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Review

Sustainability and Collaboration: Crossdisciplinary and Cross-Sector Horizons

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Abstract: The title of this article signals increasing collaboration across boundaries aimed at understanding and solving complex scientific and societal problems. The article is a reflective analysis of five intersecting keywords in discussions of sustainability and boundary crossing. This genre of discourse studies interprets language use, drawing in this case on a representative sample of authoritative definitions, case studies, and state-of-the-art accounts. The Introduction situates the discussion around the increasing number and size of teams as well as research across both academic disciplines and other sectors, followed by the five keywords that structure the overall argument. Section 2 examines the first of the five keywords, defining interdisciplinarity by marking its alignment with integration, confluence, interdependence, interaction, and balance. Section 3 considers the second keyword—transdisciplinarity—by tracing evolution of a problem-focused connotation, links to sustainability, inclusion of stakeholders, the imperative of critique, and transdisciplinary action research. Section 4 brings together insights on inter- and trans-disciplinarity in a composite "crossdisciplinary" alignment with collaboration, factoring in the nature of teamwork, public engagement, and translation. Section 5 then turns to learning, noting the difference between education and training then emphasizing transformative capacity, double- and triple-loop learning, reflexivity, and a transdisciplinary orientation. Section 6 takes up the final keyword—knowledge—by calling attention to inclusion, indigenous and local perspectives, nomothetic versus idiographic perspectives, the question of fit, and the nature of crossdisciplinary knowledge. The article concludes by identifying future research needs.

Keywords: interdisciplinarity; transdisciplinarity; collaboration; learning; knowledge

1. Introduction

Two developments frame this exploration of the relationship of sustainability and collaboration: the growing number and size of inter- and trans-disciplinary research teams and the growing focus on cross-sector research. The first development is amply documented in a 2015 state-of-the-art report from the US-based National Research Council (NRC) on *Enhancing the Effectiveness of Team Science.* Increased involvement in teamwork is driven in no small part by the scale and complexity of scientific and societal problems, including challenges to sustainability as well as health and peace [1] (p. 2). The second development is an increase in cross-sector research bridging not only academic disciplines and fields but also occupational professions, government, industry, and communities in the North and Global South. It is documented in accounts of engaging stakeholders and end-users in the actual research process. The overlap of collaboration and cross-sector work in these areas is affirmed in not only a growing literature but also efforts by professional organizations to advance theory and practice of collaborative work.

Three groups in particular stand out. The Integration and Implementation Sciences (i2S) network is part of a global initiative to improve research on a range of complex real-world problems. The

Resources page on the i2S website leads to tools, approaches, and cases, along with information about pertinent journals, conferences, and other professional associations and networks. The site's blog also provides a forum for sharing concepts and methods, training and education, as well as research projects and programs [2]. The Network for Transdisciplinary Research website, in turn, is a tri-lingual international forum for news, updates on conferences and literature, as well as a toolbox featuring methods for solving complex problems, knowledge synthesis and integration, stakeholder engagement, participatory research, team research, disciplinary collaboration, and design [3]. And, the Team Science Toolkit is a user-generated searchable repository leading to key publications, tools, measures, an annotated bibliography, and editors' Best Picks [4]. However, despite the abundance of literature, online resources, and state-of-the-art reports, uncertainty persists about the best way to organize and conduct collaboration. Lack of familiarity with pertinent literature is a major reason, though institutional barriers and disincentives also continue to curb efforts. Beyond these limits, core terms are often used imprecisely as well.

This contribution to the special issue on "Collaboration for Sustainability" addresses the last reason. It brings clarity to uncertainty about core concepts through discourse analysis of five keywords that intersect with sustainability. Discourse analysis is not a typical method in sustainability literature but offers valuable insights by identifying patterns of meaning. It does so by combining humanistic and social scientific understanding of language use in written, oral, and other forms of communication. The locus of study ranges from individual words and sentences to conversations and texts, to patterns of argument in communities of practice and full-fledged fields. This reflective analysis is an example of the latter, unfolding in the following sequence. Each section answers the question of what the keyword means by bringing together defining topics:

- (Section 2) Interdisciplinarity: integration, confluence, interdependence, interactions, and balance
- (Section 3) Transdisciplinarity: problem-oriented connotation, stakeholders, critique, and transdisciplinary action research
- (Section 4) Collaboration: primary group relations, teamwork, public engagement, and translation
- (Section 5) Learning: education versus training, transformation, double and triple loop learning, reflexivity, and transdisciplinary orientation
- (Section 6) Knowledge: inclusion, indigenous and local knowledge, nomothetic and idiographic perspectives, fit, and crossdisciplinary knowledge
- The conclusion identifies future research needs.

