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A conceptual framework for knowledge integration in cross-disciplinary collaborations

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ABSTRACT

This paper synthesizes three domains of literature to develop a conceptual framework for knowledge integration in cross-disciplinary and cross-sectoral collaborations: (1) studies of inter- and transdisciplinarity, (2) studies of knowledge co-production in sustainability research, and (3) studies focusing on factors influencing knowledge integration in the Science of Team Science field. Combining a scoping review methodology with a cited reference search approach, we identify eight dimensions of knowledge integration: *types of knowledge integrated*, *competencies and education required to practice knowledge integration, organizational structure*, *types of actor involvement*, stages of *collaboration*, *contextual factors*, *processes and mechanisms of knowledge integration*, and *types of knowledge integration outcomes*. We structure these dimensions across four interconnected components of collaboration: knowledge gathering (inputs), structural dynamics and collaborative dynamics (processes), and integrative outcomes (outputs). We identify the different types of knowledge mobilized in cross-disciplinary collaborations – *epistemic*, *experiential*, *contextual*, *cultural*, *applied*, *specialized*, *knowledge for systemic change*, and *normative knowledge* - and link them to the structural features (e.g., team composition, governance) and collaborative dynamics (e.g., stakeholder engagement, interaction frequency, and roles) of cross-disciplinary teams that influence the processes and outcomes of knowledge integration. This framework is intended to function as a heuristic to prompt teams to adapt it to specific contexts, projects, and team configurations. It can also be used a scaffold for designing and evaluating knowledge integration efforts in diverse collaborative settings.

1. Introduction

Collaborative and cross-disciplinary research approaches like multidisciplinary, interdisciplinary, transdisciplinary, and convergence research are being applied to address global challenges, such as climate change, sustainability, energy transitions, food security, water management, public health crises, and more (Boyd et al., 2015; Ambole et al., 2019; Liehr et al., 2017; Grant et al., 2022; Gajary et al., 2023; Cummings et al., 2013; Misra et al., 2024). These approaches have the potential to generate novel frameworks that integrate knowledge from diverse disciplines with professional and community-based knowledge, leading to the development of sustainable and socially acceptable solutions to complex problems (Rhoten and Parker, 2004; Walter et al., 2007; Hansson and Polk, 2018).

Since relevant insights on cross-disciplinary research are dispersed across literatures and distinctions between unidisciplinary and cross-disciplinary research depend on how individual disciplines are defined by communities of scholars, a preliminary definition is in order. Cross-disciplinary research attempts to combine, and in some cases integrate, data, methods, tools, concepts, or theories from two or more disciplines. Three approaches to cross-disciplinary research have been described in the literature - multidisciplinary, interdisciplinary, and transdisciplinary or convergence research (Misra et al., 2024; Gajary et al., 2023). Multidisciplinary research is the least integrative form of cross-disciplinary research, where scholars or researchers remain conceptually and methodologically anchored to their respective

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disciplines even though they may share a research goal. The collaborative processes and outcomes of interdisciplinary research are more integrative in that participating scholars draw on their respective disciplines to integrate knowledge to address a common problem, question, or topic. Transdisciplinary research (also known as convergence research in some literatures) transcends disciplinary worldviews and boundaries of academic, public, and private spheres engaging stakeholders and community members in co-production of knowledge and generating new conceptual and methodological frameworks (Misra et al., 2024).

Despite increasing recognition of the significance of cross-disciplinary research for addressing societal problems, gaps remain in our understanding of knowledge integration (KI) in cross-disciplinary collaborations (CDC) - a foundational methodology for successful inter- and transdisciplinary collaboration (Pohl et al., 2008; Gajary et al., 2023; Misra et al., 2024). First, existing frameworks addressing KI are fragmented, discipline-specific, and lack a unified frame of reference that teams across fields, problems, and settings could apply to plan, design, and evaluate integrative processes and outcomes (Cummings et al., 2013; Bammer, 2013). Over the past five decades, we have seen notable progress in defining inter- and transdisciplinary research (Klein, 1990, 1993), defining and understanding knowledge integration, including its methods and procedures (Hoffmann et al., 2017a, 2017b; Pohl et al., 2021), and evaluating the collaborative processes and outcomes of cross-disciplinary collaborations (Hitziger et al., 2019; Klein, 2021; Gugerell et al., 2023). However, we know relatively little about the various dimensions of knowledge integration and the factors that facilitate or constrain knowledge integration. There is a need for a widely generalizable framework that teams could apply to organize their collaborative and intellectual activities and make informed decisions about team composition, organizational structure, and collaborative mechanisms depending on the intended integrative outcomes of their project.

Second, there are relatively few frameworks for evaluating knowledge integration processes and outcomes that address inputs, processes, and outcomes of knowledge integration and can be applied at different stages of a collaborative effort (for exceptions, see Misra et al., 2024; Hoffmann, Pohl and Hering, 2017a, 2017b; Bergmann et al., 2005; Bergmann and Jahn, 2008). There is a need for an evaluation framework that can inform the assessment, comparison, and improvement of KI initiatives across domains, settings, and problems.

To address these gaps, we develop a conceptual framework for planning, designing, and evaluating KI in a variety of CDCs across various problems, settings, and contexts. To develop this conceptual framework from the ground up, we drew on three bodies of literature where the majority of the work on KI can be found: (1) studies of inter- and transdisciplinarity; (2) studies of knowledge co-production in sustainability research; and (3) research on the Science of Team Science (SciTS). We addressed the following research questions: What are the various epistemological perspectives on KI? What are the various theoretical and methodological approaches to KI? What key factors influence KI in CDCs? How can this information be used to plan, design, and evaluate KI?

This paper is organized as follows. In Section 2, we use the extant literature to define KI and discuss the epistemological perspectives on KI. Section 3 examines current theoretical and methodological approaches to KI. Section 4 presents the findings from our scoping review, detailing the key dimensions of KI that emerged from the literature review. In Section 5, we introduce a new conceptual framework for KI, which elaborates each stage of O'Rourke et al.'s (2016) Input-Process-Output (IPO) model to identify four key dimensions that influence KI at different components of a collaboration. This includes Knowledge Gathering (Inputs), Structural Dynamics and Collaborative Dynamics (Processes), and Integrative Outcomes (Outputs). Finally, Section 6 discusses the framework's applications, limitations, and contributions to advancing our understanding of KI in CDCs.

2. Epistemological perspectives on KI

Scholars have defined knowledge integration as a multidimensional and systemic process that combines theoretical, methodological, and experiential perspectives from diverse academic disciplines and real-world contexts to generate novel conceptual frameworks for addressing complex real-world challenges (Pohl and Hirsch Hadorn, 2007; Lang et al., 2012; Klein, 2010). It requires co-learning, inclusivity, and continuous adaptation to ensure that the knowledge generated is both scientifically sound and socially relevant (Wyborn et al., 2019; Norström et al., 2020). The integration of diverse knowledge systems includes *cognitive processes* (how knowledge is understood), *emotional factors* (how people feel during collaboration), and *social dynamics* (how people interact and collaborate), all of which require adaptation and reflection to remain effective and relevant (Pohl et al., 2021; Stokols, 2010).

Further, KI is a *dynamic* (Klein, 2010; Bammer et al., 2020), *iterative* (Lang et al., 2012; Norström et al., 2020; Gugerell et al., 2023) and *context-sensitive process* (Nowotny et al., 2001; Klein, 2010; Lyotard, 1984; Foucault, 1972). Each CDC aims to tackle specific problem or achieve a targeted objective, necessitating the involvement of context-specific stakeholders and professional experts (Gibbons et al., 1994). KI involves continuous adaptation to new information through a process of co-learning among stakeholders.

KI is shaped by underlying philosophical assumptions concerning knowledge that different actors bring to the collaboration. Epistemology is a theory of knowledge that focuses on what knowledge is, how we acquire it, and what makes it valid or justified (Trivedi, 2020). Ontology is the study of what exists and how we define and understand reality. This includes exploring questions about what is real, how we perceive reality, and whether those perceptions are universal or subjective (Hofweber, 2020; Steup and Neta, 2020; Trivedi, 2020).

For instance, the *positivist epistemology* emphasizes empirical evidence and the systematic synthesis of data. However, it may be less suitable for addressing complex social dynamics (Popper, 1983). In contrast, *constructivist and postmodernist epistemologies* allow for more inclusive approaches to knowledge through collaborative meaning-making and the recognition of diverse perspectives. However, these epistemologies can complicate consensus-building due to their emphasis on context and subjectivity (Berger and Luckmann, 1966; Lyotard, 1984). From an epistemological standpoint, KI involves more than a simple aggregation of data. It recognizes knowledge generation as dynamic, contextual, and interpretive process that engages cognitive, emotional, and social dimensions (Stokols, 2010; Pohl et al., 2021).

With respect to ontological perspectives, *realist approaches* focus on uncovering objective truths, while *constructivist and postmodern orientations* emphasize the socially constructed and context-dependent nature of knowledge (Popper, 1983; Berger and Luckmann, 1966). While the realist approach of uncovering empirical truths and objective realities may be essential in many types of scientific inquiry, it may overlook the contextual and social elements of knowledge creation (Popper, 1983). On the other hand, relativism has the potential to include diverse, context-specific perspectives. Yet, unifying these diverse perspectives into a cohesive framework remains a challenge (Berger and Luckmann, 1966). Thus, successful KI requires balancing these opposing philosophical perspectives, ensuring that both objective data and subjective, context-specific insights are integrated to address complex real-world challenges (Stokols, 2010; Nowotny et al., 2001).

