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Review article

Operationalising local knowledge to enhance climate services: evidence from a systematic review

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HIGHLIGHTS

- Our review examines how local knowledge is used to produce usable climate services.
- Studies on local knowledge are growing, yet real integration cases remain limited.
- Local knowledge is often narrowly defined and excludes diverse knowledge holders.
- Exploration of local knowledge is often explored for its own sake, not connected to decisions.
- We propose a framework that broadens and embeds local knowledge across the climate service value chain.

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ABSTRACT

Climate services (CS) often face usability challenges, with many climate information products lacking uptake and use. Integrating local knowledge (LK) can enhance the credibility, salience and legitimacy of CS. Although international frameworks increasingly call for incorporating LK, how it is studied and applied in practice remains unclear. We conducted a systematic review of CS and climate change adaptation literature (119 articles) and operational CS projects (22 projects) to examine where LK is explored, whose knowledge is considered, and how it is used within CS. Our review shows a growing body of scholarship focusing on LK related to risk knowledge, monitoring and prediction, risk management, and collective action. These dimensions add value by improving the usability of CS and providing a resource for communities or individuals to build resilience. Despite these advances, the actual integration of LK into operational CS remains limited. This gap stems from insufficient conceptual clarity regarding what constitutes LK, approaches that separate LK from the context of its use, and the tendency to recognise LK only at the end-user level, neglecting more tacit forms of LK mobilised by other actors throughout CS development. We argue that addressing this challenge requires reframing LK within the context of CS production and the decisions CS aim to support. Exploration of LK should start from decision-making and the ways in which LK is mobilised. A decision-focused perspective applied throughout the CS value chain can enable a more systematic and sustained integration of LK across all actors engaged in CS provision.

Practical implications: Climate services (CS) are typically produced through collaboration among stakeholders on the CS value chain. The actors on the value chain perform crucial functions, converting raw climate data to downscaled sector-specific information that is not only locally relevant but is communicated through channels and in ways that align with knowledge generation and sharing mechanisms of the end user. The end user, in this case, may be a local community, business or an institutional agency and organisation (e.g., water management agencies, line ministries, civil society organisations, etc.). Usability of CS, therefore, hinges on these being embedded in the local decision-making processes of stakeholders. Knowing what works on the ground, what

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information is needed to inform decisions, when and how, as well as building trust with users, is critical for the uptake of CS. This is precisely why integrating local knowledge (LK) is crucial.

We find that even though CS are produced through collaboration among stakeholders on the CS value chain, the exploration and integration of local knowledge remain disconnected from this reality. Efforts to incorporate LK largely confine it to the end-user level, often reducing LK to a set of indicators of interest. Moreover, documented examples of LK integration in operational CS remain scarce. The narrow understanding of what LK entails and who holds it has constrained its practical use. In doing so, the central aim of producing decision-oriented information remains only partially realised.

To address this gap, we argue the need to reframe LK through the lens of the CS value chain, recognising that CS are co-produced through collaboration and negotiation among diverse knowledge systems. Adopting a broader conception of LK means acknowledging the different ways it is generated: through personal experience, tradition, culture and norms, recent human-climate interactions, and structured or formalised processes. This broader framing of LK allows us to identify relevant knowledge not only at the end user level but throughout the climate services value chain. Doing so can help embed climate services more effectively in the local context and improve their credibility, salience and legitimacy. Practical ways in which our reconceptualisation can help in identifying and articulating LK across different levels of the CS chain include (but are not limited to):

- Data providers, integrators, modellers: Engaging with the LK of global and local data providers can help sharpen decisions on data and model selection, improve model calibration, help bridge gaps between global datasets and local realities, and produce a more nuanced understanding of what climate services can or cannot do.
- Service providers: Stakeholders like government agencies or private sector companies are often responsible for providing climate sectoral information tailored to a specific sector. Given the role of service providers in translating and tailoring the climate information, engaging with their tacit knowledge is critical in understanding the broader landscape within which climate services are embedded, how information can be made more salient and more closely linked to action, and managing knowledge flows across institutions, sectors and scales.
- Service purveyors: Their proximity to the local context provides them with the know-how of both the end user and their physical environment. This positioning enables them not only to translate information into usable formats, identify trusted communication channels, and build legitimacy, but also to validate climate data and model outputs against local insights.
- End users: Valuing their diverse experiential and intergenerational knowledge ensures services are aligned with real needs, enabling better-informed and more resilient decisions.

Furthermore, our recommendation on how to operationalise this reconceptualisation is not by viewing integration of LK as a goal in itself, but rather to understand how knowledge is mobilised for decision-making. Therefore, the entry point to integrating LK should not be the knowledge itself, but rather the relevant decisions or processes that CS aims to support. Such integration is key to overcoming the usability gap that continues to limit the effectiveness of many CS.

1. Introduction

Climate services (CS) offer resources (e.g., seasonal forecasts, climate projections and scenarios, impact advisories) that empower citizens with data and information to support decision-making. The European Commission defines CS as the "transformation and delivery of climate-related research, information and data – together with other relevant information – into customised products that may be of use for society at large to plan for long-term adaptation" (Street, 2016, p. 3). This description highlights two facets: firstly, climate information by itself is insufficient and needs to be combined with other types of information and knowledge to be made useful, and secondly, CS are designed inherently to support planning and decision-making (Goddard, 2016). What is less explicitly emphasised, but has been increasingly recognised within literature, is that CS functions both as a product (i.e., forecasts, advisories) and as a process (i.e., collaborative and iterative engagement between producers, intermediaries and users) (Bremer and Meisch, 2017). Provision of usable CS, therefore, requires attention to be paid to these different aspects.

Climate services are produced at the interface of science and society through collaboration among data providers, integrators, service providers, purveyors, and users, who form the CS value chain (Hewitt and Stone, 2021). Resting on the premise that a broad knowledge base is required to tackle societal challenges, the provision of CS requires each link in the CS value chain to leverage its knowledge to create value (Weber and Khademian, 2008; Kirchhoff et al., 2013; Hewitt and Stone, 2021). In a practical sense, this means that beyond climate science itself, knowledge of the local context and an understanding of the decision-making process of CS users are critical to ensuring that both the mechanism established to produce the CS and the CS itself remain responsive to local realities and traditions related to knowledge generation and use (Vincent et al., 2018).

Climate services have greatly benefited from improvements in monitoring and data computation capabilities. Despite this, uptake of CS by decision-makers has remained limited (Dilling and Lemos, 2011; Lemos et al., 2012; Buontempo et al., 2014; Webber, 2019). This "usability gap" arises from factors such as a lack of understanding of the decision-making context of users of CS, their capacities, and poor recognition of different types of knowledge that underpin the CS development process (Lemos et al., 2012; Daniels et al., 2020; Williams et al., 2020). Overcoming these challenges has prompted the adoption of co-production techniques that emphasise deliberate and cyclical cooperation across the CS value chain to co-produce "actionable knowledge" (Kirchhoff et al., 2013). Such knowledge, as described by Cash et al. (2003), has to be credible (the knowledge has scientific integrity and is adequate to inform the advice), salient (relevant to the needs of its beneficiaries), and legitimate (the knowledge was produced as a result of a process that was inclusive of different beliefs and values), thereby requiring working across boundaries and negotiating between different knowledge systems.

Within CS, calls for integrating local knowledge (LK) emerged from the need to make weather forecasts more useful (supporting the decision-making process) for the intended users (Easterling and Stern, 1999; Patt and Gwata, 2002). The importance of LK has also been reiterated for effectively communicating scientific information and advice to ensure ownership and uptake (Sivakumar, 2006; Pulwarty and

Sivakumar, 2014). International frameworks like the World Meteorological Organization's (WMO) Global Framework for Climate Services (GFCS), Hyogo Framework for Action and Sendai Framework for Disaster Risk Reduction also call for integrating different types of knowledges within CS, including LK. Emergent scholarship on integrating LK within CS has focused on understanding LK across different geographical contexts, studying LK integration within CS (e.g., (Masinde, 2015; Plotz et al., 2017) and evaluating its credibility and value for CS (e.g., (Andersson et al., 2020; Streefkerk et al., 2022)). This growing interest in integrating LK within CS warrants understanding what is understood as LK within CS and how it is included in the CS design and delivery process.

This paper is positioned as a "reflective pause" to unpack how LK is currently understood and exploited within CS literature (Hadlos et al., 2022). Although discussions on LK are well established across a range of disciplines, this review is intentionally scoped to inform the LK discourse within the context of CS research and practice. As such, both the organisation of the review and the framing of its findings are designed to shed light on how LK is understood, discussed and translated into practice within CS. We aim to investigate whether the way LK is understood and explored within CS has supported its integration. We also look at LK beyond just the CS literature, reviewing the understanding of LK and its use across climate change adaptation (CCA) literature. Our intention of looking at LK more broadly is justified, as most CS projects aim to support adaptation actions of communities and individuals. Therefore, reviewing CCA literature can help unearth dimensions of LK that may not yet be fully considered within CS scholarship but may be valuable to include. With this, we aim to elucidate the topic of LK and present a coherent understanding that encourages its integration within CS. This in-depth exploration of LK seeks to contribute towards developing CS that supports decision-making. To do this, it is also paramount to understand how LK informs or aids decision-making. Thus, beyond examining how LK is explored within CS and CCA literature, this review also aims to uncover how LK explicitly supports decision-making processes of organisations, communities or individuals. In doing so, our interest is to inform the way in which LK is tackled within CS.

The research questions guiding the review are:

- What different LK forms (dimensions) appear across CS and CCA literature?
- In what ways (if any) does the inclusion of LK add value?
- How can LK help in understanding decision-making?