2. Sustainability and Interdisciplinarity

The first question is the meaning of "interdisciplinarity" and its connection to sustainability. Authors of a 2005 state-of-the-art report on *Facilitating Interdisciplinary Research* from the US-based National Research Council (NRC) presented a definition that is widely cited: "Interdisciplinary research (IDR) is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice" [5] (p. 2). This definition captures the centrality of integration, affirmed in authoritative accounts and handbooks. Klein and Newell, for instance, called integration the "acid test" of interdisciplinarity [6], and Pohl, van Kerkhoff, Hadorn, and Bammer called it "the core methodology underpinning the transdisciplinary research process" [7]. In citing sustainability as an example, the NRC report traced emergence of a dedicated science to the environmental movement during the 1960s and 1970s. Academic and general interest expanded as awareness of related problems mounted in scope and magnitude. The report only briefly addressed the relationship of sustainability and interdisciplinarity, however, while highlighting the linkage of physical and social sciences with engineering.

Other sources, though, provide a fuller definition by scholars active in the field. When William C. Clark described the relationship in 2007, for example, he called sustainability science an "emerging interdisciplinary frontier" and a "use-inspired field." He also affirmed integration as the benchmark of interdisciplinarity, describing four integrative dimensions of sustainability:

- intersections of environmental conservation, human health, and economic development;
- intersections of natural, social, and engineering sciences, as well as insights from humanities and medical sciences;
- multiple sectors of human activity;
- knowledge and action, bridging fundamental and applied work.

Acknowledging the field's cross-sector character, Clark further noted integration spans not only disciplines but also expertise in public and private sectors [8]. Clark's focus on intersections, multiple domains, and bridging of knowledge and action captures the complexity of sustainability research from inside the field.

Fernandes and Philippi Jr.'s account in the 2017 *Oxford Handbook of Interdisciplinarity,* though, is a more detailed examination of the link between sustainability and the first keyword. Calling the field "naturally interdisciplinary," they highlighted the "confluence" of environmental concerns and an international political movement that generated sustainability-themed scientific analyses. "Interdependence" between and "interactions" of society and nature occur on both local and global scales [9]. Drawing on I. Sachs's definition, they also suggested sustainability can be expressed as a "balance" of environmental, social, and economic factors [10]. This widely cited triangulation implies a new integrated whole. However, when the authors examined patterns of language use their findings indicated otherwise. They built on Kajikawa et al.'s analysis of publications from 1990 forward using the terms "sustainability" or "sustainable," culled from the Thompson Reuters and the Web of Science databases. Kajikawa et al.'s results revealed the large scope of the field [11]. However, Fernandes and Phillipi's repeat of the search in 2016 comparing uses of "sustainability" and "sustainability science" in articles from the Scopus and the Web of Science databases found more disciplines treat sustainability as an object of research than a separate field. Of publications using "sustainability or sustainable," 50% was spread across several disciplines while the remaining 50% was distributed among environmental, engineering, social, agricultural, and biological sciences. Searching "sustainability science" further revealed environmental and social sciences dominate, at over 60%. In contrast, fewer interests appeared in engineering, agricultural, and biological sciences when using the search words "sustainability" or "sustainable."

Fernandes and Philippi concluded the greater frequency of "sustainability" indicates an emerging interdisciplinary field subject to several sciences rather than a single discipline, though another study questioned how interdisciplinary sustainability science actually is. Based on citation analysis of articles published between 1996 and 2009 using the search term "sustainability," Schoolman, Guest, Bush, and Bell concluded the field falls short of balance in the ideal model of integrated environmental, economic, and social sciences [12]. Their data revealed sustainability research is more interdisciplinary than scientific research in general, based on comparison with a random sample of articles during the same period in relevant categories of natural, economic, and social sciences within Scopus. Here too, though, variances appeared. The smallest number of articles on sustainability were in economics, though it had the largest proportional increase and the authors deemed it the most interdisciplinary pillar of the tri-part model. Environmental sciences exhibited a greater number of articles but drew the least on external disciplines. Moreover, research is centered around a relatively small number of interdisciplinary journals. Nearly 70% of sustainability articles in economics and 68% in social science sciences were from journals cross-listed with at least one other pillar, compared to only 34% in environmental sciences. Two implications follow from reflection on definition and tracking patterns of language use in this section.

The first is the challenge of bridging separate discourses. "Interdisciplinarity" is a term of increasing reference in literature on sustainability and "sustainability" is looming larger in counterpart literature on the first keyword. However, the NRC definition is a truncated and selective alignment with a particular segment of sustainability research. Clark's definition was more expansive, identifying three relevant features of working across boundaries in intersections, multiple sectors, and bridging of basic and applied work. Fernandes and Philippi, though, were steeped in both literatures so could identify a cluster of terms that sharpen definition. The second implication is the difference between invoking a term at an abstract level and deploying it in particular projects, programs, and fields. Along with Schoolman, Guest, Bush, and Bell, Fernandes and Philippi gleaned insights from tracking use of core terms. Their findings counter two superficial generalizations; that interdisciplinarity creates a new unified whole and that a successful field becomes just another discipline. Neither is true. Individuals and groups affiliate with particular interests, expanding global awareness and legitimacy of concepts such as interdisciplinarity and sustainability. Yet, communities of practice construct research and education differently. Their trajectories and outcomes vary as well. Representation does not end here, either. The recent ascendancy of transdisciplinarity is a major development in the history of the keyword interdisciplinarity, raising the question of what that term means and its relationship to sustainability.