Leveraging the clarity of objective data while also incorporating the nuanced, context-driven insights of participants can be achieved through reflexive practices, iterative learning, and open communication, ensuring that both empirical rigor and contextual relevance are maintained in addressing complex real-world problems (Godemann, 2008; Lang et al., 2012; Klein, 2021). In Table 1, we describe what KI could look like for each epistemological approach with an example of integration for each approach.

Table 1
Epistemological Approaches to Knowledge Integration.

Approach	Type of Knowledge Production	Type of Knowledge Integration
Epistemological Perspective		
Positivist	Emphasizes empirical evidence and objective reality. Knowledge is created through quantifiable data and factual information.	KI involves systematic synthesis and standardization of empirical data.
Example: The Sea Level Affecting Marshes Model (SLAMM) used across United States helps in the production of scientific knowledge used to assess the vulnerability of coastal wetlands to rising sea levels. This positivist approach involves the collection of hydrological data, sea-level rise projections, and wetland characteristics, which are integrated to create predictive models. KI, in this context, is used to generate scientifically validated insights, ensuring that decisions about wetland management are grounded in empirical evidence and can be universally applied across different coastal environments (Lee et al., 2014).		
Constructivist	Emphasizes context and subjectivity. Knowledge is created through social interactions and shared experiences.	KI involves the collaborative creation of meaning and understanding.
Example: In the Kenyan sustainable river basin management study, scientific knowledge gathered from ecological and hydrological data monitoring is integrated with the contextual and experiential knowledge of local stakeholders including farmers and pastoralists who are most affected by water management decisions. This participatory approach recognizes that knowledge is co-created through collaboration and not merely discovered. KI ensures solutions are scientifically informed as well as contextually relevant and grounded in lived experiences (Kiteme and Wiesmann, 2008).		
Postmodern	Challenges the idea of a single, objective reality. Knowledge is seen as multiple, often conflicting perspectives.	KI involves recognizing and integrating diverse, marginalized voices and deconstructing dominant paradigms.
Example: In the Nanoscience and Nanotechnologies study, nanotechnology development aims to be socially responsible and inclusive of diverse perspectives. Here, KI occurs through socio-technical scenarios. These scenarios incorporate the context-specific viewpoints of various stakeholders, including scientists, technologists, and societal actors along with computer model-based scenarios. Stakeholders engage in reflexive dialogue through participatory workshops, to acknowledge uncertainties and explore multiple potential futures for nanotechnology development. By deconstructing traditional, linear paradigms of technological development, this example demonstrates how postmodern principles of inclusivity, reflexivity and multiplicity can drive KI (Rip, 2008).		

3. Theoretical and methodological approaches to KI

Meta theories like Systems Theory, Social Learning Theory, and Critical Theory provide lenses through which KI can be understood and applied in cross-disciplinary settings. *Systems Theory*, for example, emphasizes the integration of knowledge within complex, interconnected systems (Capra, 1996; Luhmann, 1995), while *Social Learning Theory* focuses on the collective learning processes that underpin successful collaboration (Bandura, 1977; Wenger, 1998). *Critical Theory*, on the other hand, highlights the importance of addressing power dynamics and inequalities in knowledge production, ensuring that KI is not only integrative but also transformative (Habermas, 1984; Freire, 1970).

These metatheoretical approaches in turn inform the methodological choices for KI. Depending on the epistemological stance, different methodologies are appropriate. Quantitative approaches lend themselves well to positivist perspectives, providing numerical data to measure KI outcomes (Creswell, 2014). Qualitative approaches, aligned with constructivist and postmodern paradigms, offer rich insights into the subjective and relational dimensions of knowledge (Lincoln and Guba, 1985). Mixed methods can provide a bridge between these two methodologies, combining the strengths of both approaches for a more comprehensive analysis that accounts for both measurable outcomes and contextual nuances (Tashakkori and Teddlie, 2010; Johnson and Onwuegbuzie, 2004). Equally, teams choose from a broader toolbox of integration methods, from boundary object development and participatory modeling to multi-criteria assessments and iterative integration labs, catalogued by Bergmann et al. (2005), Bergmann and Jahn (2008); and Bergmann et al. (2012).

In Tables 2a and 2b, we provide a sampling of the metatheoretical and methodological approaches for KI and provide a brief description of how KI occurs for each theoretical and methodological approach.

4. Dimensions of knowledge integration: results of a systematic review of the literature

Having addressed the epistemological, theoretical, and methodological foundations of knowledge integration in Sections 2 and 3, we go on to use the literature to address the processes of KI, the factors that promote or impede KI, the barriers and challenges of KI, and the tools that can promote KI. We combined two approaches distill the dimensions of KI in cross-disciplinary and cross-sectoral collaborations: a scoping review methodology and a cited reference search. We describe our methodology in detail below.

In the first step, we used a scoping review approach to: (1) map the landscape of the literature relevant to KI; (2) identify seminal theoretical contributions to knowledge integration; (3) identify cases and practical applications of knowledge integration; and (4) categorize them into our three domains. Scoping reviews are particularly useful in cross-disciplinary research, where diverse perspectives and methodologies need to be integrated (Peters et al., 2015). They follow a defined set of criteria to conduct comprehensive searches that address specific research questions (Peters et al., 2021). The PubMed, JSTOR, and APA PsycINFO databases were used to collect the articles for the scoping review. A date range was not specified because the focus of this review was to provide a broad understanding of KI across various research

Table 2a
A Sampling of Metatheoretical Approaches for Knowledge Integration.

Type of Meta-Theory	Purpose of Knowledge Integration
Systems Theory	To recognize the interconnections and interactions between different knowledge domains within a complex system, resulting in a more holistic understanding of the complex problem (Capra, 1996; Luhmann, 1995). Emphasis is on the role of feedback loops, self-organization, and boundary objects in fostering collaboration among diverse stakeholders, enabling emergent, context specific solutions to complex problems (Innes and Booher, 1999)
Social Learning Theory	To show how KI occurs through collective learning processes, shared practices, and the development of social networks, emphasizing social interaction and collaboration (Bandura, 1977; Wenger, 1998)
Critical Theory	To examine power dynamics and inequalities, aiming to challenge and transform oppressive structures through reflexivity and emancipatory practices (Habermas, 1984; Freire, 1970).
Actor-Network Theory	To show how knowledge is integrated through networks of human and non-human actors (technologies, tools, documents, natural elements), where interactions and negotiations between diverse entities shape the emergence of knowledge (Callon, 1986; Latour, 2005).
Triple Helix Model	To show how knowledge is integrated through interactions and collaborations between universities, industries, and governments. The model emphasizes the co-evolution of these sectors, facilitating innovation and the creation of hybrid organizations and knowledge ecosystems (Etzkowitz and Leydesdorff, 2000).
Cognitive Integration Theory	To show how knowledge is integrated through the development of shared cognitive frameworks, enabling individuals and groups to synthesize and apply diverse information. This theory emphasizes mental processes, understanding, and the alignment of different knowledge domains (Fiol and Lyles, 1985; Hutchins, 1995).

Table 2b
A Sampling of Methodological Approaches and Tools for Knowledge Integration.

Type of Methodology	Type of Knowledge Integration
Quantitative	Integrates numerical data to identify trends and measurable relationships (Creswell, 2014).
Qualitative	Synthesizes narrative and contextual data to capture depth, meaning, and complexity of experiences (Lincoln and Guba, 1985).
Mixed Methods	Combines quantitative and qualitative data to provide a comprehensive understanding of the problem, using triangulation to enhance validity and reliability (Tashakkori and Teddlie, 2010; Johnson and Onwuegbuzie, 2004).
Knowledge Co-production	Joint knowledge production between experts from different disciplines, sectors, and decision levels, including joint problem formulation, knowledge generation, application in both scientific and societal practice, and mutual quality control of scientific rigor, social robustness, and practical relevance (Polk, 2015).
Collaborative Model Building	Collective model building where joint knowledge gathering, structured model development, and consensus-building occur by identifying key variables, mapping relationships, and validating model components, enabling a unified representation of diverse expertise (Voinov and Bousquet, 2010; Gray and Purdy, 2018).
Boundary Object Development	Co-creation of shared artifacts such as prototypes, narratives, or digital tools through structured information exchange and iterative cycles of feedback, clarification, and contestation, ensuring all collaborators have the opportunity to refine shared understandings (Cash et al., 2002).

domains, rather than examining trends within a specific time period. Restricting by date could have excluded both foundational works (e.g., Klein, 1990) and recent advances (e.g., Gajary et al., 2023), which are essential for understanding the evolution of KI and current practices across inter- and transdisciplinarity, sustainability research, and the Science of Team Science. We selected a total of 262 unique and relevant articles across the three domains. We used this corpus of articles to develop a broad understanding of knowledge integration in cross-disciplinary research. They primarily informed the theoretical, epistemological, and methodological foundations of knowledge integration described in Sections 2 and 3.

