya, Isao	2019	Strengthening the capacity of local communities for fostering community-based resources management/co-management: a case study in Khammouane Province, Lao PDR	Fish for the People
Ruszin, Natasha	2019	Evaluating co-management of Lake Nipissing's fisheries	University of Toronto's TSpace repository
Ebel, S. A.	2020	Moving beyond co-management: Opportunities and limitations for enabling transitions to polycentric governance in Chile's territorial user rights in fisheries policy.	International Journal of the Commons
Ogier, Emily Jennings, Sarah Fowler, Anthony Frusher, Stewart Gardner, Caleb Hamer, Paul Hobday, Alistair J. Linanne, Adrian Mayfield, Stephan Mundy, Craig Sullivan, Andrew Tuck, Geoff Ward, Tim Pecl, Gretta	2020	Responding to climate change: Participatory evaluation of adaptation options for key marine fisheries in Australia's South East	Frontiers in Marine Science
Mc Clenachan, Loren Scyphers, Steven Grabowski, Jonathan H.	2020	Views from the dock: Warming waters, adaptation, and the future of Maine's lobster fishery	Ambio

Agricultural food systems			
Adhikari, L; Tuladhar; Hussain, A; Aryal, K	2019	Are yraditional food crops really ‘future smart foods?’ A sustainability perspective	Sustainability
Aniah P; Kaunza-Nu-Dem, MK; Ayembilla, JA	2019	Smallholder farmers' livelihood adaptation to climate variability and ecological changes in the savanna agro ecological zone of Ghana	Heliyon
Assefa, Y; Yadav, S; Mondal, MK; Bhattacharya, J; Parvin, R; Sarker, SR; Rahman, M; Sutradhar, A; Prasad, PVV; Bhandari, H; Shew, AM; Jagadish, SVK	2021	Crop diversification in rice-based systems in the polders of Bangladesh: Yield stability, profitability, and associated risk	Agricultural Systems
Bonifacio, A	2019	Improvement of Quinoa (Chenopodium quinoa Willd.) and Qanawa (Chenopodium pallidicaule Aellen) in the context of climate change in the high Andes	Ciencia e Investigación Agraria
Camacho-Villa, TC; Martinez-Cruz, TE; Ramírez-López, A; Hoil-Tzuc, M; Terán-Contreras, S	2021	Mayan traditional knowledge on weather forecasting: Who contributes to whom in coping with climate change?	Frontiers in Sustainable Food Systems
Chaudhary, BR; Acciaioli, G; Erskine, W; Chaudhary P	2021	Responses of the Tharu to climate change-related hazards in the water sector: Indigenous perceptions, vulnerability and adaptations in the western Tarai of Nepal	Climate and Development
Dhakal B; Kattel RR	2019	Effects of global changes on ecosystems services of multiple natural resources in mountain agricultural landscapes	Science of the Total Environment
Dutta, S; Maiti, S; Garai, S; Abrar, F; Jha, SK; Bhakat, M; Mandal, S; Kadian, KS	2020	Analyzing adaptation strategies to climate change followedby the farming community of the Indian Sunderbans using Analytical Hierarchy Process	Journal of Coastal Conservation
Huynh, CV; Le, QNP; Nguyen, MTH; Tran, PT; Nguyen, TQ; Pham, TG; Nguyen, LHK; Nguyen, LTD; Trinh, HN	2020	Indigenous knowledge in relation to climate change: adaptation practices used by the Xo Dang people of central Vietnam	Heliyon
Maikhuri, RK; Rawat, LS; Maletha, A; Phondani, PC; Semwal, RL; Bahuguna, YM; Bisht, TS	2019	Community Response and Adaptation	Tropical Ecosystems: Structure, Functions, and Challenges in the Face of Global Change

