

Review

Weaving Indigenous and Western knowledge systems across a continuum of knowledge and decision-making spaces



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Researchers and practitioners in many fields are increasingly bringing together (i.e. weaving) Indigenous and Western Knowledge Systems to address intertwined issues of environmental sustainability and social justice. However, varying expectations of what it means to 'weave' knowledge systems in practice can reinforce existing power structures, even in well-meaning collaborations. For instance, weaving knowledge systems to generate new insights about a managed ecosystem without simultaneously enabling collaborative decision-making for the management of that system can ultimately serve the dominant Western Knowledge System and undermine Indigenous sovereignty. Building on the growing literature on this topic, we address this ambiguity in expectations by articulating how weaving knowledge systems can happen along separate gradients in both knowledge and decision-making spaces. We present a framework for supporting collaborators in identifying more equitable ways of working along these gradients. We posit that Western researchers and practitioners must engage in an iterative process of deep learning to weave knowledge systems in a good way. Such learning requires Western researchers, practitioners, and institutions to not only question their assumptions about how knowledge can be acquired, but also grapple with the beliefs and value systems in which their knowledge is embedded. Given the plurality of views, experiences, goals, and contexts inherent to weaving knowledge systems, there should not be just one path forward. However, clearly articulating where collaborators find themselves within the knowledge-decision continuums — and where on these continuums they wish to go — can improve the effectiveness of pluralistic collaborations while holding those in power to account.

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Positionality statement

The ideas in this paper emerged from our own work toward supporting the weaving of Western and Indigenous Knowledge Systems (IKS) in issues related to the environment. We come from a mix of backgrounds and positionalities, with some of us embedded in academia (NCB, HVW, AF, AR, K LW), employed by an Indigenous Nation (Kitasoo Xai'xais Stewardship Authority (KXSA), SH, MRN, CNS, each with > 10 years with KXSA), a federal government agency (Fisheries and Oceans Canada) as scientists (RF, CH, DLC) and policy experts (LR), with some having experience in all of these spaces (LI). Some of us identify as Indigenous (SH, MRN, Kitasoo Xai'xais Nation; KM,

Ugpi'ganjig First Nation; AR, Nisga'a Nation; LI, Anishinaabe from Lac Des Mille Lacs First Nation), others identify as settlers of European origin (NCB, HVW, AF, RF, CH, K LW, CNS, nmb, DLC), and of South American origin (LR), with all of us living in the country now called Canada. In this paper, we seek to illustrate ways of moving from Western dominance toward weaving knowledges while respecting IKS. Several coauthors are collaborators on a project that seeks to weave IKS — in this case, Kitasoo Xai'xais knowledge systems — with Western science and decision-making in fisheries management, focusing on Pacific herring (*tskqh* in Sgüüx̓s, the language of the Kitasoo People; *wá'úi* in Xai'xais; scientific name *Clupea pallasii*). The case study is situated in Kitasoo Xai'xais territory, in what is now known as the central coast of British Columbia, Canada. The Kitasoo Xai'xais Nation is interested in advancing thinking around transparent and just knowledge weaving due to past frustrations with their knowledges not being recognized, while also having extensive experience in leveraging the tools of Western science to directly support their Stewardship. Our emphasis on examples from this region reflects our collective experiences and working relationships; we acknowledge that similar work is also happening elsewhere, and could lead to different understandings than those presented here.

We also recognize that our context influences our choice of language throughout this work. At its core, our work is rooted in epistemic pluralism, positing that there is more than one legitimate way of understanding the world [1]. We focus on how different knowledge systems can be actively brought together by practitioners of each system. Various terms are used to describe the bringing together of knowledge systems, including braiding [2,3], integrating [4], bridging [5–7], pairing [8], weaving [9–11], and interfacing [12]. Each of these terms carries different connotations given their use (and misuse) throughout the literature. Some function as euphemisms for the assimilation of one knowledge system into another dominant one (see [8,13]), and many privilege the bringing together of knowledge systems over knowledge coexistence without such active engagement. Recognizing the challenges of an ever-evolving terminology, we adopt 'weaving' in our writing to describe a process through which multiple knowledge systems are equitably brought together in a new shared 'ethical space' [14], while respecting and maintaining the integrity of each knowledge system [11]. In the context of environmental research and management, this process is intended to generate shared insights and actions. While this process is not the only path forward, the ideas we present in this paper are intended to support those engaged in the act of weaving knowledge systems when Indigenous collaborators deem this path to be appropriate.