To address the factors that influence KI in CDCs, we conducted a cited reference search. We were interested in selecting three articles (one from each domain), from these initial 262 articles that: (a) made a foundational contribution to the theory of KI and/or collaborative dynamics of KI; (b) had high citation counts; (c) had recurring references in the literature; and (d) addressed our research questions. In consultation with two experts in the field of cross-disciplinary collaboration from our scholarly network, we selected one article as a representative piece from each of three fields. We oriented our experts to our research questions and criteria for selection and requested their suggestions for three articles from our corpus of 262 articles, one in each field, along with their reasoning for their choices. We took these suggestions into consideration to select the articles. For the Science of Team Science, we selected Stokols et al.'s (2008) article on the ecology of team science because it is one of the earliest articles in the SciTS field that presents a theory of the contextual circumstances that facilitate or constrain team science initiatives drawing on four distinct fields – social and organizational psychology and management research on teams, cyber-infrastructures designed to support remote collaborations, evaluation studies of community-based action research projects, and studies focusing on the antecedents, processes, and outcomes of cross-disciplinary scientific and training initiatives. This article directly addresses the collaborative dynamics of knowledge integration. For inter- and transdisciplinary studies, we selected O'Rourke et al.'s (2016) article because it presents a philosophical framework for cross-disciplinary integration drawing on literatures from cross-disciplinarity and philosophy. For knowledge co-production in sustainability, we picked Pohl et al.'s (2021) because it provides a comprehensive, multidimensional framework for knowledge integration, encompassing cognitive, emotional and social-interactional processes and applies the framework to an environmental / sustainability project. It was important that each representative piece drew on a sufficiently diverse body of literature and made contributions to divergent fields beyond their fields of origin. We limited our representative pieces to one article in each domain to keep our citation analysis manageable, although we acknowledge that a number of other articles could have met our selection criteria.

To mitigate any potential biases stemming from an expert-driven selection of representative pieces, we performed the cited reference search without imposing any date restrictions, ensuring that any older publications that were cited in the three pieces or newer publications that cited the selected seminal pieces were considered in our analysis. This step helped us understand the interconnections between the three domains of literature and revealed how concepts and frameworks from one domain informed or influenced others.

This combined approach is ideal for investigating broad and complex topics that span different fields. It provides a well-rounded understanding by synthesizing both foundational and emerging concepts, identifying research gaps, and mapping the integration of frameworks across disciplines (Arksey and O'Malley, 2005).

Using Google Scholar's "Cited by" feature, we retrieved all English language peer-reviewed journal articles and book chapters that cited any of the initially selected seminal pieces. We used Google Scholar because it has been shown to provide the broadest coverage of citations across a wide variety of subject areas, far ahead of Scopus and Web of Science. Further, correlations between citation counts in Google Scholar and Web of Science or Scopus have been found to be high (Martín-Martín et al., 2018). No publication-year cutoff was applied, so that both pre-2008 works (if cited by Stokols et al., 2008) and post-2021 developments (if citing Pohl et al., 2021) could be a part of our pool. We applied the following inclusion criteria to select works relevant to our research questions. Peer-reviewed article or book chapter that

1. "Proposes a conceptual framework or analytical framework for KI" OR,
2. "Examines factors that influence KI" OR,
3. "Discusses KI processes" OR,
4. "Explores challenges and barriers to KI" OR,
5. "Proposes tools to support KI".

After manually screening for these criteria, 82 pieces (book chapters or articles) remained in our final sample. Some of these addressed topics spanning multiple domains (e.g., Peek et al., 2020; Wagner et al., 2011), so we coded them under all applicable categories. We included 15 additional articles to our initial corpus of 82 articles that were more recent and addressed our selection criteria resulting in a total of 97 articles.

Each of these 97 articles were manually annotated by the first author and no AI tools were used to summarize the focus, methods, and relevance to KI dimensions. Next, we conducted a thematic analysis on these annotated entries and identified recurring themes and patterns related to: (a) how KI is conceptualized across these domains; and (b) the key dimensions of KI (see Sections 4.1 - 4.4 for findings from each of the three domains and their comparative overview and Section 4.5 for distilled dimensions of KI).

4.1. Studies of inter- and transdisciplinarity

The concepts of inter- and transdisciplinarity started gaining traction in the 1960s and 1970s in response to the growing complexity of global challenges and the limitations of traditional, discipline-bound approaches to address them (Jantsch, 1970; Piaget, 1972; Klein, 1990; Rosenfield, 1992; Gibbons et al., 1994). Over the decades, scholars have offered different interpretations and frameworks for these concepts, helping shape our understanding of KI in CDCs.

Julie Thompson Klein (2021) remarked that interdisciplinarity is heterogeneous, with definitions varying based on modes of research and education, levels of interaction, and goals. Earlier work by Rosenfield (1992) provided foundational definitions of multi-, inter-, and trans-disciplinary research that continue to shape how scholars and practitioners approach cross-disciplinary collaborative problem-solving. Interdisciplinary research involves integrating methods and theories from different disciplines while maintaining the distinctiveness of each field. This approach fosters collaboration without fully dissolving disciplinary boundaries. Transdisciplinary research, on the other hand, results in knowledge that transcends disciplinary boundaries, integrating knowledge from academic and societal actors from policy, practice, and community domains to create a unified framework for addressing complex issues (Rosenfield, 1992). Jean Piaget introduced this term, viewing knowledge as a multi-level network rather than isolated silos (Scholz et al., 2024; Lotrecchiano and Misra, 2020). Building on Piaget's work, Basarab Nicolescu emphasized the integration of multiple levels of truth, advocating for a holistic and inclusive approach to knowledge generation (McGregor, 2014; Cockburn, 2022).

Our understanding of interdisciplinarity and transdisciplinarity was enriched by Erich Jantsch (1970), an Austrian philosopher who extended our understanding of transdisciplinarity by emphasizing the need for coordinated efforts across disciplines in education and innovation systems. His work highlights the importance of coordinated efforts across disciplines to bridge academic research and real-world application, emphasizing the role of stakeholder engagement and process facilitation as key enablers of integration.

A common theme across these scholarly contributions is the importance of exchanging, co-producing, or integrating different types of knowledge to develop a holistic understanding of the problem and novel conceptual frameworks that integrate insights, theories, or constructs from diverse disciplines that lead to the design and implementation of sustainable solutions. Klein's (2015) work underscores the importance of integration in cross-disciplinary activities, showing how engaging societal actors can lead to comprehensive solutions. Similarly, Gibbons' idea of Mode-2 knowledge production emphasizes collaboration between academia and external stakeholders to produce knowledge that is both scientifically and socially robust (Gibbons et al., 1994; Bammer et al., 2020). Further, Burger and Kamber's (2003) model emphasizes cognitive and social integration in successful transdisciplinary cooperation. At the organizational level, Kessel and Rosenfield's (2008) concept of heterarchy highlights the importance of non-hierarchical structures that value diverse disciplines equally in facilitating KI.

Further, Horn et al. (2022) argue that interdisciplinary integration hinges on two individual competencies - *epistemic stability* i.e., the ability to clarify and defend one's disciplinary perspective, and *epistemic adaptability,* the capacity to suspend judgement to engage with other epistemologies. Together, these produce integrative actors who bridge rather than merge fields. In alignment with Kessel and Rosenfield's (2008) concept of heterarchial structures, we learn that knowledge integration needs both: (a) a non-hierarchical team setup that values the contributions of different disciplines, professions, and community experiences; and (b) team members who demonstrate both epistemic stability and adaptability. Vienni Baptista and Rojas-Castro (2019) add that institutions must support these competencies through transdisciplinary training (e.g., dedicated TD courses, mentorship, and clear policies) to foster these intellectual qualities.

These foundational and evolving perspectives from the inter- and transdisciplinarity literature emphasize the epistemic and structural diversity that cross-disciplinary teams need to navigate, highlighting the importance of designing collaborative processes that are both integrative and reflexive.

4.2. Knowledge co-production in sustainability research

KI in sustainability research is conceptualized as a multidimensional, iterative process designed to address complex, real-world problems (O'Rourke et al., 2016; Pohl et al., 2021). It involves the creation of structures that support co-learning and collaboration among diverse stakeholders, ensuring that the knowledge generated is both scientifically sound and contextually relevant (Gugerell et al., 2023). The key principles guiding knowledge co-production include context-sensitivity, pluralism, goal-orientation, and interactivity, all of which contribute to producing actionable insights to address sustainability challenges (Norström et al., 2020; Wyborn et al., 2019).

Unlike a simple aggregation of knowledge, KI is an active process of integrating perspectives and methodologies without requiring full consensus (Pohl et al., 2021). The KI process includes a *cognitive* dimension such as generating shared intellectual tools, an *emotional* dimension such as trust and positive interpersonal relationships, and a *social* dimension such as effective leadership and team dynamics (Pohl et al., 2021; Boix Mansilla et al., 2016). Thus, relational and humanistic dimensions are essential for KI.

Frameworks such as the Theory of Change (ToC) and Applied Critical Realism have been used to support KI in sustainability research. ToC, for instance, helps clarify pathways to long-term goals and fosters collaboration in specific contexts (Deutsch et al., 2021). Critical realism offers tools to integrate diverse forms of knowledge while fostering transformative change (Cockburn, 2022). Both approaches reinforce the idea that KI requires continuous monitoring, evaluation, and adaptation to avoid replicating existing power structures (Gugerell et al., 2023).

Initiatives like the Swiss National Research Programme 61 on Sustainable Water Management are examples of practical applications of KI, where group learning and leader-driven integration played key roles in combining scientific outputs across various projects (Hoffmann, Pohl and Hering, 2017b). Similarly, the Wings program on water and sanitation innovations used ToC to manage diverse group compositions and time constraints effectively (Deutsch et al., 2021). More recent work by Deutsch et al. (2024) offers further insights from Swiss Inter and Transdisciplinary (ITD) initiatives, demonstrating how integrative leadership strategies such as: (a) structuring coordination; (b) facilitating inclusive interactions; and (c) navigating contextual tensions enabled KI across diverse stakeholders.