3. Sustainability and Transdisciplinarity

Fernandes and Philippi contended sustainability is both "interdisciplinary" and "transdisciplinary." They associated interdisciplinarity with bridging existing disciplines and a more growing alignment of transdisciplinarity with interactions across sectors of society and action for change [9]. The concept of transdisciplinarity (TD) is dated conventionally to the first international conference on interdisciplinary research and teaching in universities, held in 1970. The definition was "a common system of axioms for a set of disciplines" transcending the narrow scope of disciplinary worldviews through an overarching synthesis, exemplified by anthropology as a science of humans [13] (p. 26). Differences appeared, though, in participants' glosses of meaning. Jean Piaget called TD a superior stage in the epistemology of interdisciplinary relationships, based on the prospect of reciprocal assimilations in a general theory of systems or structures. In contrast, Andre Lichnerowicz advocated "The Mathematic" as a universal interlanguage, while Erich Jantsch proposed a hierarchical model of science, education, and innovation grounded imbued with social purpose [14]. Since then the term has proliferated. It now appears in conjunction with the broad scope of synoptic fields, interprofessional collaboration in healthcare, a new universality of thought informed by the worldview of complexity in science, and overarching paradigms such as general systems, feminist theory, post/structuralism, cultural critique, and sustainability.

The last example became more closely aligned with transdisciplinarity during the late 1980s and early 1990s in contexts of environmental research within German-speaking countries of Europe. The dual premise of the new connotation is that real-world problems in the lifeworld (*Lebenswelt)* ought to drive research, not disciplines, and that stakeholders in society should be involved in the research process [15]. One of the earliest mentions of TD in conjunction with sustainability, Scholz et al. recalled, occurred in environmental education in 1973 [16]. During the 1970s it also appeared in literature on co-management and decentralization in managing renewable resources and environments, though Jahn, Bergmann, and Keil called an international conference on the concept in 2000 a "normative turn" regarding real-world problems such as sustainable development [17] (p. 2). Case studies were reported in all fields of human interaction with natural systems, technical development, and areas where social, technical, and economic interests interact with value, politics, and culture. And, by 2008, the *Handbook of Transdisciplinary Research* documented spread of the discourse of transdisciplinary problem-oriented research to Africa, Latin America, and Australia. Sustainability loomed large in the *Handbook* and the themes of the book spanned participation, values and uncertainties, learning, project management, education, and integration [18].

Since the *Handbook* appeared, alignment of sustainability and transdisciplinarity has become more pronounced and also intersects with other approaches. Malin Mobjörk's 2009 literature review called attention to a multi-faceted and problem-based focus, participatory approaches, and interest in action, values, and normative judgments [19]. Wuesler and Pohl also cited open boundary work, knowledge systems, integrative research, transdisciplinary research, and transformative sustainability science [20]. Furthermore, imperatives of instrumental problem solving and critique of the existing system of knowledge and education merge in calls for science to be more accountable to challenges of sustainability. This goal, Merritt Polk exhorted, cannot be met within standard parameters. It must become subversive of science in three ways: practically, by disrupting established processes; epistemologically, by challenging conventional criteria of reliability and rigor; and contextually, by forging a neutral space between science and practice [21]. Toward that end, Bergmann and Jahn have called for a form of "Critical Transdisciplinarity" that bridges pragmatics and theory, though tensions persist between academic modes of research and societal demands for applicable knowledge. [22]. At the same time, interdisciplinary integrations of existing disciplines still occur. Knapp, Reid, Fernández-Gimenéz, Klein, and Galvin suggested transdisciplinarity (TD) exhibits both an "innate interdisciplinarity", arising from questions that require multiple disciplinary inputs, and collaboration for action, which includes a wider range of stakeholders beyond the academy [23].