Introduction

The dominant Western paradigm for how humans manage their relationships with ecosystems must be transformed if we are to successfully confront escalating global environmental crises [15]. Many scholars and practitioners posit that weaving Western and Indigenous knowledge systems (WKS and IKS) (i.e. equitably bringing them together to generate shared insights and actions; see glossary) may enable more effective responses to these crises by generating synergistic insights that are unattainable when different knowledge systems operate in isolation [16,17]. While this process has the potential to simultaneously address issues of environmental sustainability and social justice, diverging expectations among collaborators of what it means to 'weave knowledge systems' in practice can further entrench existing inequities between knowledge systems. Indeed, attempts to weave knowledge systems often serve the dominant (i.e. Western) knowledge system without centering Indigenous Peoples or their inherent rights to self-determination and sovereignty on their Lands and Waters¹ [19,20].

Understanding the historical and contemporary context of relationships among WKS and IKS is essential prior to embarking on weaving efforts. While each place has its unique colonial history, Indigenous Peoples have been subjected to genocide through colonialism in its many forms [21,22]. This includes criminalizing Indigenous governance, stealing children to force them into residential schools, deliberately introducing diseases, punishing the speaking of Indigenous languages, dispossessing Land and forcing migration [23], to name a few. Research and science have also been used as tools of colonialism, from justifying white supremacy [24] to ongoing exclusion of IKS in decision-making (e.g. in fisheries [25,26]), resulting in 'research' as a maligned word in many Indigenous communities [27]. This is not distant history; asymmetries in power and systemic discrimination are ongoing (e.g. [22]). Indeed, even discussions of weaving knowledges have inherent power dynamics, with WKS continuing to be the dominant entity that subjugates IKS [26,28].

Accordingly, we echo the message that we must avoid violence against IKS, Indigenous Peoples, and Indigenous Lands and Waters to which IKS are inextricably linked [29]. Such violence occurs "when the full breadth of a nondominant knowledge system (including its laws, ethics, beliefs, etc.) is not considered but, instead, only the parts that are relevant to the dominant knowledge system that studies it are taken"

¹ We capitalize Lands and Waters to emphasize the cultural, relational, and highly contextual positions that go beyond the strictly physical and geographical spaces [18].

[29]. To center respect of Indigenous Peoples and their rights, attempts to weave knowledges must be done in a ‘good way’ (e.g. [3,18,30,31]), such that Indigenous governance is upheld through the use of each Nation’s own protocols and processes of engagement [32–36]. Here, we articulate two dimensions of knowledge weaving and describe how collaborators can use these concepts to weave knowledge systems in a good way.