Together, these foundational perspectives from sustainability research underscore that KI is not only a methodological challenge but also a relational one, requiring context-sensitivity, adaptability, and shared commitment to achieve socially robust outcomes.

4.3. Science of team science

Focusing on the individual and team levels of analysis and predominantly on large-scale scientific team-based initiatives in health research, the SciTS field focuses on the intrapersonal characteristics, individual competencies and skills, team structures, leadership and engagement strategies, and collaborative processes that facilitate or constrain KI in scientific teams. Similar to the fields of knowledge co-production in sustainability research, and studies of inter- and transdisciplinarity, SciTS has addressed the complexities faced by transdisciplinary knowledge-producing teams, including the challenges of equitable involvement of stakeholders in research co-design and implementation, methodological pluralism, and translating scientific findings to practical applications, policies, interventions, or tools (Mâsse et al., 2008; Lotrecchiano and Misra, 2018).

Drawing on decades of social psychological and management research on teams as well as evaluations of large-scale team science and community-based action orientated initiatives, and in alignment with the literature on knowledge co-production and studies of inter- and transdisciplinarity, the SciTS literature also finds that KI requires more than technical integration. Emotional and social dimensions such as social cohesiveness, flexibility to adapt to changing circumstances, egalitarian values and mutual trust and respect among team members, and empowering and transformational leaders who are able to foster collaboration through tactical skills and inclusive orientation have been found to facilitate collaborative effectiveness (Stokols et al., 2008).

At the team level, SciTS scholars have emphasized participatory goal setting and decision-making practices, collaboration planning and partnership agreements, and team development strategies such as experiential learning and appreciative inquiry to encourage communication across disciplinary boundaries (Hall et al., 2008; Bennett and Gadlin, 2012; Hall et al., 2019). These insights complement the more recent work on integration experts and the critical role they can play in designing, planning, and implementing integration processes, translating and communicating divergent perspectives among team members and stakeholder groups, and navigating social boundaries, and power imbalances in teams (Hoffmann et al., 2022; Bammer et al., 2020).

At the organizational and institutional levels, SciTS researchers have emphasized the role of strong organizational and institutional support to encourage and sustain cross-disciplinary and cross-sectoral initiatives like modifications of merit and promotion policies that value collaborative and cross-disciplinary work, institutional policies for data sharing with international members as well as community members, and creating standards for ethical scientific conduct and management of intellectual properties. Modifications to organizational structures and routines to more easily enable co-teaching of courses, sharing of grant resources, and administrative support for large-scale team initiatives have also been found to facilitate team science (Stokols et al., 2008; Klein and Falk-Krzesinski, 2017). The SciTS field has contributed to the development of metrics, measures, and tools to evaluate the collaborative processes, products, and outcomes of team science research and training initiatives. Prominent among these measures and metrics are the transdisciplinary orientation scale (Misra et al., 2015) that has been used to assess team members' capacity to collaborate effectively in cross-disciplinary settings, including a pertinent set of values, attitudes, beliefs, conceptual skills and behavioral repertoires central to knowledge integration. Transdisciplinary orientation and earlier measures of collaborative readiness such as the interdisciplinary attitudes and behaviors and collaborative activities index have been linked to intellectual and integrative qualities of team products (Mâsse et al., 2008; Misra et al., 2009; Misra et al., 2015). Beyond bibliometric measures of the integrative outcomes of cross-disciplinary research, SciTS scholars have advanced qualitative measures of integrative attributes of research products emanating from scientific teams such as the written products protocol (Hall et al., 2008) and more recent work that provides a more comprehensive analytical framework for evaluating the processes and outputs of knowledge integration, including the breadth of integration (narrow to broad) and scope of integration (multi- to transdisciplinary), level of engagement of actors, and socio-cognitive frameworks to facilitate knowledge integration (Misra et al., 2024). This recent work integrates literature and insights from the knowledge co-production literature and studies of interdisciplinarity. In sum, the SciTS field has contributed to our knowledge of intrapersonal characteristics, including leadership, team structures, communication and team building strategies, as well as organizational and institutional factors necessary for KI.

4.4. Knowledge integration – a comparative overview

Across studies of inter- and transdisciplinarity, knowledge co-production, and SciTS, KI is conceptualized as a multidimensional process encompassing cognitive, emotional, and social dimensions. These fields share a common recognition of the importance of inclusivity, collaboration, and the merging of diverse perspectives as essential for successful KI. By considering human and relational dynamics alongside technical synthesis, KI is conceptualized as a process requiring continuous adaptation, monitoring, and evaluation to ensure relevance and efficacy (Pohl et al., 2021; Stokols, 2010). This iterative approach allows for flexibility, particularly when integrating diverse knowledge systems and addressing power dynamics in collaborative efforts (Lang et al., 2012; Gugerell et al., 2023).

Despite this common understanding, each field applies KI in distinct ways based on its context and goals. Both inter- and transdisciplinary studies and the knowledge co-production fields emphasize systemic integration of knowledge across disciplinary and sectoral boundaries through the inclusion of societal actors to create adaptable solutions that address both scientific and social needs (Pohl and Hirsch Hadorn, 2007; Lang et al., 2012). Both fields emphasize systemic integration and methodological pluralism, focusing more on the role of societal actors in creating comprehensive solutions (Klein, 2010). Further, both research areas prioritize co-learning and inclusivity, focusing on establishing structures that ensure the knowledge produced is actionable and relevant to local contexts (Norström et al., 2020). In contrast, SciTS places a stronger focus on internal team dynamics, using frameworks and tools to monitor and support KI within collaborative scientific teams (Mâsse et al., 2008).

The divergent theoretical approaches employed in the three fields further illustrate their differing approaches to KI. Inter- and transdisciplinary studies often rely on frameworks like Piaget's Cognitive Development Theory and Nicolescu's transdisciplinary methods, which emphasize systemic integration and the importance of stakeholder engagement (Scholz et al., 2024; Cockburn, 2022). Knowledge co-production approaches apply Theory of Change and Critical Realism to map pathways for achieving long-term goals and fostering collaboration in localized contexts (Deutsch et al., 2021). SciTS, on the other hand, focuses on the use of conceptual models that assess the antecedents, processes, and outcomes of scientific collaborations with an emphasis on improving the integrative capacity of teams and facilitating collaborative processes (Hall et al., 2008; Masse et al., 2008; Stokols et al., 2008; Misra et al., 2009; Salazar et al., 2012; O'Rourke et al., 2016).

Relational dynamics such as trust and respect are important across all three fields. Studies of knowledge co-production and SciTS place greater emphasis on fostering positive interpersonal relationships and building group identity as essential components for collaboration (Boix Mansilla et al., 2016; Stokols, 2010). All three fields recognize that knowledge integration is a multidimensional and interactive process wherein people from different backgrounds collaborate without necessarily knowing the final outcome. This highlights the emergent and adaptive nature of KI in practice and shows that successful KI involves not just combining knowledge but creating spaces for dialogue and collective learning.

In the preceding sections, we have shown how various epistemological, theoretical, and methodological lenses shape KI in practice. In Section 4.5, we distill these insights into eight dimensions of Knowledge Integration, grounded in the inter- and transdisciplinary, knowledge co-production in sustainability research and SciTS literatures. Taken together, these dimensions capture the structural and relational building blocks of KI.

4.5. Dimensions of knowledge integration

Building on the insights from our scoping review, we have identified seven critical dimensions essential for knowledge integration, as outlined in Fig. 1.

5. A conceptual framework for knowledge integration

Next, we introduce a conceptual framework for KI that builds on O'Rourke et al.'s (2016) input-process-output (IPO) model (Fig. 2a). The framework illustrates how KI unfolds dynamically over time within CDCs and clarifies the types of knowledge integrated, the conditions under which integration occurs, and the outcomes it can produce. It organizes insights from our review into three interactive components -

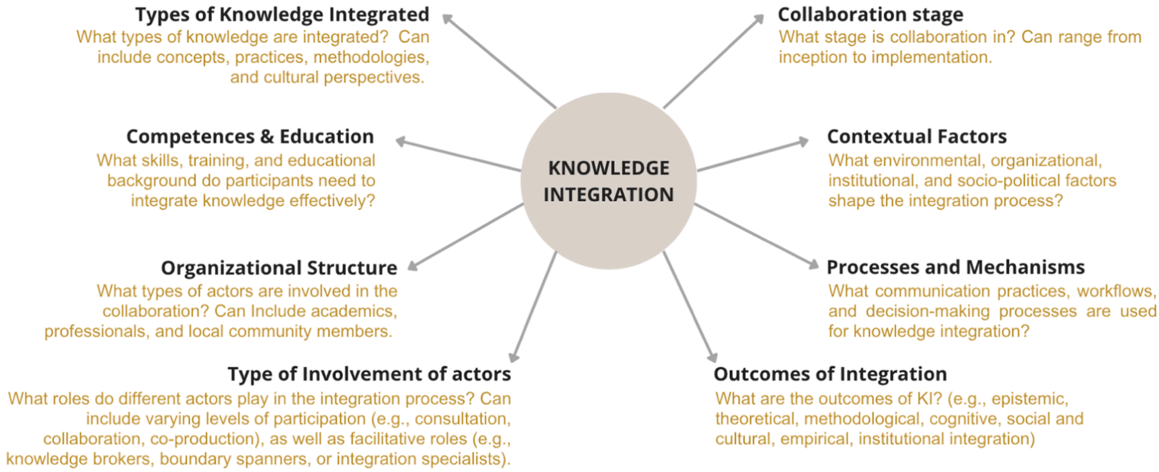

Fig. 1. Dimensions for Knowledge Integration. *Sources:* Huang and Newell (2003); Burger and Kamber (2003); Zierhofer and Burger (2007); Godemann (2008); Kessel and Rosenfield (2008); Hall et al. (2008); Stokols et al. (2008); Lang et al. (2012); Salazar et al. (2012); Cummings et al. (2013); Scholz and Steiner (2015); Klein (2013, 2021); Hoffmann et al. (2017a, 2017b); Lotrecchiano and Misra (2018); O'Rourke et al. (2019); Hitziger et al. (2019); Pohl and Wuelser (2019); Vienni Baptista and Rojas-Castro (2019); Peek et al. (2020); Pohl et al. (2021); Klein (2021); Horn et al. (2022); Gajary et al. (2023); Scholz et al. (2024); Misra et al. (2024).