Ascendancy of problem-oriented TD has also heightened the case for transdisciplinary action research. This approach, Daniel Stokols explained in his recent book on Social Ecology, advances a multi-level, system-oriented approach to complex environmental, health, and social problems. It investigates how surroundings influence behavior and well-being in human transactions with natural, built, social, and virtual surroundings. Transdisciplinary action research is not value-neutral. It is guided by normative judgments about impacts of action research and integrates concepts and methods from different disciplines while transcending them. Stokols defined three modes of collaboration that affirm intersections identified in this article. They are interdisciplinary, interprofessional, and cross-sector. They occur among scholars of different disciplines, researchers from multiple fields, community practitioners representing different professional and lay perspectives, and among community organizations across local, state, national, and international levels. Contexts, he added, also differ. Some forms of collaboration prioritize scientific discovery, while others translate scientific findings into new interventions aimed at reducing societal problems, while others integrate expertise of disciplines and professions in a community-wide effort to design and implement policies for improving environmental, social, and public health outcomes [24]. The ascendancy of transdisciplinarity further illustrates the importance of reflecting on language use from a historical perspective.

To wit: the organizing languages of the ground-breaking 1970 seminar on interdisciplinarity were logic, cybernetics, structuralism, general systems, and organizational and information theories. Today the typical warrants are complexity, transdisciplinarity, convergence, contextualization, innovation, socially robust knowledge, and critique [25]. Some scholars also cite E.O. Wilson's concept of consilience, though it is an imperialistic reading of history and culture through the narrow lens of biological determinism. The problem-oriented connotation of transdisciplinarity also benchmarks ascendancy of problem solving over unity of knowledge as the goal of crossdisciplinary work. Moreover, when a wider range of expertise is recognized, a shift occurs from solely reliable scientific knowledge to include Gibbons et al.'s concept of "socially robust knowledge" [26] (pp. 78–80). Roland Scholz has argued that socially robust knowledge responsive to the needs of stakeholders and end-users involves a form of epistemics that bridges scientific and experiential knowledge. Reflecting on the future of interdisciplinarity, Machiel Keestra called for greater commitment to a socially-robust connotation of transdisciplinarity that still requires metacognition and reflection in order to grapple with differing worldviews with their attendant norms and values. Involvement of stakeholders outside the academy also moves beyond defining interdisciplinarity solely in juxtaposition to disciplinarity, prioritizing action research guided by a democratic imperative [27].

4. Sustainability and CrossDisciplinary and Cross-Sector Collaboration

The meaning of collaboration might seem on the surface to be an easy question to answer. However, it assumes many forms. Teams vary in size, composition, mission, and context. Studies of crossdisciplinary and cross-sector collaboration, though, highlight a crucial shift from individual to group identity. In an early study of interdisciplinary teams Anthony Stone reported young teams exhibit secondary-group relations. Individuals are self-protective, thinking in terms of "I". In contrast, individuals in primary-group relations think in terms of "we" [28]. Freeth, Clarke, and Fam warned, however, against a strictly linear progression from "I" to "we." Tensions recur, illustrated by a transdisciplinary sustainability project at a German university. The heterogeneity of the research team increased as it moved from eight principal investigators to 23 participants, including partners outside the academy. Heterogeneity adds more approaches and resources. Yet, it is often accompanied by increased differences. At an initial retreat, participants became aware of conflicting priorities of PhD students' research proposals and the overall transdisciplinary agenda of the project. This tension was resolved by letting students prioritize their individual agendas, foregoing participation in selecting case studies and integrating work packages of the project. Yet, other tensions subsequently surfaced. At a second retreat a year later, differing connotations of integration were evident, and at a third retreat tensions resurfaced around boundary objects, including significant concepts such as transformation, systems thinking, and collective and transdisciplinary research practices [29].

Inclusion of stakeholders in the research process has heightened interest in public engagement, though it presents added complications for collaboration. Public engagement, Tebes and Thai reported, goes by many names, including participatory action research, citizen science, patient and public involvement, stakeholder engagement, community-engaged or community-based participatory research, and participatory team science [30]. Citing participatory rural appraisal as an example, Knapp, Reid, Fernández-Gimenéz, Klein, and Galvin emphasized its cross-sector nature, involving stakeholders in all phases of research from design to implementation and interpretation [23]. Yet, the process is fraught with challenges. Tebes and Thai cautioned that involving stakeholders at all stages is typically unrealistic, cost prohibitive, and unsustainable [27]. Russell, Wickson, and Carew further warned against idealizing the agora. It is a heterogeneous and complex space with its own imbalances of power [31]. And, Wuesler and Pohl's study of 10 Swiss-based land-use projects documented continuing dominance of academic science. The ideal model of transdisciplinarity holds that research should start from societal actors' problem perceptions and knowledge needs. Yet, they found the crucial framing stage of projects was influenced more by scientific considerations, including existing infrastructure, previous research, funding opportunities, and the academic reward system. As a result, perspectives and needs of societal actors had only indirect influence on defining research questions [20].