Weaving knowledge systems in environmental research and decision-making

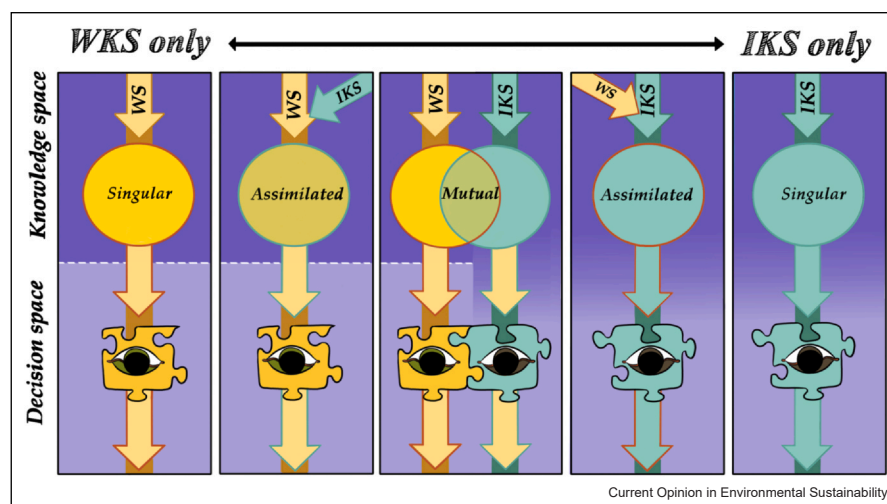
There is a growing academic literature on weaving (and various related terms) IKS and WKS (e.g. 5,6,8,11,37–40). While numerous Indigenous frameworks for how knowledge systems can be brought together exist - such as *Waka-Taurua* in Māori or Double-Canoe; *Kaswentha* in Haudenosaunee or Two-Row Wampum; *Ganma* in Yolngu or Two Ways [8] — a key inspiration for many, especially in North America, is the concept of *Etuaptmunk*, Mi’kmaw for “the gift of multiple perspectives” or “Two-Eyed Seeing.” *Etuaptmunk* was first shared by Mi’kmaw Elders Dr. Albert Marshall and Dr. Murdena Marshall as “learning to see from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of mainstream knowledges and ways of knowing, and to use both these eyes together, for the benefit of all” [41]. Reid et al. [8] explored its application to fisheries, developing a typology of ways that knowledge systems can be brought together (panels 1–3 of Figure 1). We suggest that additional archetypes for weaving knowledges that are IKS-centric also exist, whereby Indigenous Peoples may choose to use WKS to

complement their IKS, or use only their IKS in knowledge and decision spaces [42] (panels 4–5 of Figure 1).

Different knowledge systems can inform both how understandings of a system are developed (the ‘knowledge space’), and how stewardship or management actions are decided (the ‘decision space’) [8]. For instance, in the Two-Eyed Seeing archetype (Figure 1, center panel), “knowledge transforms the holder and [...] the holder bears a responsibility to act on that knowledge” [8], thereby linking the knowledge and decision spaces. This is reflective of the ethos of IKS, in which knowledge is inseparable from the individual, and hence the decision and knowledge spaces are not separate [43,44]. In contrast, WKS typically separate knowledge generation and decision-making processes in an effort to maintain an idealized notion of the objectivity of Western science, with frequent calls among the scientific community to keep values and personal beliefs out of scientific advice for decision-makers [45,46]. Knowledge generated from Western science is intended to act as impartial evidence. The extent to which this evidence is then applied (or not) to decisions depends on the values and beliefs of decision-makers and those to whom they are accountable [47,48]. Such separation is structurally reinforced through the development of distinct science and resource management institutions in many countries.

The frequent separation of knowledge and decision spaces within WKS means that those engaged in knowledge (co)production often lack the power to make management decisions. Most literature on weaving knowledges consequently focuses on the knowledge

Figure 1



An expanded conceptual framework of the flow of knowledges (WS, Western sciences; IKS; WKS) that underpins management decisions. Inspired by [8] (Figure 3 within that paper), we expand upon their framing by adding the two rightmost panels to reflect IKS-centric archetypes: knowledge integration whereby WS is added to IKS; and IKS-only knowledge and decision spaces. In IKS the distinction between knowledge and decision spaces is blurred. Artwork by nicole marie burton created for this paper.

space (e.g. [5,8,28,37,39,49]), with less emphasis on the extent to which decision-making responds to co-produced knowledge [9,50]. Often the co-production of decisions is an implied or assumed downstream consequence of knowledge co-production. However, without the explicit engagement with IKS in the flow from knowledge to decisions, the power to make decisions remains in the hands of those operating within the dominant knowledge system [25,26], thereby perpetuating violence against IKS [29]. With increasing calls to weave knowledge, attention on both knowledge and decision spaces is needed to ensure more equitable and effective collaborations.