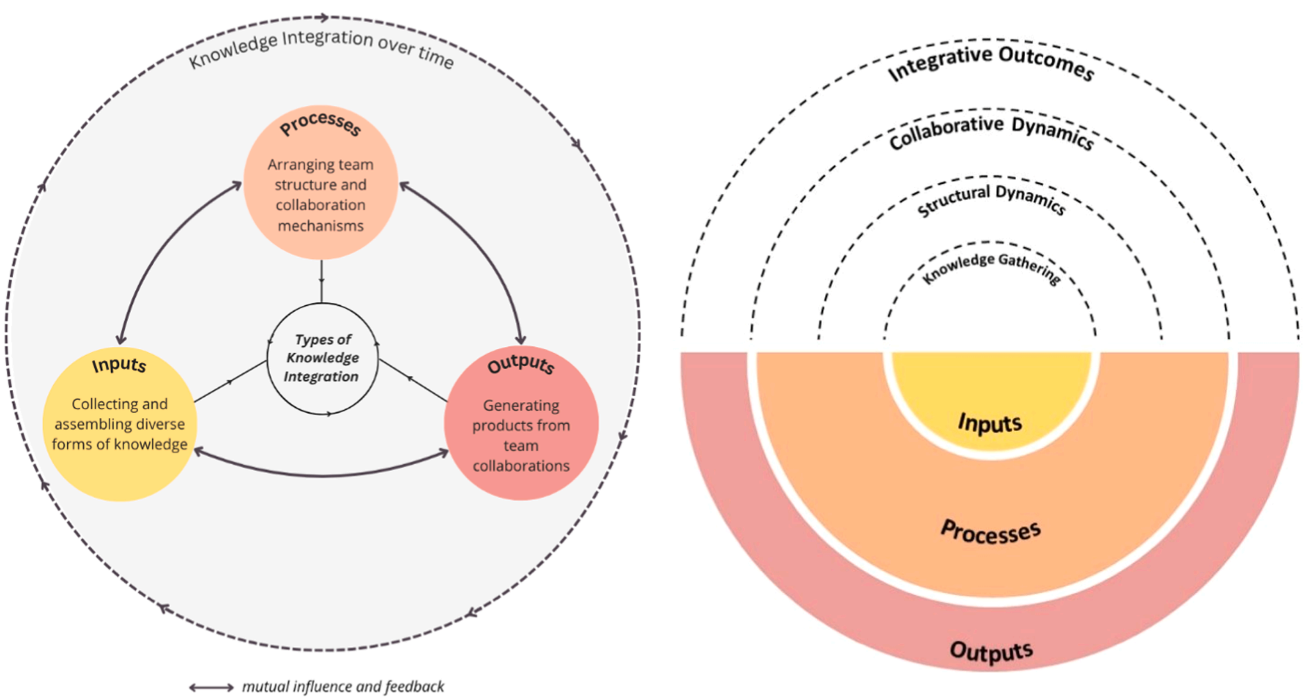

Fig. 2. (a) Conceptual Framework for Knowledge Integration Elaborating the Input, Process, and Output Model by O'Rourke et al. (2016); types of KI (center) refer to the different types of knowledge integration resulting from a collaboration; three colored nodes (Inputs, Processes and Outputs) represent three components of knowledge integration; bidirectional arrows illustrate how inputs, processes and outputs continuously influence one another throughout the collaboration; outer dashed circle shows that these mutual influences unfold dynamically over the lifecycle of a cross-disciplinary collaboration. (b) Four sub-components of the proposed framework – Knowledge Gathering (Input), Structural Dynamics and Collaborative Dynamics (Processes), Integrative Outcomes (Output).

Inputs, Processes and Outputs, each associated with distinct dimensions of KI.

In the *Inputs* component, teams gather diverse forms of knowledge to establish shared goals and a common understanding of the problem. The *Processes* component encompasses structural and collaborative mechanisms that influence the knowledge integration. Finally, the *Outputs* component represents the outcomes of integration, which vary depending on team composition, collaboration dynamics, and structural factors. This framework elaborates the IPO model by elucidating the four dimensions of KI that emerged from the literature under each stage of the model and across the lifecycle of a collaboration (Hall et al., 2008; Kessel and Rosenfield, 2008; Leydesdorff, 2011; Hoffmann et al., 2017a, 2017b; Cockburn, 2022; Misra et al., 2024). Fig. 2b illustrates the four components of the proposed framework distilled under the three categories: *Knowledge Gathering* (Inputs), *Structural Dynamics and Collaborative Dynamics* (Processes), and *Integrative Outcomes* (Outputs).

Inputs - This component corresponds to the knowledge gathering dimension of CDCs, where the focus is on the initial assembling diverse forms of knowledge, including ideas, methodologies, experiential insights, and expertise from multiple disciplines and sectors. The types of knowledge teams prioritize at the outset, i.e., whether they foreground empirical measurements (positivist) or lived experience (constructivist) is derived directly from their underlying epistemologies. Establishing this broad base of information is critical for setting the foundation for more advanced integrative processes.

Processes - Structural and collaborative dynamics facilitate or constrain KI. *Structural dynamics* refer to organizational and collaborative frameworks that influence integration—such as team composition, configurations, and organizational structures that impact the success of KI. *Collaborative dynamics* refers to interactions among team members, such as the level of stakeholder engagement, participant roles, and the depth of collaborative integration.

Outputs - This component corresponds to the integrative outputs and outcomes of KI including both the near-term tangible products that result from KI (referred to as outputs) as well as the longer-term changes, benefits, or effects that occur through the accumulation of outputs (referred to as outcomes) (Misra et al., 2024). Integrative outcomes include theoretical, methodological, and epistemic integration, and context-specific solutions to problems.

The epistemological and methodological choices laid out in Sections 2 and 3 shape the decisions throughout the project collaboration. For example, the decision about which knowledge to gather (inputs) is informed by one's epistemic stance (positivist vs. constructivist) and by meta-theoretical lenses such as Systems Theory or Critical Theory. Likewise, how outputs are evaluated, through quantitative indicators or participatory outcome mapping, reflects those same methodological commitments.

5.1. Inputs of knowledge integration: knowledge gathering

Knowledge gathering involves collecting and assembling diverse forms of knowledge—including ideas, methodologies, experiential insights, and disciplinary expertise—from various academic, professional, and community sources. This broad base of information is essential for laying the groundwork for subsequent, more complex integrative processes.

As inputs, participants share and compare their problem framings and findings without necessarily engaging in deeper synthesis or transformation. In the Swedish Sustainable City Project, diverse knowledge types were integrated to create an environmentally sustainable and socially inclusive urban neighborhood. *Epistemological knowledge* contributed scientific data on the city's environmental impact, while *Procedural and practical knowledge* from environmental engineers and urban planners guided the development of eco-friendly infrastructure. *Contextual knowledge* provided by residents offered insights into how the community could best adapt to new green initiatives. *Cultural knowledge* from indigenous and traditional practices informed land use and supported community-driven efforts, enriching green space planning. Finally, *Systems knowledge* enabled effective management of the complex interactions within urban ecosystems. Together, these knowledge types fostered a holistic approach to sustainable urban planning (Bibri et al., 2020). While these knowledge forms remain in their original formats, this aggregation sets the stage for more advanced integration in later components.

Knowledge gathering helps categorize and map the diverse expertise within the team. By recognizing each participant's contribution—-whether theoretical, practical, or cultural—the team ensures that no form of knowledge is undervalued. An inclusive approach – one that does not seek to erase differences or resolve epistemic tensions but rather embraces epistemic pluralism by recognizing that diverse and even incommensurable knowledge claims can hold value and help promote more structured and intentional efforts in the later stages of integration (Miller et al., 2008). In this sense, integration is not necessarily about synthesis or agreement but about fostering mutual understanding, dialogue, and co-existence across epistemic boundaries (Scholz and Steiner, 2015; Boix Mansilla et al., 2016; Cockburn, 2022). In practice, this may involve: (a) spaces to have a dialogue between team members to articulate and situate their knowledge; (b) use of boundary objects to bridge the understanding amongst team members without reducing or disregarding them; and (c) use of reflexive practices to identify how power, values, and language shape the different knowledge claims.

Table 3 categorizes the different types of knowledge that may be

Table 3
Types of Knowledge Assembled during Knowledge Gathering.