Ndalilo, L; Wekesa, C; Mbuvi, MTE	2020	Indigenous and local knowledge practices and innovations for enhancing food security under climate change: Examples from Mijikenda communities in coastal Kenya	Sustainability
Novotny, IP; Tittonell, P; Fuentes-Ponce, MH; Lopez-Ridaura, S; Rossing, WAH	2021	The importance of the traditional milpa in food security and nutritional self-sufficiency in the highlands of Oaxaca, Mexico	PLOS One
Ravera, F; Reyes-García, V; Pascual, U; Drucker, AG; Tarrasón, D; Bellon, MR	2019	Gendered agrobiodiversity management and adaptation to climate	Agriculture and Human Values
Singh, RK; Kumar, A; Singh, A; Singhal, P	2020	Evidence that cultural food practices of Adi women in Arunachal Pradesh, India, improve social-ecological resilience: insights for Sustainable Development Goals	Ecological Processes
Son, HN; Kingsbury, A; Hoa, HT	2021	Indigenous knowledge and the enhancement of community resilience to climate change in the Northern Mountainous Region of Vietnam	Agroecology and Sustainable Food Systems
Song Y; Dong Y; Wang J; Feng J; Long C	2020	Tartary buckwheat (Fagopyrum tataricum Gaertn.) landraces cultivated by Yi people in Liangshan, China	Genetic Resources and Crop Evolution
Theodory, TF	2020	Understanding the relevance of indigenous knowledge on climate change adaptation among mixed farmers in the Ngono River Basin, Tanzania	African Journal of Science, Technology, Innovation, & Development
Balehegn, M; Balehey, S; Fu, C; Liang, W	2019	Indigenous weather and climate forecasting knowledge among Afar pastoralists of north eastern Ethiopia: Role in adaptation to weather and climate variability	Pastoralism: Research, Policy and Practice
Camacho-Villa T.C., Martinez-Cruz T.E., Ramírez-López A., Hoil-Tzuc M., Terán-Contreras S.	2021	Mayan traditional knowledge on weather forecasting: Who contributes to whom in coping with climate change?	Frontiers in Sustainable Food Systems
Chaudhary B.R., Acciaioli G., Erskine W., Chaudhary P.	2021	Responses of the Tharu to climate change-related hazards in the water sector: Indigenous perceptions, vulnerability and adaptations in the western Tarai of Nepal	Climate and Development
Ebhuoma, EE	2020	A framework for integrating scientific forecasts with indigenous systems of weather forecasting in southern Nigeria	Development in Practice
Grey, MS	2019	Accessing seasonal weather forecasts and drought prediction information for rural	Jamba – Journal of