Gradients of knowledge and decision spaces in collaborative work

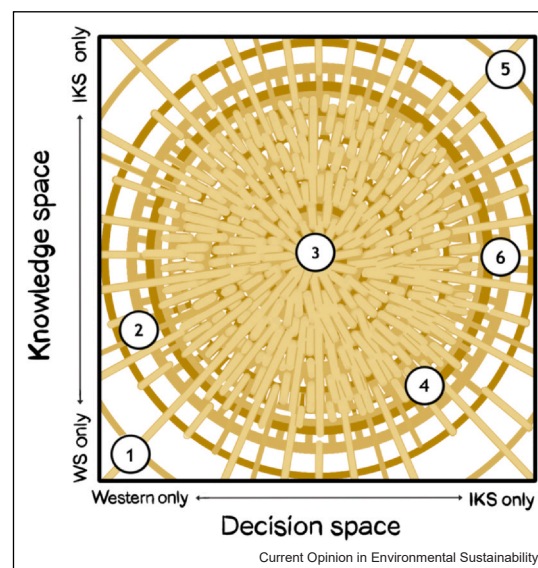
Extending our thinking about how knowledge systems can be brought together beyond discrete archetypes (Figure 1) may better support collaborations between Indigenous Peoples and Western scientists and practitioners. We propose that, given the frequent separation of knowledge and decision spaces in WKS, the contributions of different knowledge systems to collaborative work in Western-dominated spaces necessarily exist along separate gradients in knowledge and decision spaces (Figure 2a). A key implication of this separation is that weaving in one space does not necessarily lead to weaving in the other; rather, weaving in either space must be a deliberate decision.

We recommend using Figure 2a as a guide for collaborators identifying the degree to which they expect to work together in either space. The process may identify barriers to the work (e.g. if all collaborators lack the power to make management decisions, projects may only focus on the knowledge space while contributing to status quo decision-making) and help avoid harms that can arise from such barriers (e.g. clarity about project limitations may deter colonial governments from using cases of Indigenous participation in research as a means of deflecting their obligations to share power). There is no ‘ideal’ location within these spaces, and it may be appropriate for components of a project to be conducted at different locations (examples shown in Figure 2b). Ultimately, a shared understanding of where collaborators intend to work along both the decision and knowledge spaces is necessary for equitable and effective weaving, and may evolve along with collaborative work.

Learning needed for weaving knowledges

Weaving knowledges, when appropriate, requires an understanding of the different methodologies (how is research done?), epistemologies (how do we know what exists?), ontologies (what exists?), and axiologies (what are the values or foundations of being and sustaining that being?) that underpin knowledge systems and are

Figure 2



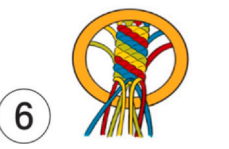
Gradients of weaving IKS and WKS in knowledge and decision spaces, with examples. (a) The process of weaving knowledge systems can take place across gradients of contributions from Indigenous and WKS in both knowledge and decision spaces. Here, the gradients are depicted as an artistic representation of a woven basket,

with a tighter weave representing more even contributions of both knowledge systems in both spaces. Collaborative projects can be pursued at any point across the knowledge-decision space. The numbers 1–6 in Fig. 2a illustrate examples of projects located along the gradients of knowledge and decision spaces, described in Fig. 2b. Western science, WS. **(b)** Examples from different parts of the knowledge and decision spaces, as depicted in Fig. 2a. Artwork by nicole marie burton created for this paper.

invoked in writings on Indigenous methodologies [51,52]. Much of Western scientific training implicitly asserts its own superiority over other ways of knowing [53], with IKS considered to need validation by scientific data and methods [54,55]. Consequently, deep learning and unlearning are required for those embedded within WKS to truly respect and understand another knowledge system [35].