2. Theoretical background

Scholarship on LK has evolved across disciplines like anthropology (Geertz, 1983), ecology (Berkes et al., 2000), collaborative and environmental governance (Carlile, 2002; Weber and Khademian, 2008; Raymond et al., 2010; Taylor and de Loë, 2012), disaster risk reduction (Dekens, 2007; Hermans et al., 2022; Hadlos et al., 2022) and climate change adaptation (Naess, 2013). Early discussions emerged from anthropology and sociology, particularly in human ecology and ethnoscience, where the notion was to understand how communities classify, interpret and interact with their environments (Geertz, 1983). This strand of scholarship emphasised LK as a system of meaning and practice embedded in the local contexts. Studies subsequently approached LK through a utilitarian lens, valuing it primarily for its role in resource management and subsistence activities. This led to LK being mobilised within development practice as a counter to top-down interventions that marginalised local perspectives. Within this framing, LK was often treated instrumentally, i.e. as a means to improve agricultural productivity, strengthen natural resource management and secure local "buy-in" for externally driven projects (Agrawal, 1995; Sillitoe, 1998). Critique of this framing, within postcolonial scholarship, pointed out how this led LK to be frequently framed in essentialised ways, "tied exclusively to particular places and peoples" (Briggs and Sharp, 2004). More recently, recognition of LK has been reinforced by efforts to decolonise scientific discourse with recognition of indigenous peoples' rights and knowledge (Brondízio et al., 2021). In its many interpretations across different disciplines and discourses, LK is sometimes referred to as Indigenous knowledge (Iloka, 2016), traditional ecological knowledge (Berkes et al., 2000), tacit knowledge (Meisch et al., 2022) or stakeholder knowledge (Kloprogge and van der Sluijs, 2006). Ongoing debates over terminology are also acknowledged by the Intergovernmental Panel on Climate Change (IPCC), reiterating the challenges that come with defining LK (IPCC, 2019). While each term invokes a slightly different epistemology, IPCC defines LK as "the understanding and skills developed by individuals and populations, specific to the place where they live", while indigenous knowledge is defined as "the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings". These related knowledges have often jointly been referred to as Indigenous and Local knowledge or ILK to refer to knowledge that is highly context-specific, dynamic and relied on by local communities as a form of human capital to help them cope or adapt (IPCC, 2019).

Within CS, the conceptualisation of LK has often been borrowed from related disciplines and applied in varying ways. Interpretations range from a broad view of LK as skills and understanding developed by individuals to interpret their surroundings, solve problems and validate new information (Plotz et al., 2017; Streefkerk et al., 2022; Zvogbo et al., 2022), to indigenous knowledge that has been institutionalised within long-settled communities and passed down generationally (Guthiga and Newsham, 2011; Kolawole et al., 2014; Wilk et al., 2017). Local knowledge has also been framed more narrowly as the contextual, practice-based knowledge of farmers (Roncoli et al., 2002; Knudson and Guido, 2019; Guido et al., 2020). While these studies provide empirical cases of LK exploration and integration, they also illustrate the conceptual diversity and fragmentation of LK within CS, and the absence of a systematic theoretical framing. Beyond this, there is also a lack of discussion regarding whose LK is being intercepted. As outlined in the introduction of this paper, CS are generated through collaboration among a wide range of stakeholders, including forecasters, researchers, national and sub-national hydrometeorological authorities, line ministries, NGOs, civil society organisations, and end users. However, there is limited explicit reflection on whether and how the LK of these different stakeholders is considered during the process of CS development. In light of the conceptual plurality and limited clarity, this review does not adopt a fixed definition of LK. Instead, drawing on Berkes et al. (2000) and as reiterated by Naess (2013), we understand LK as a "hierarchical knowledge-practice-belief system" that is intricately linked to socio-economic and institutional context. By this, we refer to the idea that empirical observations and observable practices of local communities are underpinned by deeper normative values, worldviews and belief systems (Berkes et al., 2000). While knowledge and belief can be analytically distinguished, in reality they are intertwined, jointly informing perception, interpretation and decision-making (ibid). We use this framing of LK as a way to approach it holistically, capturing both experiential and normative dimensions of LK. Accordingly, we describe LK as a knowledge embedded in local institutions, communities and individuals; derived from practical experience, encapsulating culturally derived values, deeply rooted in the local context, accumulated over time, and used by these actors to understand, interpret and act upon their contexts (Food and Agriculture Organization, 2005; IPCC, 2019). Our framing of LK also covers indigenous knowledge and other related terms that have been used across literature.

3. Methods

3.1. Systematic review

This review is a stocktake of the current understanding and use of LK, evidence of its value-add, and ways in which LK informs decision-making. In the absence of a recognised definition or framework for LK within CS, we refrain from defining it from the outset in order to capture the widest set in our corpus of articles. A keyword-based literature search was conducted across CS and CCA literature. The study follows a systematic review methodology, following the steps highlighted in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. Fig. 1 presents a visual representation of the document selection and screening process.

3.1.1. Search strategy and document selection

The search for articles was limited to the SCOPUS database, as it is one of the largest resources for peer-reviewed literature (Singh et al., 2021). Below are the search strings that were used to extract relevant literature.

(TITLE-ABS-KEY ("local knowledge" OR "indigenous knowledge" OR "traditional knowledge") AND TITLE-ABS-KEY ("climate services" OR "seasonal forecasts" OR "climate information" OR "impact-based forecasts" OR "impact forecasting" OR "early warning system" OR "early warning")).

(TITLE-ABS-KEY ("local knowledge" OR "indigenous knowledge" OR "traditional knowledge") AND TITLE-ABS-KEY ("floods" OR "drought" OR "water scarcity") AND TITLE-ABS-KEY ("climate adaptation" OR "climate change adaptation" OR "adaptation")).

For LK, the keywords ("local", "indigenous", "traditional" and "knowledge") were selected based on an initial search to determine coverage and relevance, as well as based on other comparative reviews on LK, namely, Hadlos et al. (2022) and Hermans et al. (2022). These principal keywords were combined (using the "AND" operator) with the iterations of two different search strings to source articles across CS and CCA literature. Given that this review primarily centres on furthering the discourse on LK within CS, we cast a wide net to capture a diverse scholarship within CS literature. For instance, we use search terms typically associated with disaster risk reduction (like early warning and impact forecasting) to find relevant articles. For CCA literature, however, a more constrained approach was used, whereby a set of intermediate keywords ("floods", "droughts", and "water scarcity") was utilised to focus the search, recognising that a major focus of CS interventions is to support planning and adaptation in response to water-related issues and challenges (Boon et al., 2022). Moreover, given that water-related challenges are often cross-cutting across sectors, our focus on related articles allows us to capture diverse scholarship. Understanding LK use within that subset of CCA literature allows for a consistent and thorough examination. Additionally, given the importance of WMO's GFCS program in promoting the development of user-driven CS, we applied a temporal limit to our search – limiting the review to articles written from 2010 onwards (until May 27, 2023) (World Meteorological Organization, 2011). Finally, we selected relevant filters in SCOPUS (limiting the search to Subject Areas: Environmental Sciences, Social Sciences, Earth and Planetary Sciences, Agricultural and Biological Sciences, and Multidisciplinary and Decision Sciences) and only included scientific articles to constrain our search. This yielded 117 and 193 articles across CS and CCA literature, respectively. Before screening the abstracts, duplicate articles and articles that were either not accessible or did not have an abstract (24 in total) were removed. A total of 286 articles were passed through an abstract screening process and were subjected to eligibility criteria (Fig. 1). A final set of 119 abstracts (CCA abstracts = 79; CS abstracts = 40) were selected for analysis.

3.1.2. Document screening, coding and analysis

The analysis followed a two-step process – firstly, we performed a *meta*-analysis, mapping metadata and categories derived from the research questions (dimensions of LK, knowledge holders consulted and reported or implied value-add). To identify and categorise the different knowledge holders, we use the framework proposed by Hewitt and Stone (2021) which structures the actors involved in producing CS along a value chain, highlighting different roles these actors have in producing, translating and delivering climate information.