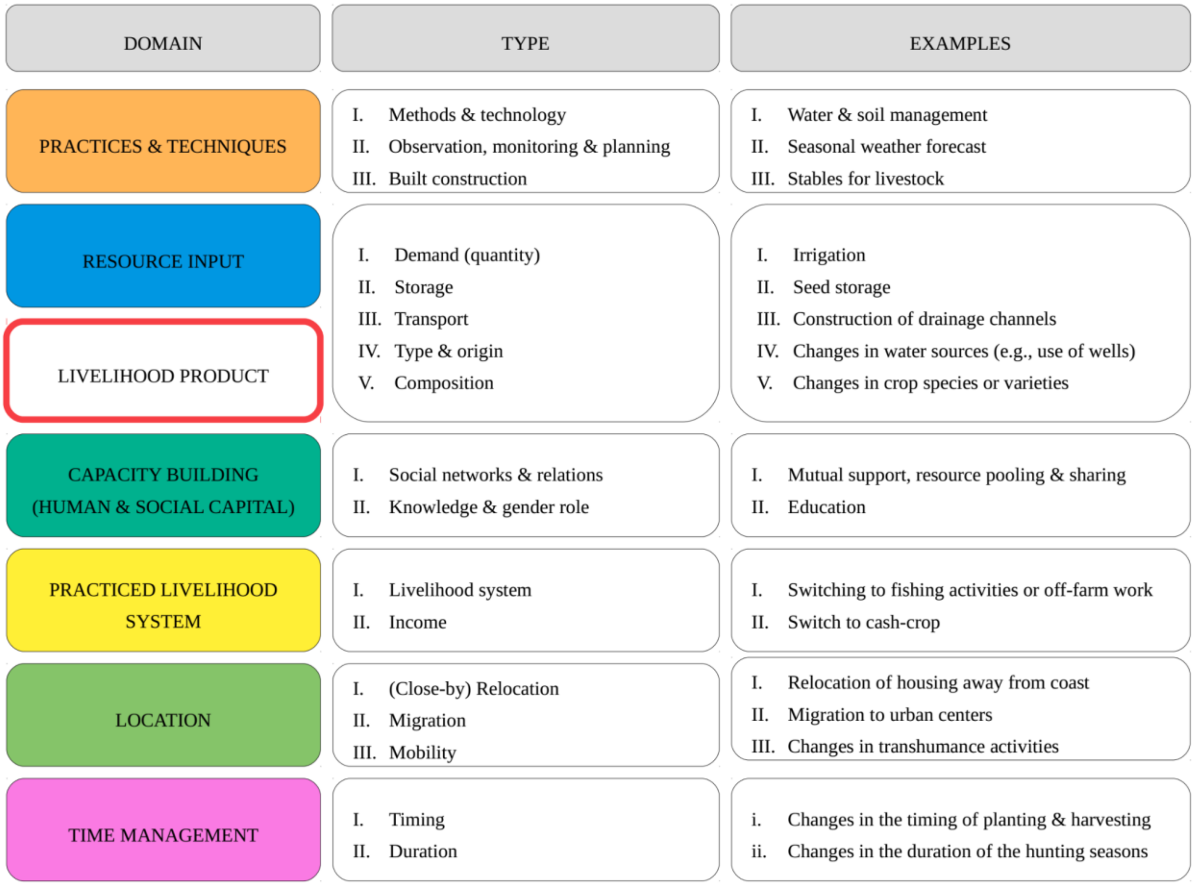
		households in Chirumhanzu district, Zimbabwe	Disaster Risk Studies
Hosen, N; Nakamura, H; Hamzah, A	2019	Adaptation to Climate Change: Does Traditional Ecological Knowledge Hold the Key?	Sustainability
Huynh, CV; Le, QNP; Nguyen, MTH; Tran, PT; Nguyen, TQ; Pham, TG; Nguyen, LHK; Nguyen, LTD; Trinh, HN	2019	Indigenous knowledge in relation to climate change: adaptation practices used by the Xo Dang people of central Vietnam	Heliyon
Iticha, B; Husen, A	2019	Adaptation to climate change using indigenous weather forecasting systems in Borana pastoralists of southern Ethiopia	Climate and Development
Mogomotsi, PK; Sekelemani, A; Mogomotsi, GEJ	2020	Climate change adaptation strategies of small-scale farmers in Ngamiland East, Botswana	Climatic Change
Nkuba M.R., Chanda R., Mmopelwa G., Kato E., Mangheni M.N., Lesolle D.	2020	Influence of Indigenous knowledge and scientific climate forecasts on arable farmers' climate adaptation methods in the Rwenzori region, Western Uganda	Environmental Management
Pauli N., Williams M., Henningsen S., Davies K., Chhom C., van Ogtrop F., Hak S., Boruff B., Neef A.	2021	"Listening to the sounds of the water": Bringing together local knowledge and biophysical data to understand climate-related hazard dynamics	International Journal of Disaster Risk Science
Radeny, M; Desalegn, A; Mubiru, D; Kyazze, F; Mahoo, H; Recha, J; Kimeli, P; Solomon, D	2019	Indigenous knowledge for seasonal weather and climate forecasting across East Africa	Climatic Change
Ruzol C., Lomente L.L., Pulhin J.	2021	Cultural consensus knowledge of rice farmers for climate risk	Climate Risk Management
Son, HN; Kingsbury, A; Hoa, HT		Indigenous knowledge and the enhancement of community resilience to climate change in the Northern Mountainous Region of Vietnam	Agroecology and Sustainable Food Systems
Tume S.J.P., Kimengsi J.N., Fogwe Z.N.	2019	Indigenous knowledge and farmer perceptions of climate and ecological changes in the bamenda highlands of cameroon: Insights from the bui plateau	Climate
Ubisi, NR; Kolanisi, U; Jiri, O	2020	The role of Indigenous knowledge systems in rural smallholder farmers' response to climate change: Case study of Nkomazi local municipality, Mpumalanga, South Africa	Journal of Asian and African Studies
Abeywardana, N; Schütt, B; Wagalawatta, T; Bebermeier, W	2019	Indigenous agricultural systems in the Dry Zone of Sri Lanka: Management transformation assessment and sustainability	Sustainability