Even with challenges, however, a growing body of case studies record successful outcomes. Quick and Feldman's study of public problems at a mid-sized US city further illustrates the role language plays in shaping how problems are perceived and handled, in this instance grappling with challenges in the built environment. Urban planning often uses specialized language and performance measurements that are reinforced in academic professional education. In contrast, neighborhood expertise reflects residents' knowledge of and feelings about the spaces they occupy. In this particular case, stakeholders agreed in advance to introduce nonresidential uses or increase housing units in some areas. Yet, zoning guidelines on density needed updating. Collaboration across professional and community expertise began at an open meeting in which residents proposed replacing the standardized definition with a combination of control measures customized for different areas. Despite the complexity of the code they ultimately adopted, the planning director was willing to use her expertise in zoning law and implementation to draft new language because she had community support. Setting aside strictures of specialized language facilitated discovering options and co-producing a novel zoning system with tools each neighborhood could use to reassemble practices and resources for a sustainable future [32].

Boundaries also became junctures for action. Quick and Feldman identified three related boundary work practices. The first was translating across differences through language or other means of expression. The second was aligning differences to find ways of enhancing connections and resources, and the third was decentering a dominant idea or changing its meaning [29]. This case and others have particular implications for the first practice—translation. The 2015 state-of-the-art report on *Enhancing the Effectiveness of Team Science* aligned the concept of translation with "application" and "transfer" of scientific knowledge to professional practice [1]. Widespread as the two descriptors are, however, they ignore a large body of expert literature in humanities and translation studies on the complex material, textual, and cultural dimensions of translation. It is not a rote transmission from one context to another. Translation is a dynamic process that requires understanding the context into which academic expertise is being directed. Implementation scientists also conceive of Knowledge Translation (KT) as a dynamic process entailing exchange and synthesis. Although McWilliam et al. retained the term "application", they recognized that KT entails social interactions involving participation and contextualization [33]. In yet another example of public engagement, Knapp, Reid, Fernández-Gimenéz, Klein, and Galvin cited the practice of translational ecology. It focuses on bringing ecological scientists and stakeholders together in a cumulative effort involving collaboration, engagement, co-production, mutual learning, and communication, as well as integrative process and decision-framing [23].

Once again, reflection on language use in this section reinforces the importance of bridging literatures that invoke the same keywords. Insights derive from scholarship on teamwork in academic and public sectors with a range of purposes, from needs of the marketplace and national defense to needs of local communities. Introducing the updated edition of *The Oxford Handbook of Interdisciplinarity*, Robert Frodeman reported the first keyword in this article is most often used as a portmanteau word for all approaches to more-than-disciplinary approaches to knowledge [34]. The most common means of sorting differences is a taxonomy of terms. Harry Graff faulted the "name game", however, for generating more confusion than clarity: charging "The endless typologies, classifications, and hierarchies of multi-, inter-, and trans-disciplinarities are not helpful." [35]. A more rigorous study of terminology, though, suggested "diversity does not have to be an adversity." The occasion was an INTREPID workshop involving researchers, practitioners, and policy makers from 27 countries. Participants identified sub-terms "cooperation," "trust," and "integration" across the core terms. Interdisciplinarity, though, was linked primarily with connectedness and combination, while transdisciplinarity was associated with normative dimensions and change consistent with the ascendancy of transdisciplinarity traced here. The authors still cautioned, though, any general definition is complicated by involvement of actors outside the academy, requiring finer-grained understanding of how collaboration occurs across sector boundaries as well as disciplines [36].

5. Learning

The final two keywords answer the question of how members of teams learn to collaborate and what form of knowledge it entails. Clark et al. contended managing sustainability issues requires researchers to shift from knowing to learning [37]. Formats differ, however. The NRC report on team science distinguished "education" in the formal curriculum from "training" or "professional development" that typically occurs outside the classroom and may range from an hour-long presentation to a full-scale intervention aimed at improving a team's performance [1]. This distinction is not air-tight, though. Increasing interest in teamwork has resulted in adding training units to the traditional curriculum, including workshops, short courses, online modules, and summer residencies. Pedagogies differ as well, from formal didactics to research and project-based learning. Regardless of context, models of crossdisciplinary and cross-sector collaboration are typically based on progression through stages that appear across contexts.

Akkerman and Bakker identified four mechanisms of learning across boundaries that develop over time:

- <u>Identification</u> is a dialogical process of revealing differences that factor in both constructing and reconstructing boundaries.

- Reflection entails meaning-oriented learning processes that render participants' perspectives, practices, and identities visible.
- Coordination enables cooperation.
- Transformation leads to more significant changes, even the possibility of a new "boundary practice" [38].

Identification and Reflection are essential beginning steps that start with articulating individuals' perspectives then reflecting on what participants have learned from listening to them. Coordination of information and communication is key to taking the next step, cooperating on a common purpose even while continuing to negotiate differences in perspectives.