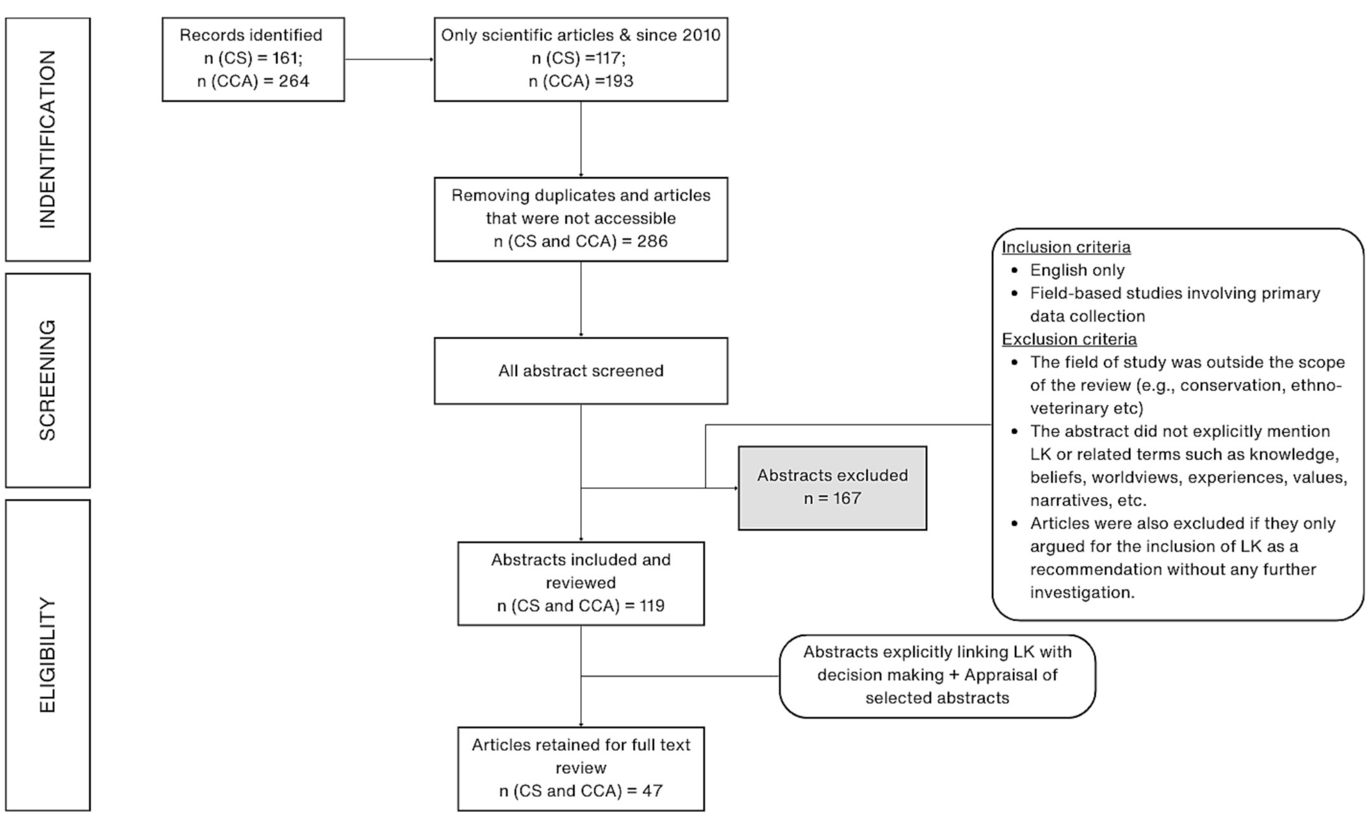

Fig. 1. Document selection and exclusion PRISMA diagram.

At the *meta*-analysis stage, we also filtered abstracts that explicitly connected LK to decision-making. This includes abstracts that explicitly mention LK triggering or influencing individual or community-level actions or informing the choice of management or adaptation strategies. This subset of articles was further evaluated, yielding 47 articles eligible for a full-text review. We first qualitatively coded the data (in Atlas.ti) and then performed thematic analysis to systematically identify how LK has been reported to support decision-making in practice. All references to the scientific articles reviewed in this study are numbered within square braces. The numbers directly correspond to the item number in the Supplementary data sheet.

3.2. Grey literature

In addition to peer-reviewed literature, we also included grey literature to understand how LK is conceptualised and operationalised in operational CS initiatives. Our intention was not to review grey literature in general, but to assess how LK is addressed within CS implementation on the ground. This enables a comparison between academic discourse and operational practice. Given the challenge of reviewing the entire breadth of grey literature on CS, we restricted our focus to reviewing projects documented under the GFCS program of the WMO and the ERA4CS program of the Joint Programming Initiative on Climate (JPI Climate) by the European Union. These programmes were selected because they represent prominent, well-documented, and institutionally significant funding streams explicitly dedicated to advancing CS. The GFCS is widely regarded as a foundational global framework for CS, shaping standards, priorities, and implementation approaches across regions and countries in the Global South (Hewitt et al., 2012; Vaughan and Dessai, 2014). Focusing on GFCS projects, therefore, allows us to examine how LK is positioned across interventions that reflect internationally endorsed norms and principles. In parallel, the ERA4CS program provides a complementary Global North perspective, concentrating on regionally oriented CS development across Europe. The ERA4CS projects emphasise transdisciplinary collaboration, co-production of knowledge, and sectoral integration within European governance contexts (JPI Climate, 2016). Together, these two programmes provide ample geographical diversity as well as insight into how CS and the role of LK within them are framed across different implementation contexts.

We manually searched the organisational websites to identify relevant projects (Yoshida et al.,2024). A total of 65 projects were screened (GCFS = 39; ERA4CS = 26). Documents such as project proposals, progress reports and deliverables, workshop notes, etc, were reviewed to curate a list of eligible projects. Projects were included if they explicitly mentioned LK (or other related terms like traditional or indigenous knowledge) and how it was integrated within the project. A subset of 22 projects (17 from WMO GFCS and 5 from JPI Climate ERA4CS) were retained for *meta*-analysis and review. We present the findings from grey and peer-reviewed literature separately to detect similarities or incongruities between LK research and integration in theory and practice. Reviewed projects are similarly referenced as the peer-reviewed literature.

4. Results

4.1. Geographical scope and trend in local knowledge research

We see a steady increase (Fig. 2) in the number of articles published on LK, signalling its growing relevance within CS and CCA literature. Despite the review being constrained by the availability of scientific articles and project documents written in English, we find appreciable coverage regarding the geographical spread of scholarship on LK (Fig. 2). Most peer-reviewed studies focus on countries in the Global South, particularly sub-Saharan Africa. This may be because a large part of research on LK is being conducted within the context of international donor-funded development projects wherein the inclusion of LK stems from efforts to recognise local context and agency (Agrawal, 1995; Dekens, 2007; Harvey et al., 2019). The coverage of countries in the global North is predominantly due to the subset of grey literature chosen (CS projects in Europe). We also see certain geographical blind spots (for example, in the Middle East and North Africa region), possibly due to

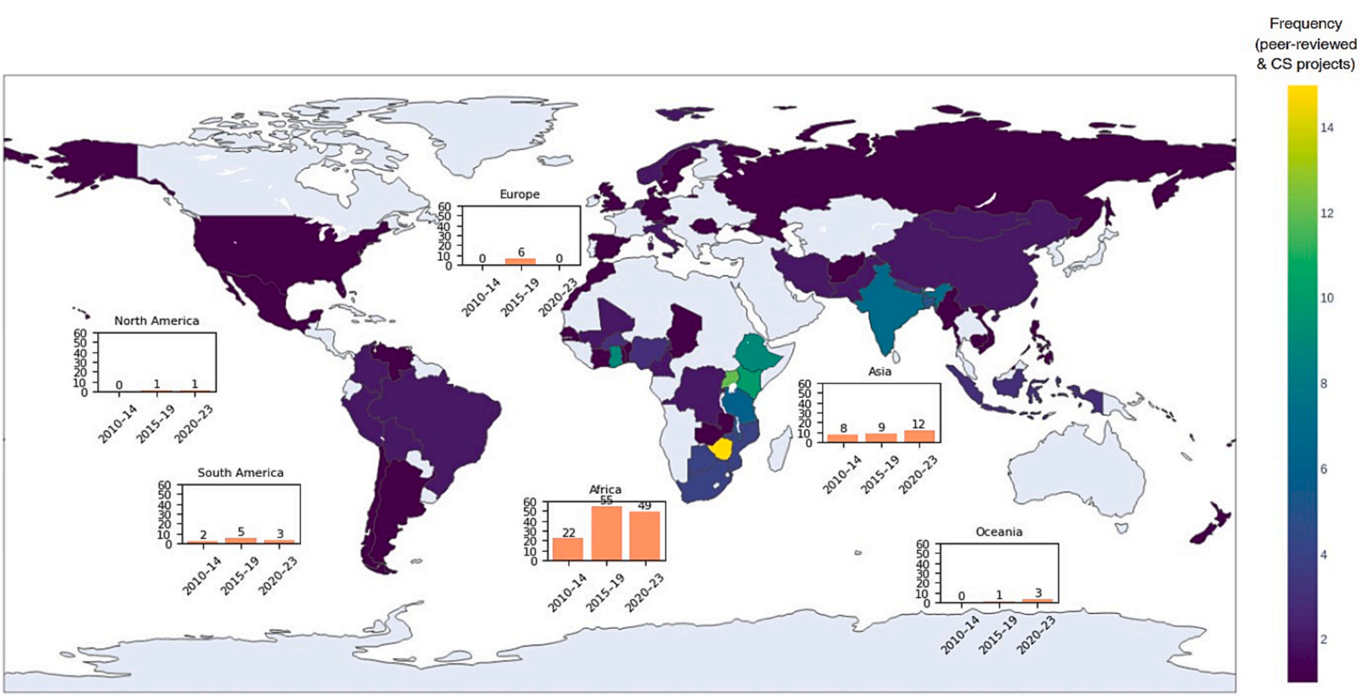

Fig. 2. The geographical and temporal distribution of all peer-reviewed articles and CS projects (grey literature) analysed in this study is represented by the shaded regions in this map. The choropleth map shows the geographical distribution, while the bar graphs show the temporal distribution aggregated per continent. Note that for grey literature, only the starting year of a project is considered when plotting the bar graphs.

research of LK in French, Arabic, or other local languages. The review is also limited by the choice of terms used to refer to LK or CS, which omits articles that may employ less recognised terminology for both. Lastly, our focus on water-related hazards within the CCA literature presents another limitation, as it excludes regions where other hazards and climate-related challenges are more prominent.

4.2. *Local knowledge dimensions and value-add*

Our thematic analysis of abstracts reveals four main dimensions anchoring the LK discussion. These are LK associated with risk knowledge, monitoring and prediction, risk management, and collective action. To disentangle the current understanding and use of LK, we present the LK dimensions discussed within CS and CCA literature. We further relate these LK dimensions to any evidence of value-add (potential or demonstrated) that the studies may have reported. We define an outcome as value adding when a study (abstract) describes benefits gained from integrating or applying LK, whether for improving CS processes or for the lives of communities and individuals. The emerging themes of value-addition comprise the inclusion of LK to validate scientific information or obtain a better understanding of risk patterns locally (*improving understanding*), improved accuracy of information (*improving credibility*), identification of locally appropriate interventions and strategies (*improving saliency*), greater participation and ownership (*improving legitimacy*), LK providing a framework for communities to act (*supporting decision-making*), and LK based strategies supporting in coping (*enhancing resilience*).