Ahmad, Z; Fazlur-Rahman, Dittmann A; Hussain, K; Ihsanullah	2020	Water crisis in the eastern Hindu Kush: A micro-level study of community-based irrigation water management in the mountain village Kushum, Pakistan	Erdkunde
Ahmed, AIA; Eldoma, IM; Elaagip, EEAH	2020	Effects of Indigenous cultivation practices on soil conservation in the hilly semiarid areas of Western Sudan	Water
Aniah, P; Kaunza-Nu-Dem, MK; Ayembilla, JA	2019	Smallholder farmers' livelihood adaptation to climate variability and ecological changes in the savanna agro ecological zone of Ghana	Heliyon
Alvar-Beltrán, J; Dao, A; Dalla Marta, A; Heureux, A; Sanou, J; Orlandini, S	2020	Farmers’ perceptions of climate change and agricultural adaptation in Burkina Faso	Atmosphere
Asmamaw, M; Mereta, ST; Ambelu, A	2020	The role of local knowledge in enhancing the resilience of dinki watershed social-ecological system, central highlands of Ethiopia	PLoS ONE
Dutta, S; Maiti, S; Garai, S; Abrar, F; Jha, SK; Bhakat, M; Mandal, S; Kadian, KS	2020	Analyzing adaptation strategies to climate change followedby the farming community of the Indian Sunderbans using Analytical Hierarchy Process	Journal of Coastal Conservation
Ghorbani, M; Eskandari-Damaneh, H; Cotton, M; Ghoochani, OM; Borji, M	2021	Harnessing indigenous knowledge for climate change-resilient water management–lessons from an ethnographic case study in Iran	Climate and Development
Hosen, N; Nakamura, H; Hamzah, A	2019	Adaptation to climate change: Does traditional ecological knowledge hold the key?	Sustainability
Nguyen, AT; Hens, L	2021	Diversified responses to contemporary pressures on sloping agricultural land: Thai farmer’s perception of mountainous landscapes in northern Vietnam	Environment Development and Sustainability
Nyantakyi-Frimpong, H	2020	What lies beneath: Climate change, land expropriation, andzaïagroecological innovations by smallholder farmers in Northern Ghana	Land Use Policy
Radcliffe, C; Raman, A; Parissi, C	2020	Entwining indigenous knowledge and science knowledge for sustainable agricultural extension: exploring the strengths and challenges	Journal of Agricultural Education and Extension
Rivera-Ferre, MG; Di Masso, M; Vara,I; Cuellar, M; López-i-Gelats, F; Bhatta, GD; Gallar, D	2021	Traditional agricultural knowledge in land management: the potential contributions of ethnographic research to climate change adaptation in India, Bangladesh, Nepal, and Pakistan	Climate and Development

Postigo, J	2020	The role of social institutions in indigenous Andean Pastoralists’ adaptation to climate-related water hazards	Climate and Development
Upadhaya, K; Barik, SK; Kharbhih, VM; Nongbri, G; Debnath, G; Gupta, A; Ojha, A	2019	Traditional bun shifting cultivation practice in Meghalaya, Northeast India	Energy, Ecology and Environment