Learning theory [56] can elucidate why engaging with another knowledge system is challenging, and support movement toward weaving in a good way. Learning is often conceptualized as occurring within different loops [57] (Figure 3), which typically characterize whether learning occurs: (1) within one’s existing mental model of the world, ‘single-loop’; (2) when one’s mental model of the world is questioned and adapted, ‘double-loop’; or (3) when one’s overarching values and beliefs are questioned and adapted, ‘triple-loop’ [58] (Figure 3, see glossary). Insights from learning theory could be used, for example, when developing training and onboarding materials for those embedded within WKS to more fully understand IKS and the kind of personal and

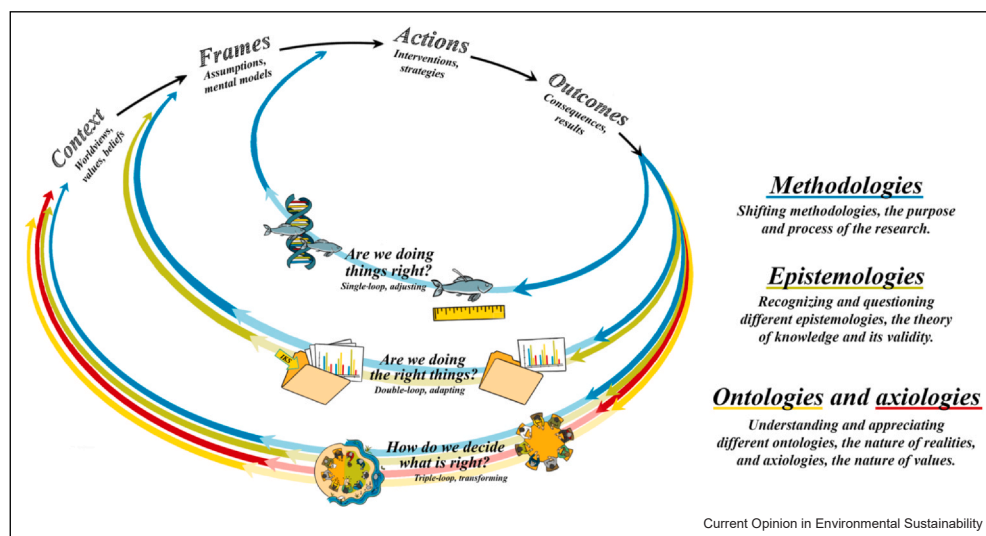
Figure 2

Position in Fig. 2	Description	Examples from the Kitasoo Xai'xais Nation
	Colonial histories led to the status quo, such that only Western science (WS) commonly informs decision-making by Western authorities on Indigenous Lands and Waters. When this happens without the consent of Indigenous People, it perpetuates colonial power and the control of knowledge, and fundamentally limits the opportunities and abilities of Indigenous Peoples to exercise their understanding and ways of being to protect their Lands, Waters, culture, and existence in the present and into the future.	Most integrated fisheries management plans by the Canadian fisheries management agency (DFO) currently do not consider weaving in both knowledge and decision spaces [26]. For example, management of geoduck fisheries in Kitasoo Xai'xais territory is not respecting their traditional management practices about taboo activities in culturally or ecologically important areas.
	Incremental efforts to include Indigenous Knowledge Systems (IKS) commonly attempt to integrate IKS into Western frameworks and decision-making as "data", separating that knowledge from its context and the people who hold the knowledge. Unless such efforts are directed by Indigenous partners, this approach can perpetuate ontological violence [29].	In 2016, DFO agreed to use Kitasoo Xai'xais knowledge of local Pacific herring abundances to close, on the First Nation's request, commercial fisheries at a key spawning area while maintaining commercial access at an alternative area. Up to that point, however, DFO had unilaterally decided on commercial openings based on regional abundance estimates derived from Western science.
	Co-governance means shared decision-making that uses multiple knowledge systems equally to make decisions. This requires sharing power and understanding multiple knowledge systems.	The Kitasoo Xai'xais guardians and BC Parks worked together to have Indigenous guardians receive the same legal authorities as park rangers within parks and protected areas. Decisions about patrols are made using both Kitasoo Xai'xais and BC Parks knowledges.
	Management primarily by Indigenous Peoples may draw mainly on Western science to inform decisions, recognizing the many tools that Western science can provide.	The Kitasoo Xai'xais Stewardship Authority commonly uses Western science tools in their work. For example, they are using statistical sampling methods to inform the number of genetic samples needed to understand whether sub-populations of Pacific herring exist, seeking to minimize disturbance on herring during sampling.
	Management decisions are made by Indigenous Peoples using their own Indigenous Knowledge Systems.	The Kitasoo Xai'xais are using their traditional practices to restore herring, transplanting eggs on branches as guided by Kitasoo Xai'xais legal principles and stewardship practices.
	Indigenous decision-making may use both Indigenous Knowledge Systems and Western science, valuing the complementary strengths of both knowledge systems.	The Kitasoo Xai'xais Nation used both their own knowledge and Western science to inform the design and implementation of Indigenous Protected Areas in their territory.