Type of Knowledge	Description
Epistemological Knowledge	
Declarative Knowledge	Factual knowledge about objects, events, and concepts (Squire, 1987)
Procedural Knowledge	Knowledge about how to perform specific tasks and procedures (Anderson, 1983).
Conceptual Knowledge	Knowledge about the interrelationships among basic elements within a larger structure (Chi et al., 1982).
Metacognitive Knowledge	Knowledge about one's own cognitive processes, including monitoring and controlling them (Flavell, 1979).
Experience-based Knowledge	
Tacit Knowledge	Personal, experiential knowledge that is often difficult to articulate (Polanyi, 1966).
Experiential Knowledge	Knowledge gained through direct experience and practice (Kolb, 1984).
Reflective Knowledge	Knowledge gained through reflection on experiences, leading to deeper understanding (Schön, 1983).
Experiential-Scientific Knowledge	Knowledge that emerges from collaborative learning processes combining practical and local experience with scientific evidence (Raymond et al., 2010)
Contextual Knowledge	
Local Knowledge	Context-specific insights that are unique to a particular geographic area or community (Chambers, 1983).
Global Knowledge	Broad, widely applicable knowledge recognized and utilized worldwide (Held and McGrew, 2003).
Situated Knowledge	Knowledge that is context-dependent and specific to situations or environments (Lave and Wenger, 1991).
Embedded Knowledge	Knowledge built into organizational routines, processes, and norms (Nonaka and Takeuchi, 1995).
Cultural Knowledge	
Traditional Knowledge	Knowledge passed down through generations within a community (Berkes, 2008).
Indigenous Knowledge	Knowledge held by indigenous peoples, encompassing traditional practices and cultural heritage (Battiste, 2002).
Applied Knowledge	
Strategic Knowledge	Knowledge used to plan and implement strategies to achieve specific objectives (Mintzberg, 1994).
Practical Knowledge	Knowledge applied in everyday tasks and activities, often involving common sense (Polanyi, 1966).
Heuristic Knowledge	Knowledge of rules of thumb or strategies derived from experience for solving problems (Gigerenzer and Todd, 1999).
Action-oriented Knowledge	Knowledge that emerges through the integration of multiple kinds of knowledge and ways of knowing to intentionally design and implement context-specific actions, build agency and develop capacities for transformative change (Caniglia et al., 2020)
Specialized Knowledge	
Domain-Specific Knowledge	Knowledge specific to a particular field or domain of expertise (Ericsson et al., 2006).
Novice Knowledge	Basic knowledge held by individuals new to a field or discipline (Dreyfus and Dreyfus, 1980).
Expert Knowledge	Advanced knowledge held by individuals with significant experience and expertise (Ericsson et al., 2006).
Knowledge for Systemic Change	
System Knowledge	Understanding of the complex interactions within a system (Checkland, 1999).
Target Knowledge	Knowledge focused on specific goals or outcomes (Probst and Büchel, 1997).
Transformation Knowledge	Knowledge about how to bring about change within a system (Loorbach and Rotmans, 2010).
Normative Knowledge	
Ethical Knowledge	Knowledge about values, ethics, and responsibilities related to environmental decisions and sustainability actions (Raymond et al., 2010).

assembled while gathering knowledge – epistemological, experiential, contextual, cultural, applied, specialized, knowledge for systemic change, and normative knowledge. It is important to note that knowledge gathering and assembly occur throughout the collaboration and are not limited to the inception phase of CDCs as participants learn more about each other's knowledge and experience and potential contributions to addressing the problem (Misra et al., 2024).

5.2. Processes of knowledge integration: structural dynamics

Building on the systemic breakdown of structural enablers proposed by Deutsch et al. (2024), which spans the individual level (e.g., personal incentives, epistemic competencies), team level (e.g., group norms, trust, communication), program-level (e.g., budgets, deliverables), institutional level (e.g., reward systems, organizational culture), and social-political level (e.g., funding mandates, regulatory frameworks), we focus specifically on structural conditions that project leaders and team members can shape directly within a CDC. Higher-order structures (program, institutional, and socio-political) are discussed under contextual factors (Section 4.4) and again under the section on processes of KI (Section 5.3).

Structural dynamics, including team composition, configurations, and governance mechanisms, and participant competences and education, can facilitate or hinder the integration process (Gibbons et al., 1994; Hoffmann et al., 2017a, 2017b; Vienni Baptista and Rojas-Castro, 2019; Horn et al., 2022). Importantly, beyond *who* is on the team and *how* it is arranged, *who does what* matters profoundly. Sustainability science and transition scholars have shown that researchers enact multiple, evolving roles (reflective scientist, process facilitator, change agent) that shape how structural conditions are enacted and sustained in practice (Wittmayer and Schäpke, 2014).

However, decisions about team structures, stakeholder roles and integration strategies, and the skills or training members bring are not made in a vacuum. They are guided by underlying epistemological stances and theoretical commitments. For example, a team adopting constructivist epistemology may prioritize co-design workshops and shared boundary objects, a team drawing from systems theory may favor feedback loops and adaptive governance, whereas one drawing from a social learning approach may emphasize sense-making and collective reflection.

5.2.1. Team composition (which actors are involved?)

Team composition significantly influences KI (Misra et al., 2024). Moreover, who fills which role matters just as much. For example, assigning a "process facilitator" versus a "change agent" can shape not only who participates but how power, ownership, and action are negotiated in the team (Wittmayer and Schäpke, 2014). Each type of team composition offers specific advantages, such as enhanced theoretical depth in academic teams (Edmondson and Harvey, 2018), effective technology transfer in academic-industry partnerships, and culturally robust solutions when local actors are involved in CDCs (Agrawal and Gibson, 1999; Clark and Wallace, 2015).

However, each type of team composition can have potential drawbacks. For example, although academia-industry partnerships may promote innovation, they may encounter conflicts between the pursuit of academic rigor and commercial interests, potentially leading to compromises in research depth or transparency (Lang et al., 2012; Scholz et al., 2024). Including local communities may enhance the societal relevance of the research, but can introduce variability in values, perspectives, interests, and needs, sometimes resulting in challenges in decision-making or delays in reaching consensus (Burger and Kamber, 2003). Finally, large multi-sector teams involving academia, industry, government, and non-profits can include diverse insights but may face coordination difficulties, the challenge of inequitable contributions, and increased complexity in aligning objectives (Huang and Newell, 2003; Lotrecchiano and Misra, 2018).

5.2.2. Configurational dynamics (what is the structure of the team?)

Teams can adopt either fluid or fixed configurations, depending on the project's needs (Vogel and Hunecke, 2024). Fluid configurations are adaptable, evolving in response to changing project dynamics, tolerating ambiguity, and allowing for flexible integration of diverse perspectives (Kessel and Rosenfield, 2008). This adaptability may foster exchange of information across disciplines, enabling team members to bring fresh insights and reshape the project based on evolving needs (Cummings et al., 2013; Gugerell et al., 2023). However, while fluid structures support innovation, they may struggle with team cohesion.

In contrast, fixed configurations can provide stability and predictability, often essential in projects requiring strict adherence to protocols or regulatory compliance (Leydesdorff, 2011). Structured and static roles support systematic and predictable KI, benefiting projects that require rigorous, step-by-step integration processes (Hoffmann et al., 2017a, 2017b).

The choice between these configurations may influence how knowledge is shared and integrated, shaping a project's ability to generate comprehensive solutions (Mobjörk, 2010). Fluid team structures may benefit from individuals who can span boundaries and connect diverse perspectives, whereas fixed team structures may rely on stable coordinating roles that oversee tasks and maintain coherence (Schreyögg and Sydow, 2010).

5.2.3. Dynamic equilibrium (what is the team's approach to KI?)

Achieving *dynamic equilibrium* within a team involves balancing innovation and stability. Teams with *creative equilibrium* encourage the development of new frameworks and methodologies, integrating diverse disciplinary insights to foster novel outcomes (Hoffmann et al., 2017a, 2017b). This is often seen in sustainability projects that require the integration of ecological, social, and economic dimensions (Clark and Wallace, 2015). Alternatively, teams with a *conservative equilibrium* rely on established norms and methods, fostering reliability and predictability, particularly in clinical or standardized research settings (Leydesdorff, 2011). Many CDCs often adopt a hybrid model, adjusting the balance between innovation and stability as they evolve, enabling both flexibility and consistency in the KI process (Gibbons et al., 1994).

5.2.4. Epistemic cultures (how are different types of disciplinary knowledge valued?)

Epistemic culture refers to the norms governing how knowledge is created and valued within a project (Kessel and Rosenfield, 2008). Teams can adopt a heterarchical structure, where contributions from all disciplines are equally valued, fostering collaboration and synthesis across fields (Kessel and Rosenfield, 2008). This approach is appropriate for projects requiring the integration of diverse knowledge systems, such as sustainability research (Hoffmann, Pohl and Hering, 2017a,b). In contrast, a hierarchical structure prioritizes specific disciplines, streamlining decision-making but potentially marginalizing other perspectives (Kontopoulos, 1993). Choosing between heterarchical and hierarchical structures affects the depth of integration, with the former supporting cross-disciplinary collaboration and the latter offering clearer direction but risking knowledge silos (Pohl et al., 2021).