In the sub-sections below, we discuss each LK dimension separately, enumerating examples of how they appear within literature and how they add value either to the CS or the livelihoods of communities. We discuss these dimensions in a delineated manner for clarity, acknowledging that in reality, these dimensions often coexist. This follows from the recognition that knowledge held by local communities tends to be holistic without devolving into categories (Taylor and de Loë, 2012). The Sankey diagram (Fig. 3) presents the LK dimensions and the different value-add themes (mentioned in italics in the sub-sections below) that emerge from systematically reviewing the retained abstracts.

4.2.1. *Risk knowledge*

The understanding that communities have of risk and its impacts is the most widely considered LK dimension across the CS and CCA literature (n = 53). Risk knowledge of communities effectively informs scientific understanding of the spatial and temporal dimensions of the impacts. For instance, in Uganda, farmer knowledge of the false start of the growing season complemented scientific data in helping understand drought impacts [77]. Studies have also investigated risk knowledge by focusing on community recollections of past events to understand long-term changes. Farmers in Senegal use their knowledge of long-term patterns to identify periods with similar climatic trends, which informs how they manage variability between these periods [62]. Another study conducted with farmers in the USA sought to utilise their recollection to build a framework of "analogue years" to tailor climate information to inform decision-making [20], while a study in the UK used a knowledge-based inquiry to build a typology of different types of farmer-weather relationships based on the daily experiences of farmers and how they sought information about weather and climate [7].

Eliciting risk knowledge held by communities was, in most cases (n = 11), done in the pursuit of *improving understanding* of the local nature of risks and impacts or as a way to validate scientific observations and data regarding the same [8, 10, 51, 60, 61, 62, 81]. For example, a study conducted in Nigeria corroborated scientific data on rainfall onset and cessation with the knowledge of rural communities [84]. In Bangladesh and Italy, risk knowledge was used to construct risk maps, which were instrumental in improving the spatial understanding of flooding [48, 66]. Additionally, a few studies (n = 2) pinpointed that knowledge of climate risks and impacts can also serve as a valuable resource in data-scarce contexts *(improving credibility)* [36, 117], as well as in supporting the identification of strategies and management solutions that are appropriate to the local context (*improving saliency*) [48, 66, 86, 103].

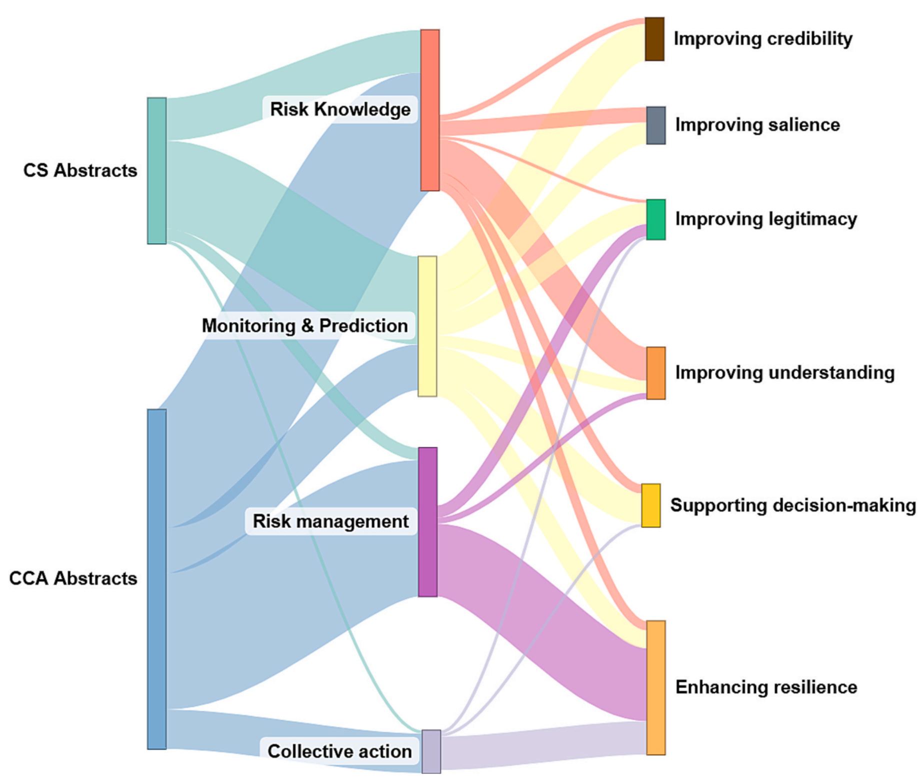

Fig. 3. Sankey diagram highlighting the LK dimensions (column in the middle) and the articulated value-addition of LK as reported in the reviewed literature.

We find that risk knowledge is often a culmination of intergenerational observations, past experiences, oral traditions, perceptions, etc., and provides insight into how risks are framed and understood at the community level.

4.2.2. Monitoring and prediction

Rural communities, especially those involved in natural resource-based livelihoods, have intricate knowledge systems, often relying on environmental, biological, or meteorological observation-based indicators to mark the passage of time (particularly seasons) or predict and understand changes in local conditions. When discussing LK, we predominantly (28 out of 40 studies) find that CS literature focuses on knowledge associated with monitoring and forecasting local weather phenomena, often distilling this knowledge to identify indicators. These indicators result from knowledge-generation processes, including years of first-hand and intergenerational observations, sociocultural beliefs, superstitions, etc. For example, communities in Zimbabwe and Ethiopia often rely on several indicators (meteorological, biophysical, and cosmological) to predict their local environmental conditions [13, 93, 24, 94]. Regarding what is being predicted, literature provides diverse examples ranging from predicting hazards to inter-seasonal variability across different geographical contexts. Local communities in India and Malawi, for example, use their knowledge of the physical environment, previous flooding patterns and local weather patterns to predict imminent flooding and heavy rainfall events [1, 32], while Afar pastoralists in Ethiopia use indicators like livestock number and length of the rainy season as a way to predict drought conditions [64]. Communities also use their LK to make predictions informing decision-making at a seasonal and sub-seasonal level, for example, predicting the onset of the rainfall season [12, 65, 84] and dry conditions during the rainfall season [26].

Only a handful of studies (n = 4) went beyond solely describing indicators for monitoring and forecasting, shedding light on how, at a community level, such knowledge is produced and shared and the governance roles associated with it. Among Afar pastoralists in Ethiopia [24], traditional institutions triangulate and evaluate information collected through environmental observations before use. A complex interlinked network of actors is involved, each with unique roles associated with collecting, sharing, or evaluating the information. In Zimbabwe [9], developing a community-centred early warning system for Malaria relied on indigenous knowledge experts and local health officials to collect and evaluate indigenous knowledge and translate and communicate warnings. Similarly, a pilot intervention in South Africa [6] found that in addition to including LK-based climate indicators, the role of champion farmers and local extension agents was vital in improving trust and the value of seasonal climate forecasts among local community members.

Across the literature, we encounter that LK-based indicators are mostly (n = 12) used to improve the accuracy of scientific forecasts (i.e., *improving credibility*), especially in cases where such indicators were better at predicting local conditions or could help in improving the spatial or temporal resolution of the scientific information [28, 92, 97]. The inclusion of LK-based indicators was also instrumental in *improving the salience* (n = 7) of climate information systems by considering risks and interactions that interest the local community [6, 9, 22, 25, 64, 87, 94]. Several studies (n = 7) also emphasised the importance of LK in improving the trust (*improving legitimacy*) associated with seasonal climate forecasts, for instance, through the use of existing localised networks for monitoring and prediction [1, 6, 9, 94]. Legitimacy is also enhanced through differentiated inquiry; for example, a study in India differentiated between men and women based on how knowledge was produced and which indicators were relied upon, thereby embedding concerns and capacities of both groups [1]. Regarding *supporting decision-making*, LK-based forecasts were reported (n = 10) to help communities triangulate and interpret useful information [1, 3, 6, 11, 13, 14, 24, 25, 29, 95]. This triangulation of information is also vital in enabling adaptation action, thereby contributing to *enhancing resilience* [11,13, 14, 24, 25]. Finally, in the CCA literature, the discussion on monitoring and forecasting indicators is limited (15 out of 79 studies). However, studies have articulated value-add in terms of *supporting decision-making* [1,3], *enhancing resilience* [63, 65, 85], *improving credibility* [64, 97], *improving salience* [64], *improving legitimacy* [1] and *improving understanding* [39, 64].

4.2.3. Risk management

Another LK dimension commonly discussed (n = 49), particularly within CCA literature, is around structural or livelihood-based measures associated with risk management for coping or adaptation. This includes locally suited techniques developed by communities to cope with varying degrees of severity of climate risk. Within our literature subset, coping and adaptation strategies associated with agriculture were most frequently mentioned. Such strategies were found to inform decision-making across different timescales. At a seasonal timescale, for instance, farmers in Senegal used their knowledge of local weather patterns and coping strategies to choose between short- and long-cycle crop varieties to cope with droughts and shorter rainy seasons [62]. Local knowledge also informed tactical (day-to-day) management strategies, such as shifting planting dates [74, 45], land preparation techniques [102], improving soil fertility [65], maintaining soil moisture [85, 102], and disease and pest management [68]. In terms of long-term changes, rice farmers in Vietnam used their LK to understand and apply modern technology (rice ratoon systems) in a locally appropriate manner, thereby alleviating risk [107]. Cases within the literature also cite instances where local communities have developed strategies appropriate to their local context and across the complete hazard management cycle. Related examples exist for different types of hazards. For example, in the case of droughts, farming communities in Iran have devised measures to be implemented before and during drought periods [53]. Similarly, local communities in Malawi have designed interventions for flood anticipation, response and recovery stages [21]. Local knowledge-based strategies also provide avenues for livelihood diversification through agroforestry [2, 4] by promoting more resilient indigenous plant species [58]. LK is also a valuable resource for pastoralists, informing their grazing and rangeland management strategies [79, 75].