SM4 Supplementary materials for Chapter 5

SM4-1 Classification of local adaptive responses



DOMAIN	TYPE	EXAMPLES
PRACTICES & TECHNIQUES	I. Methods & technology II. Observation, monitoring & planning III. Built construction	I. Water & soil management II. Seasonal weather forecast III. Stables for livestock
RESOURCE INPUT	I. Demand (quantity) II. Storage III. Transport IV. Type & origin V. Composition	I. Irrigation II. Seed storage III. Construction of drainage channels IV. Changes in water sources (e.g., use of wells) V. Changes in crop species or varieties
LIVELIHOOD PRODUCT		
CAPACITY BUILDING (HUMAN & SOCIAL CAPITAL)	I. Social networks & relations II. Knowledge & gender role	I. Mutual support, resource pooling & sharing II. Education
PRACTICED LIVELIHOOD SYSTEM	I. Livelihood system II. Income	I. Switching to fishing activities or off-farm work II. Switch to cash-crop
LOCATION	I. (Close-by) Relocation II. Migration III. Mobility	I. Relocation of housing away from coast II. Migration to urban centers III. Changes in transhumance activities
TIME MANAGEMENT	I. Timing II. Duration	i. Changes in the timing of planting & harvesting ii. Changes in the duration of the hunting seasons

Figure SM4-1. Classification system of local adaptive responses to climate change.

SM4-2 Calculation of socio-economic household and individual indices

Human capital index of household head

For the level of schooling, the following categories were recorded 'no schooling', 'primary school’, 'middle school', 'high school', and 'beyond high school', and coded as 0, 0.25, 0.5, 0.75, and 1, respectively. For second language knowledge the categories ‘no', 'a little', and ‘fluent’ were recorded, and coded as 0, 0.5 and 1, respectively. The average value over both coded indicators defined the human capital per household.

Social capital index of household

Participation in collective activities and organized groups were converted into numeric values: 0 (rarely participating), 0.5 (sometimes participating) and 1 (often participating). The variable NGO support is a binomial variable that takes the value of 1 if the household received support and 0 otherwise. The number of adult family members living outside the community was divided by the site’s maximum value to receive values between 0 and 1. We then determined the mean value across the three categories, which resulted in values between 0 and 1.

Asset ownership index of households

The household’s *asset ownership index* is the sum over the quantity of a set of 10 physical assets owned by a household multiplied by their respective local economic value in US-Dollars. We used the asset ownership index as a proxy to detect wealthier and poorer households.

Food and freshwater sovereignty index of household

The household *food and freshwater sovereignty index* comprises four aspects of sovereignty for food and freshwater: quality, quantity, control and preferences. For each aspect, and separately for water and food, we converted qualitative information into numeric values. Specifically for quality we distinguish between 0 (“quality was often not good”), 0.5 (“quality was sometimes not good"), and 1 (“quality was usually good”). For quantitative aspects we distinguish between 0 (“often we did not have enough”), 0.5 (“sometimes we did not have enough”), and 1 (“we always had enough”). For control aspects we distinguish between 0 (“no control”), 0.5 (“some control”), and 1 (“full control”), and for preference aspects we distinguish between 0 (“I rarely/never had access to my preferred water sources”), 0.33 (“I mostly did not have access to my preferred water sources, but sometimes I did”), 0.66 (“I mostly had access to my preferred water sources, but not always”), and 1 (“I always had access to my preferred water sources”) or, in analogy for food: 0 (“I rarely/never could eat the foods I like to eat”), 0.33 (“I mostly ate foods I do not prefer, but sometimes I could eat the foods I like”), 0.66 (“I mostly ate the foods I like, but sometimes had to eat something else”), and 1 (“I always ate the foods I like to eat”). For each household and separately for food and freshwater, we then determined the mean values across the four categories, which resulted in values ranging between 0 and 1.