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(continued)

Figure 3



Schematic of the different loops of learning. While different definitions of learning loops exist, we follow a scheme most commonly used in environmental research, in which single-loop learning is centered on adjusting actions within existing frames, double-loop is centered on questioning these frames and the assumptions that underlie them, and triple-loop is centered on questioning the broader context that is shaped by one's values and worldviews from which these frames emerge (diagram adapted from [58–60]). These three centers of learning can also be cast as questions with increasing complexity (adapted from [61]). The colors of each line indicate the relevant philosophical concepts discussed in Indigenous methodologies (e.g. [8,51,52]) that must be considered to grapple with each question. Examples of each type of learning in the context of fisheries research and decision-making are depicted next to the questions; the drawings correspond to locations from the knowledge-decision gradients listed in Figure 2b. In single-loop learning, for example, tools for conducting research on fish population structuring are advanced from simple tags to genetic sampling, both Western scientific approaches to sampling; in double-loop learning, the types of information used to guide decision-making are expanded to include both Western quantitative data and IKS, but the Western decision-making structure and methods for collating information remain the same; and in triple-loop learning, the composition of the group governing how decisions are made for a fishery is changed from all Western decision-makers to both Western and Indigenous leaders working together to develop a shared vision and methodologies. The most complete learning occurs when the questions are not asked in isolation but rather build off one another [61]. Artwork by nicole marie burton created for this paper.

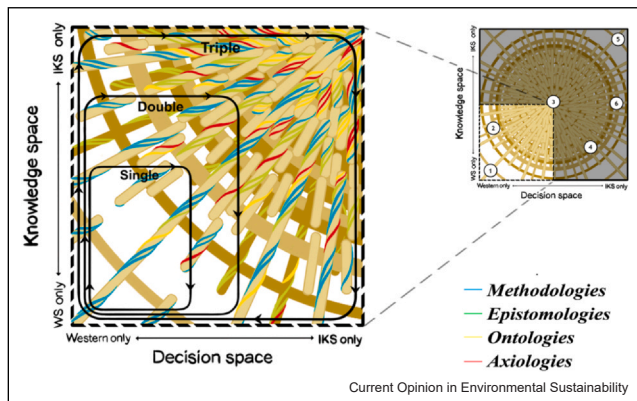
institutional changes needed to weave knowledge systems along knowledge and decision gradients.

Learning in the context of weaving knowledges is an iterative process. Although some preliminary questioning of one's mental models, beliefs, and values is required to initiate a collaboration, the act of co-producing work leads to deeper learning [62]. For Western collaborators aiming to move away from the status quo (location 1 on Figure 2a), double-loop learning can enable at least some inclusion of IKS in the knowledge space (Figures 3 and 4). This occurs, for example, when weaving aspects of IKS into fisheries management, such as consulting Indigenous partners on management objectives or specific harvest thresholds without fundamentally changing methodologies that underpin the management system [26]. However, because this approach requires only limited questioning of assumptions about the world without necessarily challenging existing beliefs and values, this inclusion is typically selective and superficial. Double-loop learning alone is insufficient for grappling with the entrenched power structures that shape how decisions are made. To truly allow for both systems to equitably inform

both the knowledge and decision spaces, Western-trained collaborators must question deep-held beliefs and values (triple-loop learning, Figures 3 and 4). When applied to the weaving of WKS and IKS, such learning requires decolonial (whereby colonial structures are revealed) and anti-colonial (whereby the dismantling of colonial structures is sought) thinking, which challenges WKS [29].