Given that much of the discussion on LK-based risk management originates from within CCA literature, the most often (n = 24) cited value-add was associated with enhancing local communities' resilience. Some studies (n = 4) have articulated the value-add of LK-based risk management strategies in helping *improve legitimacy* by encouraging participation, selecting culturally appropriate strategies, and providing opportunities for scaling up [76, 85, 91, 116].

4.2.4. Collective action

The least frequently discussed dimension (n = 14) is LK associated with cultural conventions and practices that inform community collective action. Community-based adaptation strategies originate from longstanding traditions of local governance and social cohesion. Social relationships, hierarchies, and rules within a community, we find, are crucial in explaining what knowledge is accepted and which strategies are used to build resilience [86]. For example, a study done in Iran [43] found that culturally defined roles related to water resource management led to the development of a rapid response drought coping mechanism that helped to build the adaptive capacity of vulnerable agricultural water users. Examples can be found in literature, where pooling resources (in savings clubs and granaries), working on communal land, and religious rituals provide local communities with resources to cope with disasters [103, 111, 44, 52, 101, 105]. Many of these resource-sharing activities are also embedded within the religious activities of communities as a normative code of practice. For example, women in the Limpopo province in South Africa rely on rain-making, seed-dressing, and crop maintenance rituals to cope with the impacts of insufficient rainfall [105].

When discussing the value-addition of LK-based collective action, most studies (n = 11) reported that such practices help enhance the resilience of not just individuals but communities at large [43, 44, 46, 47, 54, 78, 82, 101, 103, 105, 111]. In Zimbabwe, social relations and networks were essential in knowledge sharing about irrigation and resilient farming techniques [47]. Similarly, mechanisms of self-governance within communities and the knowledge associated with it also contribute to building the adaptive capacity of communities against external shocks [101]. Additionally, communities increasingly appraise their LK-based strategies, integrating them with suitable modern technologies [52]. A deeper understanding of LK underpinning collective action also renders itself to co-identifying management and coping strategies, thus *improving legitimacy* [86].

4.3. Knowledge holders

We examined which LK holders were predominantly addressed across the CS and CCA literature (Fig. 4). We categorise the different LK holders based on their commonly assumed position on the CS value chain, whereby data providers and integrators are mandated with the provision of data and information products, service providers translate these products to provide sector-specific guidance, service purveyors are responsible for disseminating and communication, and end users are communities or organisation which obtain value from using the data or information product (Hewitt and Stone, 2021). Having said that, we recognise that these roles are overlapping, as in some cases, CS purveyors are also the users, while on the other end, communities on the ground also have mechanisms to generate forecast information (Vaughan et al., 2016; Acharya and Prakash, 2019). We find that existing research overwhelmingly considers LK only at the level of end users. This includes LK exploration with local communities, key informants, households, religious leaders, or village elders within the community. In only a handful of cases was LK exploration found to include knowledge holders across multiple scales of governance. For example, LK exploration with local community members, indigenous knowledge experts, and health teams at ward and district levels was used to inform the development of community-centred EWS in Zimbabwe [9], or LK exploration with civil society organisations [38, 64] or agricultural extension services [93]. The reviewed academic literature did not address groups like data providers and integrators as LK holders.

4.4. Local knowledge and decision-making

Understanding how LK is made actionable by communities can support the development of usable climate information. Crucial to this is discerning the role of LK within decision-making. Across sampled literature, LK offers a resource to understand and interpret patterns, anticipate changes, and respond to adverse conditions. In doing so, LK affects the risk perception and understanding at the local level, the timing of decisions taken, and the strategies adopted to manage risk.

Rooted in practical experience and experimentation, LK offers a suite of time-tested strategies specifically suited to the local context. These strategies include providing farmers with options for resource management, i.e., land preparation and management, soil and water conservation, and strategies to improve soil fertility [5, 20, 27, 49, 53, 71, 82, 118, 119]; informing crop choices [13, 69, 73, 76, 81, 85, 97]; adjusting cropping calendars [49, 60, 71, 82, 118, 119] and; options for diversification of income [59, 118]. Many of these strategies are deployed in direct response to the information gathered from LK-based monitoring and predictive indicators. For example, a study in East Africa found that predictive indicators associated with rainfall cessation directly informed farmer decisions regarding planting and pre- and post-harvest operations [25]. Similarly, smallholder farmers in Southern Africa relied on LK-based indicators to predict a poor growing season, thereby triggering protective decisions such as food gathering and the selling of assets [95]. Even in the absence of predictive indicators, farmers responded to evolving weather conditions by relying on their LK. For example, cereal farmers in Ethiopia choose between growing an early or late-maturing (traditional) variety of crop based on the timing of rainfall [69]. In terms of longer-term decision-making, LK offers

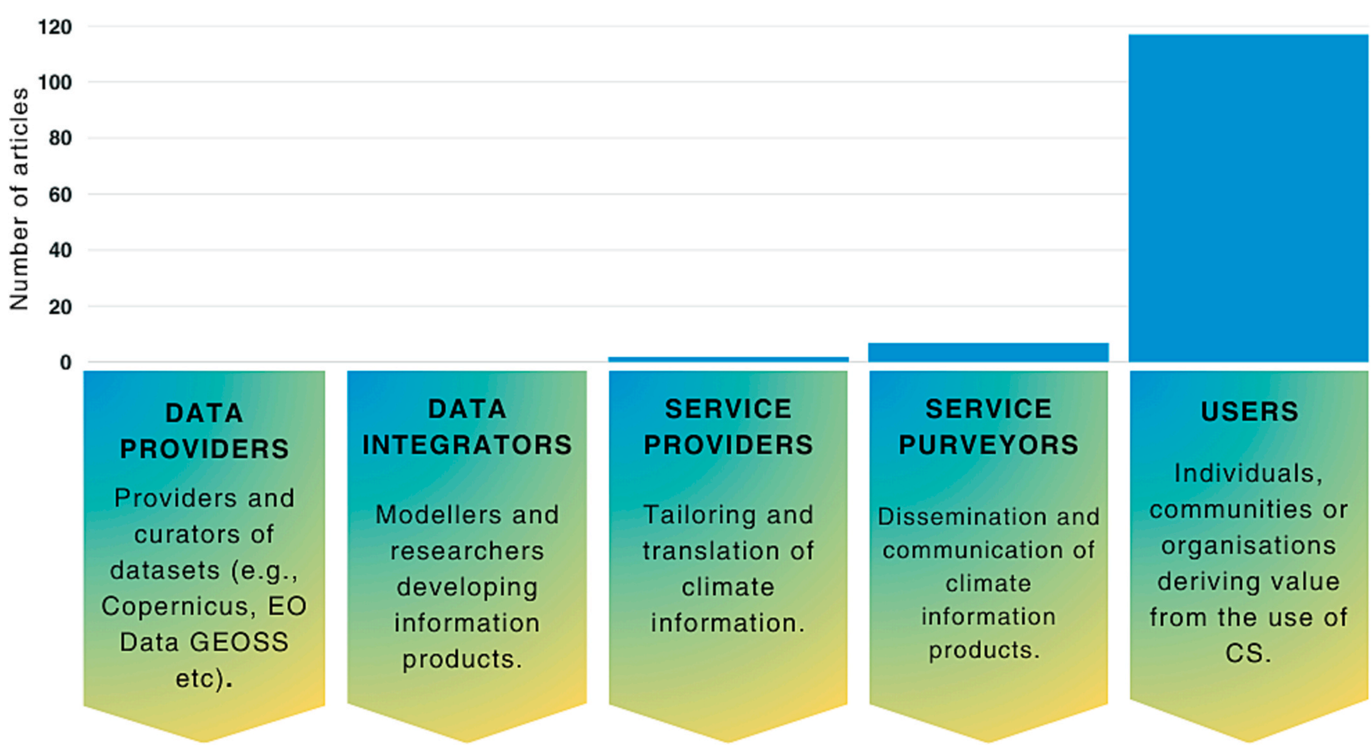

Fig. 4. Knowledge holders along the CS value chain (based on Hewitt and Stone (2021)) addressed across the reviewed articles.

communities options for diversification of income sources through e.g., agroforestry, organic farming or choosing drought-resistant crops [29, 59, 71, 103, 118], or resource management strategies like investing in traditional methods of water conservation [53, 85, 118], and land and soil management [20, 27, 53, 119].

