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Competencies for Graduate Student Training in Transdisciplinary FEWS Research

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abstract

Transdisciplinarity is gaining traction as a research approach for developing impactful solutions by bringing together diverse sources of technical and local expertise. Many of the skills and knowledge for conducting transdisciplinary research are not currently emphasized in conventional graduate education. The objective of this paper is to present a literature-supported organization of competencies that contribute to transdisciplinary graduate education. An extensive literature review of more than 160 papers was undertaken to identify competencies needed for transdisciplinary research teams. The competencies are focused on students and early career academic professionals and especially those entering careers in FEWS fields and those teaching or mentoring these groups. The review identified competencies related to six domain areas, oriented around the individual, relationships and connections, team, process, outputs and outcomes, and growth. As academic institutions continue to recognize the role of transdisciplinary research in addressing complex societal issues, graduate education programs will have to incorporate transdisciplinary competencies into the curriculum. We offer the competencies identified by the INFEWS-ER project as a contribution to this ongoing conversation about the development of transdisciplinary professionals.

introduction

To address complex societal issues, challenges or “big ideas” [1], problem solvers need to draw upon diverse knowledge systems that represent multiple disciplines as well as experiential, cultural or contextual knowledge held by non-academics and practitioners. Cross-disciplinary and problem-focused approaches such as transdisciplinary research can be effective in bringing about impactful changes [2]. As a growing societal need, there is increasing emphasis on preparing graduate students for transdisciplinary work. Although skill sets associated with specific disciplines are often reviewed through accreditation, there are few accreditation programs for graduate education relative to undergraduate degrees. In addition, how do you evaluate transdisciplinary work that evolves based on the problem context or solution, and lacks disciplinary bounds? Literature documents case studies and lessons learned from transdisciplinary research projects, but there are few frameworks for transdisciplinary competencies in graduate education. One example from Lotrecchiano et al. [3] outlines competencies for translational collaborative efforts in human health research.

The Innovations at the Nexus of Food Energy and Water Systems - Educational Resources (INFEWS-ER) is an NSF-sponsored educational program dedicated to providing training to graduate students in the skills they need to participate effectively on transdisciplinary teams designing solutions to grand challenges. The INFEWS-ER concept and structure are highlighted in other papers [4] [5]. Since the INFEWS-ER was first proposed in 2016 with an initial list of competencies curated from the experiences of project team members and literature, there was a recognized need to formalize the skills used and competencies developed in order to provide structure and support translation beyond INFEWS-ER. The initial list of competencies was refined and expanded using a comprehensive literature review and project assessment and reflection. The review and assessment/reflection activities occurred concurrently resulting in iterative adjustments to one another throughout the project. The objective of this paper is to present a literature-supported framework of competencies that contribute to transdisciplinarity and graduate education. Additional application of these competencies in educational curriculum and reflection is presented in [5].

Methods

The comprehensive literature review was initiated with articles on transdisciplinary projects already known to the authors and with searches on Google Scholar and Scopus for "transdisciplinary competencies," "transdisciplinary graduate education," "transdisciplinary skills," and "transdisciplinary research". No date range was specified. Peer reviewed articles were the preferred sources, but web articles or conference presentations from authoritative sources were included when relevant information in those supplemented the observations made from peer reviewed articles. Articles that focused on FEWS-related fields such as natural resources management, global sustainability, and socio-ecological systems were prioritized for review. Articles about transdisciplinary public health research that were either cited or returned frequently in search results were added to the initial review.

The literature review identified three main types of articles, broadly grouped as:

1. Theoretical/conceptual frameworks. The selected items represent work from authors that present their suggested competencies for conducting transdisciplinary research based on literature and their own experience [6] [7] [8] [9] [10].
2. Retrospectives or "lessons learned." The papers in this section resulted from large, complex projects that self-identified as transdisciplinary and summarized what was learned in these projects through successful efforts to conduct transdisciplinary research [11] [12] [13] [14].

3. Survey or case study. The papers in this classification contained survey data or constructed a case study in addition to theoretical or retrospective observations [15] [16] [17] [18]. Ideally, the review would include literature with comparative or controlled experimental data, but the authors were unable to identify articles with those characteristics.

A framework evolved with domains, defined as "containers that organize competencies and their underlying objectives" [19], and sub-domains. After the initial framework was created, additional literature focusing on a specific domain, subdomain or competency was identified through cited works and search phrases such as "transdisciplinary communication," "transdisciplinary leadership," etc. Efforts were made to identify literature that discussed a specific skill, knowledge or domain relative to transdisciplinary research or to identify how a skill/knowledge would be applied differently in a transdisciplinary setting compared with a traditional research setting.

The competencies underwent iterative editing and updating as surveys or reflection activities from the INFEWS-ER project warranted, and as new literature emerged. Surveys and reflection activities were conducted prior to, during, and after INFEWS-ER activities. These provided insights into the previous experience and comfort level of participants when it came to transdisciplinary competencies as well as the competencies that were most instrumental for successful team formation and functioning. An internal bias in this approach is recognized. Yet, it could be argued that a continuous review of the growing body of literature will minimize bias.