Considering how learning theory applies to Indigenous collaborators' involvement in knowledge weaving requires careful nuance. As the non-dominant knowledge system, movement away from IKS-exclusive spaces (5 in Figure 2a) is often not the result of learning, but of colonial violence [29]. For instance, IKS on their own are often not considered legitimate evidence for informing natural resource management by colonial systems. When IKS are ignored, some First Nations (e.g. Heiltsuk, Kitasoo Xai'xais, Nuxalk, Wuikinuxv Nations in Canada) have partnered with Western collaborators to collate their knowledge for peer review in a Western framework [63], or conduct scientific studies to validate their observations so that they can be used as evidence in disagreements with federal fisheries managers [64]. The

Figure 4



Movement across the collaborative knowledge-decision space requires different types of learning from Western collaborators. Here, we focus on movement out of the status quo WKS-centric corner. The colored threads woven through the figure correspond to Figure 3 and indicate the types of philosophical concepts with which one needs to engage to move from this corner to a desired location, which may vary depending on the needs and objectives of a given collaboration. Western collaborators who only question and adjust their methodologies (blue) are generally engaging in single-loop learning and will remain in the WKS-only corner. Double-loop learning, in which one begins to also question and adjust how they know what they know (epistemologies; green), can allow for movement partway along the knowledge space, as such learning enables the plural coexistence of multiple ways of knowing. Triple-loop learning, in which one begins to also question overarching values (axiologies; yellow) and beliefs (ontologies; red), can enable movement anywhere across the knowledge-decision space. Artwork by nicole marie burton created for this paper.

decision by First Nations to use science in this case was triggered by colonial disrespect of their authority to make decisions about their own territories. However, there are also many cases where Indigenous individuals, organizations, and communities seek to learn from and engage with Western scientific tools to complement their own knowledges, while directly centering their own governance structures and stewardship decision-making [42]. Importantly, engagement with these models of learning is only relevant if and when Nations choose to engage in knowledge weaving on their own terms.

Moving toward transformative change

Bringing together IKS and WKS has the potential to transform how we effectively collaborate to address environmental crises by generating synergistic insights and more socially just decisions [16,17]. However, such transformative change — moving beyond the status quo to restructure how decisions are made and by whom [58] — will require those in power to question how they know what they know, and the belief systems in which that knowledge is embedded (triple-loop learning). At an individual level, this deep learning generally requires strong personal experiences rather than explanations

[65]. These experiences are especially critical for building relationships and trust among partners who hold different knowledge systems [35,66].

Individuals within Western institutions, however, may have limited influence or be confined by a rigid structure built to resist change [67]. The failure of institutions to transform, either intentionally or otherwise [67], entrenches existing power structures and may prevent even well-intentioned collaborative work from achieving desired decisions, effectively trapping institutions in a practice of single-loop learning. For transformation to occur, individual triple-loop learning must extend to institutions (i.e. be collectively recognized and accepted [68]) [69,70]. Informal networks often emerge as a key stepping stone between individual and institutional learning. Groups unconstrained by institutional rigidity can more readily take risks and experiment with solutions to environmental crises [71,72]. As initiatives that weave knowledges become more common (e.g. [73,74]), novel co-developed methodologies can arise in these ‘boundary’ spaces [4,75] and increase the likelihood that institutions learn and transform [68].