When to act and how, we find, is also determined by the social relationships and shared knowledge and traditions of local communities. Borana pastoralists in southern Ethiopia use their collective knowledge to plan interventions across all stages of disaster management. This includes gathering evidence through observation networks, sharing knowledge among community members, and planning social protection actions for the most vulnerable members [94]. Similarly, herding communities in northern Pakistan continually rely on their collective experience not only to forecast grazing conditions and plan their short-term strategies like seasonal migration, location of campsites and collection of winter feed but also longer-term coping strategies like forming committees for livestock and feed management, using glacier melt for irrigation and diversifying income sources [75]. Decisions are also informed by communities' long-term understanding of local conditions, including nuanced descriptions of what “baseline or normal” conditions look like, locally relevant characterisations of extreme events, or a grounded understanding of impacts arising from rapid climate change. Several farming communities have longstanding traditions of classifying and naming different rainfall regimes, each corresponding to the way communities demarcate the passage of time and plan interventions [81, 95]. In some cases, the decisions of communities are also underpinned and informed by traditional tools like religious, solar or lunar calendars, which have a long history of use within the community and provide a unified framework to understand and interpret local environmental patterns and seasonal changes as well as plan associated management interventions [24, 35, 60, 78, 85]. Local descriptions of flooding patterns among farmer-fishers in the Amazon delta is an example of one such classification system based on solar and lunar calendars widely used by the community to calibrate their production strategies and coping measures [78]. Long-term memories also play a crucial role in informing the LK of communities. For instance, the experience of living through strenuous conditions during a historical drought shaped people’s understanding of the local environmental changes and practices [53, 102].

Despite the critical role of LK in informing decision-making, our results show that not all decisions are based solely on LK. While LK provides individuals with the capacity and agency to act, this capacity to cope may not be enough or may lack effectiveness. Decision-making, we find, is driven by a combination of LK and other factors like access to finance [56, 85, 98, 103], ownership of land or other resources [60, 97, 98, 103], access to farming or irrigation technology [38, 41, 98, 118, 119], access to agricultural extension, civil society organisations and social safety nets [35, 81, 82, 95, 103, 118, 119], formal education [60, 85], diversification through non-farming activities [69, 85, 98, 118] and institutional changes [79, 97].

4.5. Tracing local knowledge discussion within grey literature

In reviewing available documentation, we found that only a few projects (n = 5) explicitly referenced LK or related terms [120, 121, 124, 125, 140], while most referred to ‘knowledge’ in a more general sense. In only one case, LK inclusion was tangibly tied to a project outcome indicator [125]. With regards to knowledge holders consulted, end users were consulted the most (12 out of 22), followed by service purveyors (8 out of 22) and service providers (6 out of 22). The LK dimensions addressed across grey literature encompassed knowledge related to stakeholders’ risk understanding and perceptions [120, 121, 124, 125, 127, 128, 129, 130, 131, 133, 135, 136, 141]; forecasting and prediction [122, 123, 124, 126, 131, 137]; decision-making processes and locally suited coping and adaptation strategies [121, 126, 127, 128, 134] and; knowledge associated with CS use [122]. These dimensions have been used to either validate and/or inform forecasts, warnings and advisories [120, 121, 123, 124, 126, 127, 136, 140] or develop risk information products [128, 130, 134, 137, 138, 139] or as input to scientific models [129, 135]. Lastly, concerning LK value-add, this was reported in some projects (n = 13), citing benefits like LK serving as a “crucial entry point” for discussing the use of climate information [122, 140], better understanding of the local context [125, 134], improved credibility and salience [129, 131]; enhanced trust and acceptance of forecasts [120, 126, 127, 141] and; improved cooperation between service purveyors and end users [120, 138]. The lack of consistent reporting on LK across project documentation hinders a comprehensive investigation into the extent of LK usage within CS projects. We find that the discourse on LK predominantly sits within the academic literature. In contrast, in grey literature, LK exploration only forms a part of the participatory consultation activities geared towards producing or appraising knowledge outputs.

5. Discussion

5.1. Trends in local knowledge exploration

This review analysed field-based studies from CS literature, CCA research addressing water-related hazards, and operational CS initiatives to investigate how LK has been conceptualised and incorporated. We see an uptick, since 2010, in the number of studies addressing LK globally, with a greater focus on countries in the sub-Saharan Africa region. From a CS perspective, we see a lopsided trend whereby LK exploration within peer-reviewed literature is restricted primarily to CS end users. Across grey literature, we see a relatively broader exploration, with service providers and purveyors frequently viewed as LK holders.

Concerning the sectoral focus, most of the discussion on LK within CS and CCA literature is embedded within the agricultural sector (around 54 percent of scientific articles and projects reviewed in this study, see Appendix A), primarily featuring rural communities. These trends may be partly explained by the choice of search strings used in this research. For example, our decision to limit the search to water-related issues within CCA literature may privilege sectors like agriculture. A broader look at CCA literature, with a focus on sectors like health, infrastructure, urban development etc, may have surfaced additional bodies of literature where LK is mobilised differently. Despite this limitation, we contend that given the relative dominance of water-related issues within CS, the choice to narrow down CCA literature from this perspective allows for a coherent study of LK across the two strands of scholarship. Notwithstanding the choice of search strings used, we argue that the skewness in geography, sector, and knowledge holders may be symptomatic of an implicit bias, whereby LK is understood to be an attribute primarily associated with rural or remote communities in the Global South and engaged in agrarian livelihoods. We challenge this tunnel vision regarding LK exploration within CS, arguing that CS are needed and produced globally, in Global North and South countries alike and not just for the agricultural sector. We also contend that though it is important to understand LK use at the community level, the CS value chain comprises organisations with varying experiences and knowledge systems. Service providers and purveyors often operate as “boundary organisations” to facilitate the co-production of knowledge. In doing so, they not only moderate interlocution between knowledge systems (in this case, scientific knowledge of data providers and LK of end users) but also leverage their knowledge of the local context and institutional processes to mediate goals and interests (Kirchhoff et al., 2015; Andersson et al., 2020). Furthermore, organisations on the CS value chain often serve dual roles, as providers or purveyors, as well as users of CS (Vaughan et al., 2016). Therefore, understanding the “interplay” between tacit knowledge associated with organisational processes and information provided by CS can be critical in driving usability (Lemos et al., 2012).

5.2. Unpacking dimensions and value addition of local knowledge

Moving beyond where LK exploration is happening, our review also looks at how LK is being addressed and considered. The dimensions of LK apprehended in this study (risk knowledge, monitoring and prediction, risk management and collective action) are consistent with similar LK reviews across disaster risk management and early warning literature (Hadlos et al., 2022; Hermans et al., 2022). In CCA literature (and to a lesser extent in CS literature), LK is studied for its role in shaping risk knowledge and coping or adaptation strategies. In contrast, 70 percent of CS literature focuses on LK for monitoring and forecasting, often identifying specific indicators for predicting weather conditions. And, while we find evidence of the success of LK-based indicators in improving the credibility of CS [6, 9, 26, 34, 92], this trend within CS literature also suggests cherry-picking of specific LK dimensions over others. Reliance on only science-driven knowledge integration processes, as described by Plotz et al. (2017), may bias researchers towards capturing those dimensions of LK that are amenable to scientific testing and validation methods. How LK is framed and what aspect of each dimension is captured is strongly shaped by the research objectives and problem definitions guiding CS and CCA interventions. For example, when the aim is to improve spatial understanding of flooding, studies tend to elicit those elements of risk knowledge that support the construction of risk maps or hazard models [48, 66]. Similarly, within CS literature, LK related to monitoring and prediction is often identified with the explicit intention of generating or refining forecast products. This goal-oriented LK integration helps explain why certain forms of LK are more frequently documented than others, and why LK is often engaged in partial and instrumental ways. In contrast, dimensions of LK that are more deeply embedded in social relations, governance arrangements and collective action remain comparatively unexplored. Furthermore, the LK dimension related to risk management, though extensively documented within CCA literature, within CS literature, this dimension remains less systematically integrated. This may be due to CS initiatives, often prioritising information provision over engagement with the locally grounded practices through which climate information is interpreted and operationalised (Findlater et al., 2021).

Despite the selective integration of LK, our review reveals that LK adds value across a recurring set of themes, namely, improving understanding, credibility, salience, legitimacy and resilience, and supporting decision-making. These value addition themes have been derived based on what has been demonstrated or articulated as benefits of including LK across peer-reviewed and grey literature. Taken together, these themes illustrate that different dimensions of LK contribute to both product and process dimensions of CS. Thereby, reinforcing the notion of CS as socio-technical systems rather than purely technical information products (Vaughan and Dessai, 2014; Vincent et al., 2018). Importantly, these findings underscore that the value of LK is not limited to technical improvements in forecast performance but lies equally in its capacity to embed CS within the social, cultural and institutional contexts that shape how climate information is interpreted, trusted and acted upon.

From a product perspective, LK often serves as a complementary evidence base to scientific information. Across multiple contexts, LK helps fill gaps in data-scarce environments, validate scientific observations, or improve the accuracy of climate information. In particular, LK related to monitoring and prediction is frequently shown to capture fine-scale variability or locally meaningful thresholds that are difficult to represent in scientific models alone ([28, 92, 97]; Kniveton et al., 2015; Plotz et al., 2017; Gbangou et al., 2020). Similarly, risk knowledge contributes to enhancing credibility by corroborating or appraising scientific information [36, 117]. Rather than positioning LK in opposition to scientific knowledge, the reviewed studies largely frame it as a complementary resource that strengthens the evidentiary base of CS.

Beyond credibility, LK also plays a critical role in enhancing the salience of CS products by aligning them more closely with local priorities and decision contexts. Risk knowledge provides an insight into how climate risks are framed and prioritised at the community level, shaping which hazards matter, when they matter, and to whom (Hermans et al., 2022; Hadlos et al., 2022). The inclusion of LK-based indicators further improves salience by accounting for locally relevant risks, interactions and thresholds that may be overlooked in standardised forecasting systems. In this sense, LK contributes not only to what information is produced, but to how climate information is made meaningful and usable in specific contexts.