Here, too, terminology matters. The words "cooperative" and "collaborative" learning, for example, are sometimes used synonymously. However, Michael J. Baker highlighted a crucial distinction. Cooperative learning typically entails divisions of labor with each participant being responsible for part of a common goal. In contrast, collaboration is a synchronous activity that results from co-constructing a shared conception of a problem [39]. Cooperation helps facilitate collaboration, but collaboration presumes a high degree of joint attention, communication, and interaction. It also highlights the importance of mutual learning, which Golja, McClean, and Jordan deemed the basic principle of transdisciplinarity. Its centrality, they added, is reinforced in discussions of not only collaboration but also collective learning, co-production of knowledge, and transformation [40]. The latter concept—transformation—further requires critical reflection on the underlying assumptions in the mode of double- and triple-loop learning. In their classic definition, Argyris and Schön associated single-loop learning with assessing performance against established rules or standards. In double-loop learning, they are questioned. Argyris and Schön did not mention triple-loop learning explicitly. However, this extended concept connotes a higher or deeper level of learning that occurs when processes or methodologies generate new principles or paradigms (after Tosey, Visser, and Saunders, 2011 [41,42].

Much of the literature on interdisciplinary learning, and for that matter learning in general, has tended to focus on individuals. However, Decuyper, Dochy, and Van den Bosschec maintained their relationship is dialectical [43]. Likewise, Volet, Vaurus, and Salonen cautioned against reducing analysis to either level. Even in teamwork, individuals still need to develop Rebecca Freeth's notion of a personal "collaborative capacity" [44]. Based on studies of interdisciplinary research teams, Thompson placed "collective communication competence" at the heart of interdisciplinary collaboration [45]. It does not derive from rote learning or a pre-set formula. In a primer of methods for transdisciplinary integration, Bergmann et al. cautioned even if teams adopt formal languages as the basis for communicating across boundaries, including well known ones such as general systems theory, they must be adapted to particular contexts and configurations of disciplines and stakeholders [46,47]. Introducing a book on transdisciplinarity and sustainability studies, Katri Huutoniemi also acknowledged existing tools and methods can generate new ideas, including scenario building, expert deliberation, "what-if" modeling, and the Delphi technique of controlled iterations. Yet, even tested tools and methods must be adapted for any particular team, the problem they are addressing, and parameters of context. Heuristic approaches also build on experience-based intuition and learning-by doing, opening up alternatives and divergent thinking [48].

Given contingencies of practice, how then do members of a team communicate across boundaries? Interdisciplinary discussions, Gerhard Frey explained in an early study, normally take place on a level similar to a popular scientific presentation. They become more precise as individuals combine everyday and specialist languages [49]. Britt Holbrook [50] and J. T. Klein [51] also likened interdisciplinary communication to pidgin and creole languages. Bilingualism is a popular metaphor of interdisciplinary communication. However, mastery of two disciplinary languages rarely occurs. In linguistics a "pidgin" is an interim tongue between groups with different primary languages, while "creole" is a new first language that members of a community of practice learn. In a study of patterns of talk in project meetings, Choi and Richards identified three stages of communication. At Stage 1 disciplines dominate.

Individuals advance territorial claims by displaying, deploying, and directing their knowledge; making connections; and clarifying terminology. At later stages, aligning perspectives facilitates building collaborative knowledge and co-construction through affiliative talk. Stage 2 involves coordinated coexistence of disciplines, and Stage 3 fully integrated and adaptive teamwork [52]. Taken together, Akkerman and Bakker's scheme of four mechanisms and Choi and Richards' three stages underscore the sequential nature of learning in collaboration and importance of listening to others in the process. A final question, though, follows. Whose knowledge counts in collaborations?

6. Knowledge

Sustainability is a powerful locus for answering a question about the nature of crossdisciplinary and cross-sector knowledge because collaborative work in this area spans expertise in sciences, social sciences, humanities, and occupational professions. In their account of *The Oxford Handbook of Interdisciplinarity*, Fernandes and Phillippi (2017) recalled sustainability studies developed as a social paradigm and a field of knowledge involving diverse areas of science related to social, political, and economic problems of management [9]. Alignment with transdisciplinary cross-sector work has further heightened awareness of knowledge beyond the academy, in urban and rural communities and in the West/North and the Global South. Design and retrofitting of the built environment for sustainability is a case in point. Conceived as transdisciplinarity, Doucet and Janssens explained when introducing a book on architecture and urban planning, theory and learning are contextualized and once excluded forms of knowledge such as the understandings lay people have of their communities are placed inside of professional practice, not outside of it. Moreover, questions of design are not separate from social, political, and normative concerns [53]. Tony Fry described transdisciplinarity as a form of relational thinking that not only dissolves disciplinary differences. It constitutes a conceptual leap in a form of "redirective practice", creating new ways of dealing with complexity. "Problems are never received", he asserted, "but always interrogated and redefined." Quantitative and qualitative approaches are brought into dialogue as well [54].