SM4-3 Context-specific adaptation implementation

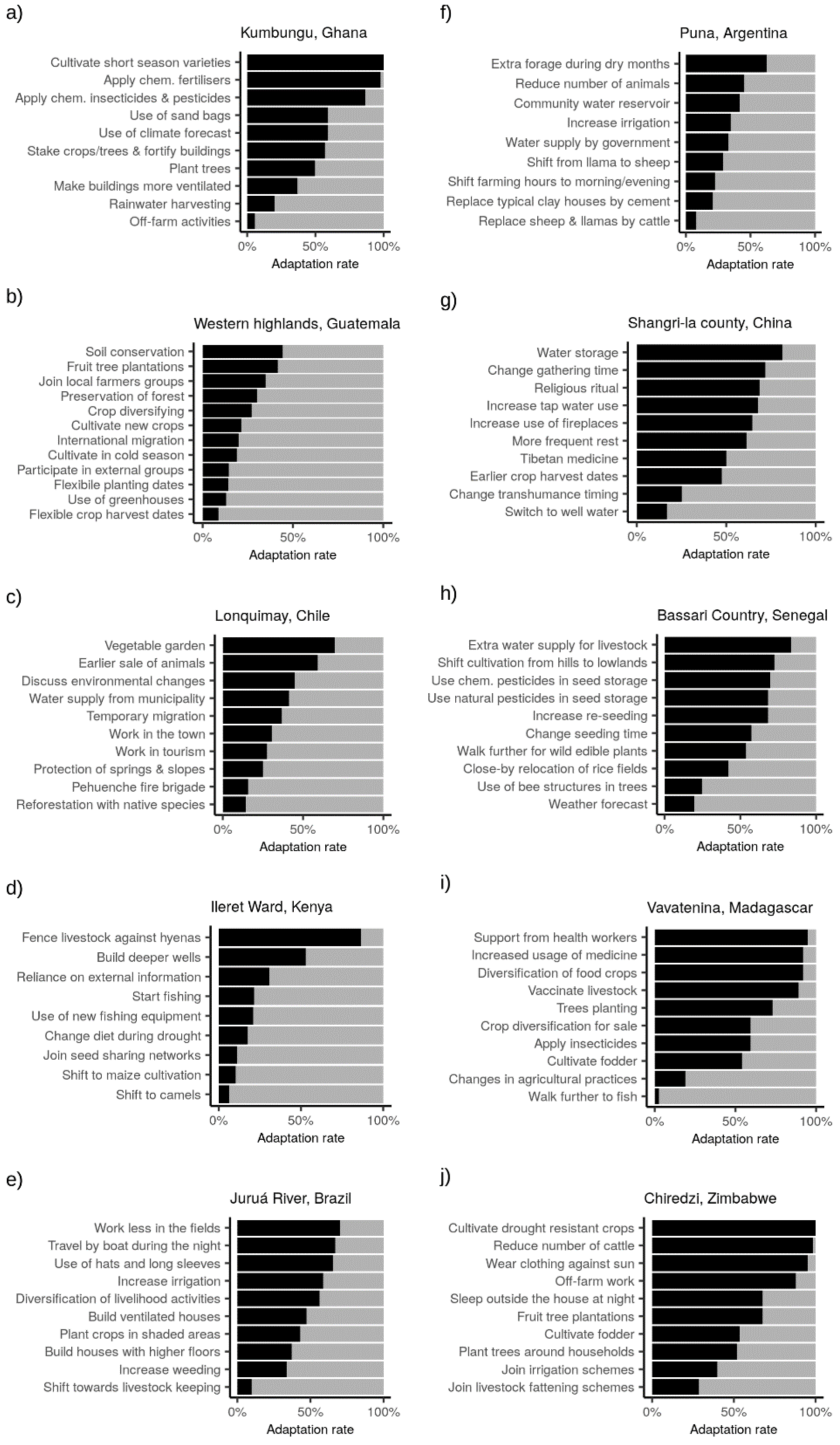


Figure SM4-3. Adaptation implementation rates (in black) for each adaptive response in the ten sites.