From a process perspective, the inclusion of LK is equally critical in shaping how CS are developed, communicated and taken up. Local knowledge constitutes a key form of human capital that communities draw upon to interpret environmental change, triangulate information from multiple sources and make decisions under uncertainty (Food and Agriculture Organization, 2005). Across the reviewed literature, LK supports decision-making by helping communities make sense of climate information, evaluate response options and select locally appropriate and time-tested coping and adaptation strategies ((for e.g., [11, 24, 95]); Šakić Trogrlić et al., 2019; Roncoli et al., 2002). These practices are shown to strengthen resilience by drawing on culturally embedded knowledge systems, encouraging participation, and aligning responses with local capacities and priorities. Recognising and embedding these processes within CS development can therefore enhance both salience and legitimacy.

Enhancing legitimacy is another significant value addition offered by LK, closely tied to the processes through which CS are co-created, disseminated and communicated. Several studies highlight that the uptake of CS products depends not only on their technical quality, but on whether they are delivered through trusted channels, communicated in accessible ways and aligned with existing knowledge systems and social networks (Harvey et al., 2019; Kirchhoff et al., 2013; Dilling and Lemos, 2011). The inclusion of LK in co-creation processes, as well as the use of LK to inform communication strategies, has been shown to enhance trust and acceptance of climate information ([120, 126, 127, 141]; Calvel et al., 2020).

Finally, despite growing evidence of value addition offered by the inclusion of LK, the actual cases of integration of LK within CS remain limited. We find that only a handful of studies (n = 7 out of 119) integrate LK to produce CS or related products (risk maps, analysis frameworks, seasonal calendars) [6, 9, 20, 26, 48, 49, 66]. Comparatively, across grey literature, we find that in almost all instances, LK exploration is tangibly tied to knowledge integration outputs [120–136, 138–140]. This presents a dissonance wherein, despite LK discussion residing primarily within academic literature (and only marginally within grey literature), cases of application to inform operational CS within the former are scant. And despite LK offering a valuable resource to enhance CS, cherry-picking of LK dimensions and selective integration leads to a situation whereby much of the potential offered by LK is overlooked. Lastly, the findings from grey literature are constrained by our methodological decision to focus on projects solely under GFCS and ERA4CS programmes. While this approach provides a close look at how donor-funded CS interventions frame and mobilise LK, it may exclude other forms of grey literature, including locally led or smaller-scale initiatives that may engage with LK differently. Future research should therefore extend the analysis to nationally or locally led CS initiatives in order to capture a broader diversity of LK dimensions and approaches for integration.

5.3. Understanding the role of local knowledge in supporting decision-making

We also reviewed the role of LK in decision-making to understand it in the context of its use. Local knowledge serves as human capital, providing communities with an intangible resource that enables them to understand their surroundings, interpret and validate information, and solve problems (Food and Agriculture Organization, 2005). We find that LK is used by communities across all stages of decision-making, from problem recognition and appraisal to triangulating information to planning and implementing management interventions. Local knowledge generation, sharing, and use are closely linked to social cohesion among community members and individuals' social capital ([24, 38, 71, 75, 94]; Hadlos et al., 2022). In a few cases, communities had well-defined roles related to knowledge gathering, communication, and the design and implementation of coping strategies [9, 24, 43]. While LK provides a framework for communities to operate within, we also find that decisions are often a product of LK, other livelihood assets, and institutional contexts (Naess, 2013; Roncoli et al., 2002). This is particularly true for decision-making on a longer time horizon, such as investments or selling of assets, buying insurance, and diversification of livelihoods [27, 35, 69, 79, 118, 119]. The coping capacity offered by LK-based approaches may also be affected by the evolving impacts of climate change (Šakić Trogrlić et al., 2019; Fitchett and Ebhuoma, 2018; Kassie et al., 2013). However, dismissing LK on the pretext that it is unreliable incorrectly assumes that LK is static in time (Tschakert and Dietrich, 2010). Lastly, articles that explicitly establish connections between LK and decision-making accounted for a larger share of LK-related studies in CCA literature (45 percent). In contrast, similar research within the CS literature was limited (about 27 percent). We argue that such selective exploration of LK in CS literature without understanding how knowledge is made actionable assumes that, firstly, all LK is equally used; secondly, by merely identifying and integrating the LK that exists, CS can be made more decision-oriented; and, thirdly, LK exists in a silo and does not interact with other stimuli or sources of information. We, therefore, assert that the significance of LK in decision-making goes beyond its ability to provide specific information for communities to act upon. Equally important is the process through which LK is created, shared, communicated, and discussed, as well as the context in which it is utilised.

5.4. Rethinking local knowledge within climate services

Collating all the evidence of where, what, and how LK is being studied to inform CS development and provision, an intriguing picture emerges, one in which crucial progress has been made in understanding and articulating the value of LK integration for CS. Despite this, cases of actual LK integration and demonstrable value-add are few. We attribute this dichotomy to a lack of systematic understanding of what constitutes LK and how it can be leveraged to inform CS development. Efforts to integrate LK, we find, are impeded by several factors, like preconceived notions about what dimensions of LK to include, often focusing on retrofitting LK to meet scientific criteria; the assumption that LK is only held by end users along the CS value chain; and integration approaches that separate LK from the context of its production and use. Meaningful inclusion of LK requires a fundamental rethink of how LK is understood in CS literature and practice.

Climate services are produced at the interface of science and society, involving organisations and individuals with diverse knowledge systems, each contributing to the co-development of the service's value (Hewitt and Stone, 2021). Therefore, how LK is conceptualised within CS must be attuned to this reality. Such an understanding of LK is pertinent for several reasons. Firstly, as highlighted in the paper by Lemos et al. (2012), recognising the "interplay" between existing knowledge and knowledge-use practices within institutions and organisations is critical to addressing the usability issues faced by CS. Secondly, scholarship within CS has long emphasised the role of boundary organisations in mediating the science and society interface, and in doing so, they leverage their knowledge of the local context to better embed both the process designed to produce CS, and the CS product itself (Lemos et al., 2012; Kirchhoff et al., 2013; Kirchhoff et al., 2015). Lastly, as pointed out by Vaughan et al. (2016), the separation between the CS providers and users is often unclear, with many CS providers also identifying as users of CS, therefore, focusing narrowly on only end users may risk excluding other key (local) actors. Together, these factors emphasise the need to look at LK more systematically, and in close conjunction with their roles and mandates, and decision-making processes. Therefore, to understand how LK is engaged and considered within the CS development process, we propose examining LK use, mediation and integration across the CS value chain. We propose using LK as an overarching concept that encapsulates knowledges differing in content and origins. To understand LK across the CS value chain, we provide a characterisation of LK, building on the work of Raymond et al. (2010), wherein the authors reviewed different types of knowledges across environmental management literature. The characterisation (see Table 1) emphasises that LK includes not only traditional and recent knowledge about the environment and livelihood processes but also knowledge gained by being embedded in structured or formalised non-scientific processes like institutional processes and settings (Weber and Khademian, 2008).

Our aim vis-à-vis this characterisation is to firstly, reject the assumption that LK is isolated only at the level of the local community and, secondly, bring to the fore less frequently discussed dimensions of LK relating to the governance and decision-making processes that are crucial to CS development. Furthermore, the goal of this characterisation is not to draw rigid boundaries between different types of knowledge or ascribe a particular kind of knowledge to a CS stakeholder, but instead to foster thinking that LK is held across the entire CS value chain, with each knowledge holder leveraging it to add value to the CS. For instance, a service purveyor, like an agricultural extension agent or a member of a civil society organisation, may possess expert knowledge of the local community and climate impacts and be uniquely placed to identify salient solutions and build trust with the local community. Similarly, CS providers, like the national hydrometeorological services, possess not only scientific knowledge but also occupational knowledge relevant to understanding how information is exchanged and utilised across government agencies. We use the CS value chain as a basis for our reconceptualisation for multiple reasons: first, the concept of value chain has been widely adopted in contemporary CS research and practice as a common organising framework. Key institutions, including the WMO and the European Commission, implicitly or explicitly use this model to conceptualise, structure, and guide climate service provision (Hewitt and Moufouma-Okia, 2023; Cortekar et al., 2020). As such, it represents a shared language through which CS are currently designed, funded, and evaluated. Second, at the level of CS implementation, many of the actors involved in co-creation processes—such as climate data providers, intermediaries, sectoral experts, and users—reflect the competencies and capacities described within the value chain (Nyamakura et al., 2025). Moreover, while we invoke the metaphor of a value chain as defined by Hewitt and Stone (2021) to illustrate the CS development process, we do not envision LK integration to be a unidirectional process (from end users to CS providers) (Bremer and Meisch, 2017). We instead recommend using the CS value chain model as a heuristic to examine whether and how different forms of LK are currently engaged, overlooked or constrained within CS architectures. In this sense, our application of the CS value chain explicitly seeks to surface opportunities for embedding LK across multiple phases of CS co-creation, rather than relegating it to data provision or validation roles. Local knowledge integration, we argue, should be viewed as a continuous process, informing CS co-creation throughout, as a way to build CS that is not only credible, salient and legitimate, but also sustainable in the long term. Relevant to this is the value of our proposed characterisation of LK, which foregrounds its dual role in enriching both the product and process aspects of CS. Results of this systematic review show that existing approaches to LK integration are predominantly geared towards enhancing the product component of CS. Our framing of LK necessitates that knowledge underpinning livelihood and governance processes be as much a part of CS development and provision. Engaging with LK from the very start of the co-creation process can help in fostering trust by grounding the process of CS development in the local context. In the scoping and fact-finding needs phase, inclusion of LK can help in

Table 1
Types of LK and different ways it can be generated (adapted based on the review and characterisation of LK by Raymond et al. (2010); (*) category directly adopted from Raymond et al. (2010); (**) category adapted from Raymond et al. (2010), and (***) category added to Raymond et al. (2010)).