On a more global scale one of the purposes of transdisciplinarity, Upendra Baxi admonished, is renouncing the logic of instrumental reason by creating a more democratic discourse of inclusion. The concept expanded, he recounted, at a time of wider crisis in human rights accountability amid demands for new modes of knowledge, discourse, and institutional frameworks across all sectors of academic, private, and public life. Achieving sustainability, then, requires bridging gaps between not only different forms of academic and professional knowledge but also Western and non-Western traditions, esoteric and organic knowledges, colonial and indigenous traditions, and official and people's knowledges [55]. Mindful of the gaps, Knapp, Reid, Fernández-Gimenéz, Klein, and Galvin included Indigenous and Local Knowledge in a roster of collaborative approaches aligned with transdisciplinarity and sustainability. It is multidimensional, encompassing traditional knowledge (passed across generations), empirical expertise (based on observation and practice), revealed wisdom (encoded in vision, ritual, and ceremony), and contemporary perspectives (developed from experience, education, and problem solving). It also bridges Western science and traditional ecological knowledge while valuing stakeholder embeddedness in the research process [23].

In making a case for decolonizing transdisciplinary research, Bagele Chilisa explained that methodologies rooted in Africa, for instance, draw on philosophies, worldviews, and history that offer alternative ways of conducting research. Ethno-philosophy, for example, can explain how myth, ritual, language, proverbs, metaphors, folklore, stories, songs, artifacts, and art inform epistemological assumptions and can guide theoretical or methodological frameworks. Indigenous methodologies also bridge divides between producers and users of knowledge, while maximizing connections, participation, and relational modes of thinking and acting [56]. Yet, limits persist. Reflecting on projects in Australia, Michael Davis asked whether efforts to incorporate both indigenous knowledge and the language of official law and policy are bridging a gap or crossing a bridge. Western intellectual traditions are often privileged as rational, rigorous, and technical, while local, traditional, and indigenous traditions and discourses are judged as intuitive and informal [57].

Clark et al. illustrated the challenge of inclusion more specifically in the context of natural resource management programs affiliated with the Consultative Group on International Agricultural Research. The group is a large network of global research organizations dedicated to sustainability in the developing world. Comparative analysis of experience in multiple countries revealed tensions between communities with different views of what constitutes reliable or useful knowledge. A gap also appears between global research programs with agendas driven by international networks and local knowledge and needs. Universal hypotheses and general conclusions generated in Europe and North America come into conflict with both local and regional contingencies [37]. More broadly, Wolfgang Krohn contended the relationship of the nomothetic and the idiographic is nothing less than the epistemological challenge of interdisciplinarity. Case studies contribute to stocks of knowledge, even though their epistemic structure differs from knowledge condensed into general theories or paradigms. A new mode of knowledge is required, one that bridges a humanistic understanding of the particularities of cases and a scientific search for common features in abstract law-like principles [58]. The ascendancy of transdisciplinarity and its alignment with sustainability have also generated new theories of knowledge production. Mode 2 theory is a major example.

The defining traits of Mode 2, Gibbons et al. proposed in 1994 are complexity, non-linearity, heterogeneity, and transdisciplinarity. They initially highlighted instrumental contexts of application and use, such as aircraft design, pharmaceutics, electronics, and other areas of product development. Yet, responding to criticism the theory elevates normative goals of application and innovation, Gibbons and Nowotny extended Mode 2 to argue that contextualization of problems requires participation in the agora of public debate, including scientifically reliable knowledge but also fostering socially robust knowledge [26] (pp. 78–80). The question of where the latter fits within traditional modes of research, however, returns discussion full circle to the emergence of environmental studies in the longer history of sustainability. When asked where interdisciplinarity fits, Lynton Caldwell argued the metaphor of fit prejudges the epistemological problem at stake in the emergence of environmental studies. Many fields arose because of a perceived misfit of needs, experience, information, and the structure of knowledge and curriculum in disciplinary organization. If the structure must be changed to accommodate a new development, he admonished, perhaps the structure itself is part of the problem [59]. The test of empirical fit, Hukkinen and Huutoniemi, further reported, continues to apply to scientific theories, in a form of technical rationality that measures the extent to which their description of a sustainability phenomenon matches its observed reality. In contrast, cognitive fit measures the extent to which a theory's description of sustainability matches the observers' reality [60].

7. Conclusion—Toward The Future

The composite of definitions, key meanings, and examples in this article underscores the sizable body of literature and online sources on crossdisciplinary and cross-sector collaboration, including growing links with sustainability. State-of-the art reports also contain detailed recommendations based on tested strategies and best practices spanning categories of organizational structure and administration, procedures and policies, funding, resources and infrastructure, and the reward system. However, more research on collaboration is still needed. The most explicit focus on related needs in the 2015 NRC report on team science is virtual collaboration among geographically dispersed researchers, including how to overcome limits to teamwork when not working face-to-face and differences in organizational and national cultures, as well as choice of appropriate technologies and users' capabilities. Other needs are also identified though in the overall report, with particular emphasis on team processes. In addition, a number of other reports on crossdisciplinary and cross-sector work add to the roster of needs, with key examples listed in Table 1.