The emergence of transformative change from widespread adoption of incremental learning can spark a tension [58]. When attempts to weave knowledge systems fail to recognize Indigenous sovereignty — such as weaving knowledge but not decisions — then incremental movement away from the status quo can actually perpetuate, rather than redress, harm on Indigenous Peoples [13,76]. Indeed, incremental learning may be deliberately or inadvertently used to hamper transformative change. For example, colonial governments and institutions may cast participation with Indigenous Peoples as a success story while shirking their responsibilities to truly share power [76]. There is no simple resolution to this tension; given the plurality of views, experiences, goals, and contexts on weaving knowledges (including whether it is needed or appropriate), there will be many paths forward. However, we believe that clearly articulating where we find ourselves within the knowledge-decision continuum — and where we wish to go — can help guide our work to be more effective and push back against the status quo.

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CRedit authorship contribution statement

NCB and HVW conceptualized the initial ideas with input from SH, CNS, and KLW. NCB drafted the initial visualizations, nmb designed them with input from everyone. NCB wrote the original draft with HVW. All authors reviewed and edited the manuscript and visualizations.

Data Availability

No data were used for the research described in the article.

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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Glossary

Knowledge systems: the broader political, cultural, economic, and educational systems from which knowledge originates [77].

Indigenous Knowledge Systems (IKS): broadly refer to those that “enable the continued generation and renewal of Indigenous Peoples to ensure their well-being” [77]. IKS are intergenerational, rooted in place, accumulated over millennia, and are thus “manifested in Indigenous bodies, hearts, and minds” [12].

Western science: a process by which information is “gathered and condensed into testable laws and principles through a systematic enterprise [...] favoring reductionism and physical law” [78,79]. This process is “derived from the Euro-American philosophical traditions of positivism and empiricism and are grounded in values of universality, objectivity, and neutrality” [80].

Western Knowledge Systems (WKS): include diverse ontologies, epistemologies, and methodologies [81], with the most dominant and widespread forms embedded within capitalist and imperial worldviews [8]. These systems often view the world as positivistic (i.e., there is a knowable truth) and draw on Western science as a primary means of understanding it.

Weaving knowledge systems: a process through which multiple knowledge systems are equitably brought together in a new shared “ethical space” [14], while respecting and maintaining the integrity of each knowledge system [11]. This process may yield new shared insights or actions.

Learning loops: Feedback loops influencing how individuals or groups learn from the outcomes of their actions, where learning is the “detection and correction of errors”, and error is “any feature of knowledge or of knowing that makes action ineffective” [82]. Originally stemming from the organizational theory literature [57], multiple conflicting definitions of these loops now exist across various fields [83]; we follow that most commonly used in the literature on learning in environmental decision-making [e.g., 58,84], where each loop corresponds to a different center of learning (i.e., the “how”, “what”, or “why” of deciding upon actions).

Single-loop learning: Questioning and adjusting actions to improve outcomes without examining the frames or contexts in which the set of possible actions is embedded [57]. Task-oriented, addresses the question: “are we doing things right?” [61]. Leads to incremental improvements in how things are done.

Double-loop learning: Questioning and adjusting frames to change the possible set of actions available to improve outcomes within a value-normative framework [58]. Examines how underlying assumptions about the focal system influence the potential decisions that can be made. Addresses the question: “are we doing the right things?” (adapted from [61], who alternatively cast this as a different form of single-loop learning). Leads to adaptation.

Triple-loop learning: Questioning and adjusting broader contexts that determine the frames of reference that guide decision-making. Interrogates the individual or

shared values and beliefs that shape how assumptions about a focal system are formed [58]. Addresses the question: “how do we decide what is right?” (adapted from [61], who alternatively cast this as a different form of single-loop learning). Leads to transformation.

Frames: The personal or shared mental models of how the world works, through which individuals or groups parse information and generate sets of possible actions. Includes assumptions about cause-and-effect relationships, how the system is structured, and how the problems being addressed are formulated [58].

Contexts: The personal or shared beliefs and values through which individuals or groups build frames, and the governance structures which emerge from these beliefs and values [58].