Generated through	Type of Knowledge	Description	References
Personal Experience	Personal, Lay, Informal or Implicit Knowledge	Knowledge or beliefs held by a specific group or individuals based on their own experiences, depicting their understanding and interpretation of the local context, situation or phenomenon.	(Fazey et al., 2006)
	Situated Knowledge	Locally grounded knowledge that arises from direct engagement with a particular place or issue. It represents a deep familiarity with site-specific conditions and challenges. Unlike external experts, who may bring specialised technical skills, those with situated knowledge understand the subtle complexities and lived realities of the area.	(Robertson and Mcgee, 2003)
Traditional cultural rules or norms	Indigenous knowledge (*)	Knowledge held by a particular group of Indigenous peoples is unique to them and their culture.	(Warren and Rajasekaran, 1995)
	Traditional Ecological Knowledge (*)	Intergenerational knowledge, beliefs, and practices related to human-environment interactions that are culturally transmitted and often are a feature of societies with longstanding continuity in resource use practices.	(Berkes et al., 2000)
Recent human climate interaction	Local Ecological Knowledge (*)	Knowledge that emerges from the interaction between communities and their surrounding environment. Unlike traditional ecological knowledge, which is rooted in long-standing cultural practices, this form of knowledge develops from more recent human-environment relationships over a shorter time span.	(Olsson and Folke, 2001)
Structured or Formalised processes	Expert knowledge (**)	Knowledge that emerges from extensive hands-on experience and practice, developed either through structured learning or through informal means. Experts often rely on this knowledge to identify patterns and respond effectively to changes in their environment.	(Fazey et al., 2005)
	Livelihood-based knowledge (***)	Experiential knowledge that is associated with livelihood management and is generated from practical experience or learning by doing. It may be accumulated through structured practices occurring year-round (e.g., farming strategies). This type of knowledge may also be informed by intergenerational traditions and practices.	(Berkes et al., 2000;
	Occupational or Tacit knowledge (***)	This refers to operational and practice-based knowledge derived from being embedded in a network or organisation. It may include knowledge accumulated as part of working in public or private institutions. This knowledge develops as a consequence of and underpins how problems are understood and solutions are appraised based on the engagement of the network or institution with the issue.	(Weber and Khademian, 2008; Meisch et al., 2022)

building salience by problem framing through identifying decision instances and underlying risks that can be informed through use of CS (Vincent et al., 2018; Lemos et al., 2012; Dilling and Lemos, 2011). Further on in the design and development phases, integration of LK can support tailoring of information as well as in discerning communication strategies that improve the usability of CS (Andersson et al.,2020; Calvel et al., 2020). While evaluation of the CS, on the other hand, can be improved through furnishing other metrics (beyond scientific benchmarks) that better align with the decision criteria of the users (Bruno Soares et al., 2018; Tall et al., 2018). Relatedly, the emphasis on different types of knowledge (framed under LK) is also to encourage knowledge exchange and transfer at each node of the value chain. This continuous integration of LK also aligns with the tenets of co-creation, whereby LK shapes not only what is produced but also how it is produced, negotiated and used. Finally, central to the objective of LK inclusion is also understanding the conditions that favour sustained integration of LK. We highlight here the importance of collaborative governance approaches as well as frameworks like the one proposed by Kirchhoff et al. (2015) to better understand conditions that create synergies among different actors on the CS value chain.

Pertinent discussions are also happening around the epistemic and ontological origins of different types of knowledges and the semantic challenges associated with it (IPCC, 2019). Our aim in reconceptualising LK is not to depoliticise it, but to make explicit the multiple nodes at which knowledge is generated, mediated and mobilised across the CS value chain. In doing so, we caution against the risk of a dominant knowledge system prevailing over others. We do not advocate broadening the concept of LK across the CS value chain as a means of undermining or relativising the LK of end users. On the contrary, recognising LK across the value chain is intended to strengthen the centrality of the end users and treat LK inclusion not as an ad-hoc exercise but a sustained process of knowledge integration across actors. We further caution against approaching our framework of LK as apolitical. Doing so can be detrimental and lead to pitfalls such as neglecting power imbalances along the CS value chain or perpetuating epistemic injustice (Byskov and Hyams, 2022). Equally, our intention is not to subsume all knowledge under the moniker of LK, thereby diluting the term, nor to posit that any one form of LK is inherently more desirable in CS integration. The choice of using LK as an overarching term is strategic, as it is already widely accepted and used within CS scholarship and practice. Anchoring our reconceptualisation in this term allows us to engage with the ongoing discourse while also deterring the tendency to treat LK as a homogenous catch-all category.

Through the reconceptualisation, our goal is to provide CS researchers and practitioners with a framework to critically engage with the form of LK they are integrating, and more importantly, reflect on what knowledge (and process) is being excluded. Finally, we emphasise that the rethinking of LK alone is insufficient to realise the outcomes of credibility, salience and legitimacy. Equally important is the process of co-creation, which provides space for negotiation between different knowledge systems.

6. Conclusion

Research on integrating LK within CS has increased many-fold in recent years owing to interest in tapping the potential of LK to build fit-for-purpose, decision-oriented and usable CS. This study systematically reviewed the evidence to unpack how LK is understood and utilised across CS and CCA literature and operational CS projects. We find that substantial progress has been made in articulating the value of LK across both academic and operational domains. Research has increasingly ventured into LK, exploring dimensions like the risk knowledge of communities, the ability to understand and forecast local weather phenomena, and knowledge associated with mitigating risks. Each of these dimensions is instrumental in producing credible, salient, legitimate and understandable information, supporting decision-making, and building resilience. However, this recognition has not translated into systematic integration of LK within CS development and provision processes. We find that while LK is increasingly studied, its exploration remains skewed, often limited to CS end users, particularly within peer-reviewed studies. Moreover, the dimensions of LK most often apprehended within CS literature pertain to knowledge associated with monitoring and forecasting, suggesting an implicit prioritisation of scientifically verifiable aspects over other equally valuable dimensions of LK, such as risk knowledge, risk management and collective action. What is also missing from current strategies of LK exploration is the need to understand LK in the context of its use. Our findings show that LK, along with other contextual factors, plays a crucial role in determining when and what decisions are made. Despite this, there is limited attention given to understanding LK and decision-making in conjunction. These biases risk oversimplifying the complexity and diversity of LK, constraining its potential contribution to CS and consequently to supporting decision-making. Finally, beyond the exploration of LK itself, our results also show that the actual cases of LK integration within operational CS remains limited. These patterns suggest that while LK is increasingly acknowledged, it is often incorporated selectively and unevenly. Rather than being systematically studied throughout the CS development process and for all actors involved in the CS value chain, LK is frequently mobilised only at specific points (often at the user interface), without sufficient attention paid to how knowledge is generated, translated, mediated and used across the value chain.

Addressing this gap requires a pragmatic rethink of LK within CS research and practice. The value of LK extends beyond providing actionable information; it lies in knowledge creation, communication, and contextual application processes. We argue for a paradigm shift in how LK is conceptualised and integrated. First, we put forth that the concept of LK within CS be revised to comprise different types of knowledges generated through observations, traditions, lived experiences, and formalised governance processes. Second, with this reframing, pragmatic inclusion of LK should entail understanding the role of LK for each actor on the CS value chain, knowledge exchange across the value chain, and proper contextualisation of the LK in the socioeconomic and political environment of the stakeholder. Actors across the CS value chain act as boundary intermediaries, facilitating the co-production of knowledge while mediating between scientific data and local contexts. Understanding how LK is generated, shared, and utilised across these governance scales is essential for addressing usability challenges in CS. Third, we contend that LK exploration should not be viewed as a goal in itself. Instead, LK must be used as a lens to understand the decision-making processes across different levels of governance, from end users to CS providers and purveyors. Equally important is the consideration that LK is not static but is altered through experiences and interaction with other stimuli. Therefore, understanding LK pragmatically also implies discerning its role in conjunction with other sources of information, which may impact how LK is applied.

The findings of this review should be interpreted in light of the methodological choices that shaped the review's scope and evidence base. Although our thematic focus on water-related issues within CCA literature allows for a consistent examination with CS literature, it inevitably excludes other climate-sensitive sectors where LK may be differently applied. Similarly, in terms of sources, the review draws on peer-reviewed literature indexed in SCOPUS and grey literature from WMO and ERA4CS, which together represent influential arenas for the development of CS. At the same time, this focus may lead to under-representation of national or sub-national initiatives or locally led CS development that falls outside the purview of international donor agencies. Notwithstanding these constraints, we argue that the findings of this review remain highly pertinent for introspecting how LK is conceptualised and operationalised within CS research and practice.

Building on these insights, future research should focus on understanding how LK is shared and negotiated among actors forming the CS value chain, identifying conditions which support the sustained integration of LK, unpacking how LK is mobilised for decision-making, and designing methodological approaches that can support the integration of scientific and local knowledge. Realising the full potential of LK requires knowledge co-production processes that are explicitly inclusive and attentive to power asymmetries, thereby reducing the risk of epistemic injustice. A systematic and inclusive approach is required to truly leverage LK to enhance the credibility, salience and legitimacy of CS. Knowledge integration should move beyond retrofitting LK to scientific paradigms and recognise its broader contextual and institutional relevance by putting the CS value chain and decision-making processes at the heart of LK exploration and integration.

CRediT authorship contribution statement

Sumiran Rastogi: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Micha Werner:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Nora van Cauwenbergh:** Writing – review & editing, Supervision. **Marc van den Homberg:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices A and B. Supplementary data

The supplementary data compiles all peer-reviewed articles and project documents reviewed in this study. Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2026.100665.

Data availability

I have attached a Zenodo link to the data

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