Table 1. Key Reports.

• European Union Research Advisory Board [EURAB]. (2004). *Interdisciplinarity in Research*. April. eurab–04–009–interdisciplinarity–research–final.pdf
• National Research Council. (2005) *Facilitating Interdisciplinary Research*. Washington, D.C. National Academies of Science. https://www.nap.edu/catalog/11153/facilitating-interdisciplinary-research
• Bammer, G. (2012). *Strengthening Interdisciplinary Research: What It Is, What It Does, How It Does It, and How It Is Supported*. Report for the Australian Council of Learned Societies. <www.acola.org.au>
• National Research Council (2014). *Convergence: Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond*. Washington, D.C. National Academies Press. https://www.nap.edu/catalog/18722/convergence-facilitating-transdisciplinary-integration-of-life-sciences-physical-sciences-engineering
• Hilton, M. and Cooke, N., eds. (2015). *Enhancing the Effectiveness of Team Science*. Washington, D.C.: National Academies of Science. https://www.nap.edu/catalog/19007/enhancing-the-effectiveness-of-team-science
• British Academy (2016). *Crossing Paths: Interdisciplinary Institutes, Careers, Education, and Applications*. https://www.thebritishacademy.ac.uk/interdisciplinarity).
• Global Research Council. (2016). *Interdisciplinarity: Survey Report for the Global Research Council 2016. Annual Meeting*. https://www.globalresearchcouncil.org/fileadmin/documents/GRC_Publications/Interdisciplinarity_Report_for_GRC_DJS_Research.pdf

In the aggregate, insights from these reports coupled with the larger literature indicate the need more research on the nature of collaboration in the following areas:

Diversity: Impact of gender, cultural context, problem contexts, levels of analysis, and mix of disciplines; differences in work based in sciences, social sciences, humanities and arts, occupational professions, and communities.

Institutional structures: Effectiveness of particular formats from programs and centers to campus-wide initiatives, challenges of small vs. large institutions, multi-institution and multi-country programs, and relationships of spatial dynamics to team performance.

Leadership: Appropriateness of particular models, such as distributed vs. top-down leadership, most effective strategies for different phases of research and different clusters of expertise, and balance of disciplinary expertise with knowledge of integration and collaboration.

Education, training, **and** professional development: Effectiveness of particular formats ranging from units and modules to full-sale curricula, appropriate pedagogies and interventions, alternatives to traditional learning activities, and outcomes within and beyond classrooms.

Research: Strategies to heighten understanding of the dynamics of teamwork, suitability of particular approaches and tools for particular problems, effective strategies for managing data and communication on teams, and integrated engagement of stakeholders.

Evaluation: Appropriate criteria rather than defaulting to discipline-based and proxy measures, assessment of integrative and collaborative process rather than product outcomes alone, and a combination of qualitative indicators rather than sole reliance on measures and metrics.

Funding: Impact of mechanisms in "regular" programs vs. targeted initiatives, extent of crossdisciplinary and cross-sector work already occurring in "regular" programs, and more explicit and appropriate criteria calls for proposals and review panels.

Outreach: Venues for publications and presentations with data on the size of their audiences, networked relationships across domains and organizations, outcomes beyond traditional academic products, and data on longitudinal impact.

Five overarching needs cut across details in this article. The first is better data on the effectiveness and the impact of particular structures and strategies, moving past generalizations to finer-grained understanding of what particular configurations of expertise require and entail. The second is more informed awareness among all team members and leaders of collaborative process, including both objective and subjective dimensions. The third follows from the second, in more informed understanding of how to move past disciplinary isolation and multidisciplinary juxtapositions of separate perspectives to proactive integration and co-production of knowledge. The fourth is a more comprehensive picture of where collaboration and boundary crossing are occurring, accounting for not only named programs and initiatives but also increases of collaborative, crossdisciplinary, and cross-sector work across traditional domains of research, curriculum, and funding. The fifth is rewarding, rather than minimizing and even ignoring collaborative work. Talk of preparing the "next generation" of researchers rings hollow when students and early-career faculty are discouraged from engaging in both teamwork and crossdisciplinary work, as well as "applied" research and problem solving outside the academy. On the longer timescale, career portfolios change over time, so tracking new interests is a crucial part of data gathering. To reiterate, familiarity with the existing body of knowledge and experience is mandatory for informed practices. However, research is still needed to understand the complexities of collaboration within and across contexts.

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