5.2.5. Governance mechanisms (how are collaborative activities managed?)

Governance mechanisms shape how decisions are made and how knowledge is integrated. *Decentralized autonomy* distributes decision-making across teams or individuals, enhancing creativity and responsiveness, particularly in dynamic, fast-paced environments (Cockburn, 2022). This structure allows teams to adapt quickly based on immediate feedback. In contrast, *centralized oversight* consolidates decision-making at the top, ensuring coherence and alignment with a unified project vision (Leydesdorff, 2011). While this approach offers consistency and control, it can limit the flexibility needed for complex problem-solving. *Decentralized governance* promotes a bottom-up approach to KI, fostering innovation, while *centralized governance* ensures top-down alignment with predefined goals and standards (Hoffmann et al., 2017a, 2017b).

5.3. Processes of knowledge integration: collaborative dynamics

Collaborative dynamics encompass the depth of stakeholder engagement, the frequency of interactions, the roles stakeholders assume throughout the integration, and the integrative methods by which teams negotiate, reflect on, and synthesize diverse knowledge streams to shape project outcomes.

5.3.1. Level of stakeholder engagement

The level of stakeholder engagement in a project can be categorized into different levels: information, consultation, cooperation, coordination, collaboration, and co-creation (Hoffmann et al., 2017b; Misra et al., 2024). *Information* refers to one-way communication between different actors where actors are informed about the synthesis project through articles, books, policy briefs, but are afforded only limited power to influence the process and/or the outcome. In *consultation*, stakeholders provide feedback without being deeply involved in decision-making. This approach may integrate external perspectives but tends to limit stakeholders' influence on the project's direction. *Cooperation* assists in sharing or dividing work amongst the team. It involves providing active assistance for a portion of a research project or process. *Coordination* helps avoid gaps and task overlaps between individuals and requires mutual understanding of project objectives. *Collaboration* involves stakeholders working alongside the core team, contributing actively to discussions and decisions but not leading initiatives. This level of engagement promotes more dynamic knowledge exchange. Finally, *co-creation* represents the highest level of integration, where stakeholders are fully involved in decision-making and implementation, fostering new forms of hybrid knowledge that are deeply contextualized to the project's aims (Lang et al., 2012; Cummings et al., 2013; Misra et al., 2024).

Earlier work by Pohl and colleagues (2017) addresses how stakeholder roles and engagement evolve over the course of the project, from problem framing and role negotiation to joint knowledge production and sustained collaboration. The stages, ranging from clarifying societal problems and aligning knowledge forms to co-designing dynamic actor involvement over time, support a more nuanced understanding of engagement that goes beyond fixed categories. They add a temporal and reflexive perspective to the classification of engagement levels, emphasizing that collaboration dynamics shift across the research cycle.

5.3.2. Frequency of interaction

The frequency with which stakeholders engage can influence the capacity for KI. One-time interactions usually occur at key decision points, limiting the ongoing integration of stakeholder knowledge (Hoffmann et al., 2017a, 2017b). Periodic interactions provide more opportunities for regular input and alignment while still allowing for flexibility (Hoffmann et al., 2017a, 2017b). Continuous engagement involves dynamic, ongoing collaboration that enhances the project's adaptability and responsiveness to new knowledge and changing conditions, fostering deeper integration (Pohl et al., 2021).

5.3.3. Role of stakeholders

Stakeholders can assume various roles that influence KI processes and outcomes, drawing on integrative competencies (Wittmayer and Schäpke, 2014; Bulten et al., 2021; Horn et al., 2022; Hofmann et al., 2025). *Advisors* provide high-level guidance without engaging in day-to-day operations, helping shape strategic direction (O'Rourke et al., 2016). *Contributors* are involved in the execution of project tasks, offering expertise but not typically making final decisions. *Leaders and decision-makers* hold authority over project direction and play a key role in synthesizing diverse knowledge into actionable strategies. Finally, *specialized facilitators* such as boundary spanners, knowledge brokers, and reflexive monitors are crucial for maintaining smooth communication and ensuring that knowledge flows effectively across disciplines (Gibbons et al., 1994; Leydesdorff, 2011; Wittmayer and Schäpke, 2014; Hilger et al., 2021).

- Boundary spanners connect different organizational or disciplinary groups, facilitating the transfer of knowledge.
- Knowledge brokers manage the translation of knowledge to ensure that it is accessible and actionable.
- Reflexive monitors continuously assess and adapt integration processes to maintain relevance and effectiveness in the face of changing project conditions (Pohl et al., 2021).

Our discussion of stakeholder roles builds on and sits alongside the more expansive framework proposed by Hilger et al. (2021). Hilger and colleagues outline a broad spectrum of stakeholder roles beyond the ones mentioned above, including boundary object designers, reflexive practitioners and others, thereby highlighting the diverse ways actors can engage in KI (Vienni Baptista and Rojas-Castro, 2019).

5.3.4. Integration strategies

Two primary integration strategies are observed in the literature: *embedded integration* and *peripheral integration*. In *embedded integration*, stakeholders are part of the core team, supporting continuous and in-depth collaboration, which can enhance the social robustness of project outputs through regular knowledge exchange (Bammer et al., 2020). *Peripheral integration*, in contrast, involves more occasional engagement with stakeholders, typically at critical junctures or phases, providing flexibility while still allowing for valuable external inputs. This approach is cost-effective and suited to projects where constant involvement is not feasible (Scholz et al., 2015).

The choice between peripheral and embedded integration depends on several factors, including: (a) alignment of objectives and timelines amongst stakeholders; (b) prior collaboration experience; (c) stakeholders' willingness and openness to cross-disciplinary teamwork; (d) geographic and organizational scope; (e) availability of time, funding and other resources; and (f) familiarity and trust amongst team members (Stokols et al., 2008).

5.4. Outputs of knowledge integration: integrative outcomes

Outputs of KI refer to the near-term tangible results and impacts of integrating diverse knowledge forms, methodologies, and perspectives (Misra et al., 2024). For instance, the development of a theoretical framework by combining theories from different disciplines represents a KI output. Subsequent changes in policies, practices, or applications that emerge as a result of the integrative theoretical framework represent longer-term integrative outcomes. Thus, this component emphasizes both the theoretical and practical outcomes that emerge from the entire KI process. Integrative outcomes (both short-term outputs and longer-term practical and societal outcomes) reflect the depth and efficacy of the collaborative efforts and serve as a benchmark for evaluating the success of KI across various dimensions—methodological, theoretical, cognitive, social, institutional, epistemic, and cultural. Table 4 presents each type of KI outcome, along with relevant examples for each category.

6. Conclusion

Our conceptual framework for Knowledge Integration makes two specific theoretical contributions to the literature on inter- and transdisciplinarity, knowledge co-production, and the science of team science. First, it draws on and synthesizes these three bodies of literature dispersed across continents, socio-environmental problem contexts, and time periods to identify the key dimensions of KI inductively — *types of knowledge integrated, competencies and education required to practice*

Table 4
Types of Knowledge Integration Outcomes with Examples.

Type of KI	Description	Examples
Epistemic Integration	Combining knowledge emerging from different epistemologies.	The "Fischnetz: Involving anglers, authorities, scientists and the chemical industry to understand declining fish yields" project combines knowledge emerging from scientific, professional practice, experiential, and cultural epistemologies by engaging anglers, authorities, local stakeholders and experts from the chemical industry to improve the understanding of fish population declines and generating practical measures for mitigating the decline of brown trout in Swiss rivers (Burkhardt-Holm, 2008).
Theoretical Integration	Integrating concepts and theories from different fields to create a cohesive framework for understanding complex phenomena.	The study "Four propositions on integrated sustainability" research integrates theories from environmental science and peace studies to create a cohesive framework for understanding the sustainability-peace nexus. This integration addresses sustainability challenges by combining insights on human needs, agency, equity, and institutional governance, supporting policies that balance ecological integrity with social well-being (Fisher et al., 2021).
Methodological Integration	Combining methodologies and research techniques from various disciplines to study complex issues.	The study on the development of multilateral environmental agreements on toxic chemicals uses integrated assessment models to synthesize scientific atmospheric modeling, environmental monitoring, and policy analysis techniques to develop effective strategies for managing toxic chemicals internationally (Castells and Guardans, 2008).
Empirical Integration	Merging empirical data (qualitative or quantitative) from different sources or contexts to generate new insights and validate cross-contextual patterns.	The "Behavioral Sciences in the Health Field: Integrating Natural and Social Sciences" study combines different empirical data, including national surveys, psychosocial questionnaires, educational feedback, and program level implementation reports to carry out a cross-level synthesis of health statistics and psychosocial data, and triangulates program effectiveness using both qualitative and quantitative evidence to inform responsive interventions (Piko and Kopp, 2008)
Cognitive Integration	Synthesis of cognitive processes, skills, and methodologies from different disciplines to address a specific problem.	The "Development of multilateral environmental agreements on toxic chemicals: Integrating the work of scientists and policy makers" study fosters KI through the synthesis of cognitive competencies, including perspective taking, reflexivity, analogical reasoning, and tolerance for ambiguity to enhance KI in inter- and transdisciplinary work. This integration of cognitive skills supports the merging of diverse disciplinary insights, enabling individuals and teams to effectively address complex sustainability issues (Vogel and Hunecke, 2024).
Social and Cultural Integration	Including diverse cultural perspectives and traditional knowledge systems, while actively engaging a variety of stakeholders—including community members in the research process to co-create solutions.	The study "Defining and implementing social integration: A case study of school leaders' and Practitioners' work with newly arrived immigrant and refugee students" focuses on integrating social and cultural practices in Swedish schools and engages diverse educational strategies like tailored educational programs, language support services, cultural competence training, mentorship programs to support newly arrived immigrant and refugee students. The approach combines traditional educational methods with practices that are sensitive to the students' sociocultural identities, promoting a more inclusive and supportive school environment (Lundberg, 2020).
Institutional Integration	Establishing research centers that bring together experts from various fields to work on common projects.	The "Catalyzing Clusters of Research Excellence: An Institutional Case Study" highlights an initiative by the University of British Columbia that integrates administrative support, interdisciplinary research

(continued on next page)

Table 4 (*continued*)

Type of KI	Description	Examples
		strategies, and community engagement to enhance the effectiveness of collaborative scientific inquiry. This institutional integration aims to overcome traditional academic boundaries by accommodating both diverse academic insights and practical community needs (Demes et al., 2019).

knowledge integration, organizational structure, type of involvement of actors, collaboration stages, contextual factors, processes and mechanisms, and outcomes of integration — thereby elaborating prior conceptualizations of KI.