SM4-4 Socio-economic characteristic among the four climate change impact - adaptation groups

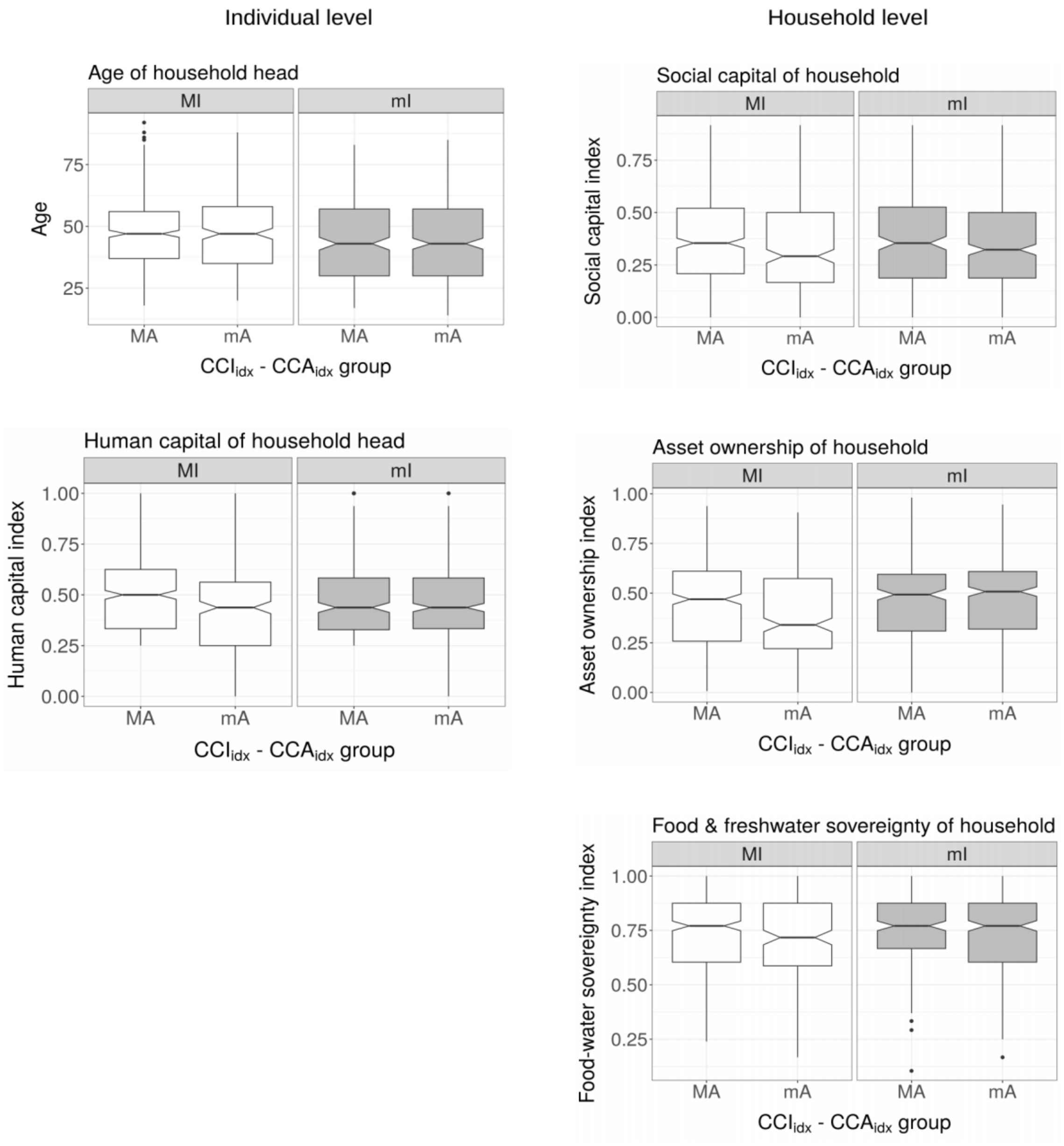


Figure SM4-4. Boxplot visualization of socio-economic differences between the four different climate change impact appraisal (CCI_{idx}) - adaptation implementation (CCA_{idx}) groups: *major impacted adapters* (MI-MA), *major impacted adaptation laggers* (MI-mA), *minor impacted adapters* (mI-MA), and *minor impacted adaptation laggers* (mI-mA). Significance levels are indicated at 5% (*), 1% (**) and 0.1% (***) probability levels.

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Additional research activities

Peer-reviewed publications (published/accepted)

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