Second, the framework elaborates each stage of O'Rourke et al.'s (2016) input-process-output (IPO) model of KI to advance our understanding of what types of knowledge can be integrated, under what conditions, and toward what outcomes. Our framework structures the dimensions of knowledge integration across four interconnected components of collaboration: knowledge gathering (inputs), structural dynamics and collaborative dynamics (processes) and integrative outcomes (outputs). Our framework identifies and organizes different types of knowledge mobilized in cross-disciplinary collaborations – epistemic, experiential, contextual, cultural, and others, and links them to structural features (e.g., team composition, governance) and collaborative dynamics (e.g., stakeholder engagement, interaction frequency, and roles) that influence the processes and outcomes of knowledge integration.

Many theoretical frameworks and empirical case studies that grounded this framework address environmental and sustainability issues. Environmental contexts provide rich settings to understand and appreciate the complexities of knowledge integration, because of the involvement of actors and agencies beyond academia, normative tensions, and epistemic diversity. However, our framework also consolidates an expansive set of international literature from other contexts and settings, such as health research, social sustainability. and community-based action research projects. Therefore, it can be broadly applicable beyond environmental and sustainability domains.

For researchers who study cross-disciplinary collaborations, the framework can generate hypotheses for studying the processes and outcomes of knowledge integration. Researchers can utilize the framework to investigate the types of knowledge assembled in team, study how different types of team structures, and participant dynamics influence integrative outcomes, and investigate what types of inputs and processes are more likely to result in different types of integrative outcomes (Bammer, 2013). Collaborations vary widely based on the problem being addressed, institutional context, team configurations, duration, and funding. Therefore, the framework is intended to be a heuristic to prompt planning, reflection, and adaptation for teams, rather than a prescriptive tool to design and evaluate knowledge integration. Acknowledging the diversity of collaborative contexts, we propose some ways in which practitioners and funders of team science can critically and creatively employ the framework to address their goals. However, further operationalization of this framework is needed in the form of easy-to-apply tools.

First, each component of the elaborated IPO model of KI—Knowledge Gathering, Structural Dynamics, Collaborative Dynamics, and Integrative Outcomes—can guide practitioners in identifying the key factors that influence knowledge integration. For practitioners, such as team leaders, project managers, and stakeholders in interdisciplinary and transdisciplinary settings, the KI framework can provide a blueprint for organizing their collaboration activities. For instance, a small team of academics focused on epistemic integration may choose to focus on assembling epistemic, experiential, and specialized knowledge compared to a large cross-sectoral team, including community and professional stakeholders that may choose to broaden the knowledge they assemble to include applied, cultural, and systems knowledge.

Second, teams may make divergent choices with respect to team composition and configuration, epistemic culture, and governance mechanisms depending on their desired integrative outcomes. For a team focused on epistemic and theoretical integration, for example, a hierarchical structure may be more appropriate than a team focused on social and cultural integration, in which a heterarchical structure may be a better fit. To be sure, these hypotheses would need to be tested in systematic studies of the integrative processes and outcomes of CDCs.

Third, project leaders can use the framework as a tool to outline the intended integrative outcomes at the outset of the collaboration. A leadership team at the initiation stage of a CDC can use the framework to discuss the kinds of knowledge and expertise they will require to achieve the intended integrative outcomes. This could lead to more informed decisions about: (a) selecting team members, identifying the kinds of knowledge and skills the team will need to address a specific problem or achieve a shared goal; (b) leveraging expertise, and designing structural and collaborative mechanisms to strategically utilize diverse knowledge and skills; and (c) defining outcomes, establishing clear goals, outputs, and outcomes.

Fourth, more mature teams can use the framework as a tool for self-reflection, evaluation, and possible course correction. For example, a team can use the framework as an intermediary self-evaluation tool to discuss how various knowledge inputs and collaborative processes have shaped the integrative and intellectual outcomes of their project and make necessary changes to promote different types of KI (Misra et al., 2024).

Finally, the framework can help team leaders, project managers, and stakeholders in interdisciplinary and transdisciplinary settings at any collaboration stage map team knowledge, select appropriate collaboration mechanisms, align KI processes with project objectives, and foster dynamic team structures. It can serve as a tool for anticipating challenges related to structural and collaborative dynamics of collaborations. Practitioners can use it to identify critical points where integration efforts may falter and adjust their strategies accordingly. The framework allows for ongoing monitoring and reflection and the development of adaptive strategies for more successful team outcomes (O'Rourke et al., 2016; Lotrecchiano and Misra, 2018; Misra et al., 2024).

Several limitations should be noted. First, we limited the representative pieces we chose to guide our cited reference search to three pieces, one from each domain (SciTS, knowledge co-production, and studies of interdisciplinarity) and used a subjective expert consultation guided approach to select articles that best addressed our research questions. It is entirely possible that this approach introduced biases and resulted in omissions of literature and perspectives relevant to our questions. For example, we acknowledge that our references are largely Euro- and North American-centric, ignoring a large body of work on inter- and transdisciplinarity published in languages other than English and by scholars in the global majority. Further, despite a 50-year history, the terms inter- and transdisciplinarity have different meanings across different scholarly communities. There are still no universally accepted definitions of these terms or methodology for transdisciplinarity (Lawrence et al., 2022; Lang et al., 2012). While there are overlaps and linkages between bodies of work and similarities between concepts in different scholarly communities, our chosen definitions of inter- and transdisciplinarity, the seed literature we chose to inform our cited reference search, our selective review of the literature and reliance on secondary literature certainly influenced the structuring terminology in the resulting framework. One way this limitation can be addressed is through empirical validation of the framework in diverse contexts.

While the scoping review attempts to synthesize knowledge from three different domains, future research should focus on applying the framework in real-world scenarios to test its applicability.

Second, with respect to the framework itself, the complexity of CDCs can result in varied interpretations of the components and dimensions of KI, which could hinder consistent evaluation of integration outcomes using this framework. Third, the study predominantly focuses on large, formal collaborations involving academic, professional, and local experts. Smaller or informal collaborations may face different collaborative dynamics that are not fully addressed by the proposed framework.

Finally, and more fundamentally, it is important to acknowledge that the majority of the literature on transdisciplinarity and knowledge co-production, including this framework, does not sufficiently address the politics of knowledge co-production. Our framework's focus on cognitive, empirical, social, and institutional integration does not adequately appreciate the political and power dynamics that often play a critical role in CDCs, especially in natural resource management and sustainability issues. For instance, stakeholders can act as obstructors who create barriers to data exchange, leading to frustration among stakeholders (Klenk and Meehan, 2017). Additionally, the dual role of stakeholders as both clients and funders can influence the research agenda and outcomes, potentially shifting the nature of collaboration towards consultancy (Klenk and Meehan, 2017). Scholars in all three domains have documented the significant political, structural, institutional, value-based, interpersonal, and communication barriers to knowledge integration in science-policy and translational science contexts (Stokols, et al., 2008; Klenk and Meehan, 2015; Lotrecchiano and Misra, 2020; Obermeister, 2017).

Some scholars argue that the depoliticization dynamics in knowledge co-production research reinforce unequal power relations and prevent empowerment and societal transformation (Klenk et al., 2025; Turnhout et al., 2020; Klenk et al., 2015). Further the uptake of knowledge co-production is complicated in contexts with deep seated, persistent, and seemingly intractable epistemological differences, structural inequities in access to governance spaces and distrust (Klenk et al., 2025). It is important to challenge the ideal of knowledge integration and co-production and consider other forms of cross-boundary engagement in these contexts, beyond the production of knowledge (Turnhout et al., 2020; Klenk et al., 2015).

Limitations notwithstanding, the framework has the potential to prompt reflection about: (a) incorporating reflexive practices to recognize and address power imbalances; (b) engaging in participatory governance models to distribute authority more equitably; and (c) employing facilitators skilled in conflict resolution to navigate political tensions.

In sum, this conceptual framework for knowledge integration can serve as a guiding frame of reference for academics, practitioners, and funders for planning, designing, and evaluating cross-disciplinary collaborations across problems, settings, and contexts. The framework's applicability to a wide variety of contexts and stages of collaboration are critical strengths. Further, the framework is not meant to be comprehensive but rather an open web that has the potential to evolve with technological advancements and shifting cultural and academic contexts (Adams et al., 2016).

CRediT authorship contribution statement

Shruti Punjabi: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Shalini Misra:** Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Megan A. Rippy:** Writing – review & editing, Funding acquisition. **Stanley B. Grant:** Writing – review & editing, Funding acquisition. **Eranga Galappaththi:** Writing – review & editing. **Theodore Lim:** Writing – review & editing. **Thomas A. Birkland:** Writing – review & editing.

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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Data availability

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

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