Results

During the review, patterns related to the competencies emerged in that they were often framed in terms of the individual, relationships and connections, teamwork, process, outcomes, and growth. These groupings were designated as the domains (Table 1). Subdomain areas were identified within each of those domains, and communication was identified as a crosscutting topic that contained competencies related to all of the domains. As such, communication is included as a subdomain within each of the six domains. Many of the competencies are interrelated and may be relevant to more than one domain or subdomain. The authors chose to list such items where the connections to reviewed literature seemed strongest, but recognize that many of the competencies could be placed in multiple or different areas than presented here. Because of this, Figure 1 represents domains as a blending of gradients rather than being separated by distinct boundaries.

Table 1. Competencies model for transdisciplinary graduate education. Communication was identified as a crosscutting subdomain that contained competencies related to all of the domains.

Domain	Subdomain	Competencies
Individual oriented	Scientific and Research Skills	-Expertise -Convergent research methods -Analytical thinking
	Mindset	-Committed to collaboration -Creativity -Intellectual curiosity -Global consciousness
	Systems Thinking	-Operationalize systems thinking -Navigate uncertainty -Manage complexity
	Communication	-Cross-disciplinary communication -Empathy -Visual mapping or modeling
Relationship oriented	Networks, Communities and Stakeholders	-Network analysis -Stakeholder engagement -Cultural competence
	Communication	-Diverse network -Knowledge brokering
Team oriented	Leadership	-Team composition -Promote effective collaboration -Collaborative leadership
	Collaborative culture (Mutual learning)	-High performance teams -Strengths/limitations of disciplines
	Communication	-Visioning -Develop shared language and understanding -Formulate transdisciplinary [research] questions
Task oriented	Project management	-Co-develop project governance -Organizational savvy -Manage disparate data -Utilize adaptive management
	Communication	-Support cross-boundary communication -Conflict management

Results oriented	Outputs, and outcomes	-Develop capacity -Develop integrated knowledge (Co-create knowledge) -Re-integrate results -Contribute to boundary objects
	Assessment and evaluation	-Process evaluation -Impact evaluation
	Communication	- Strategies for dissemination -Knowledge translation -Information visualization
Growth oriented	Continuous learning (professional development)	-Growth mindset -Contextual intelligence -Develop processes for reflection
	Transdisciplinary Pedagogy	-Principles and challenges of TD -Experiential learning -Enable student leadership -Utilize multi-mentoring
	Communication	-Build a transdisciplinary [professional] brand -Flexible facilitation

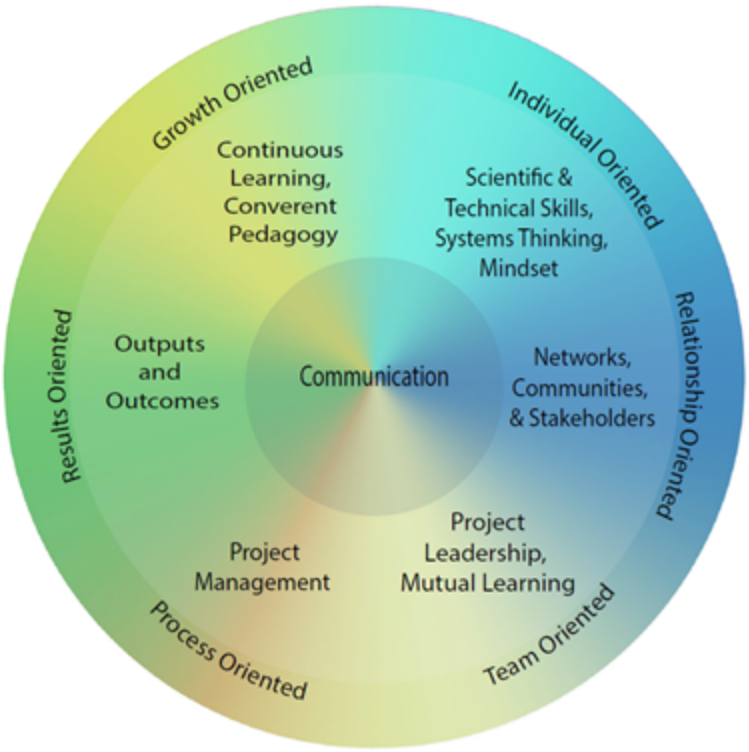

Figure 1. The "Competencies Wheel" is a graphical model to summarize the key features of pedagogical practices preparing students for transdisciplinary research. Domains are shown in the outer ring, with subdomains in the inner rings. Effective transdisciplinary and convergent research effort involves active reflection on the mastery of skills in each segment of the wheel, enablinging smoother operation.

The domains shown on the left side of Table 1 correspond to the outer ring of the wheel (Figure 1). The subdomains in the second column on the table are the same as the middle ring in the wheel. The individual competencies are listed in the third column on Table 1 but are not listed on the wheel. The cross-cutting subdomain, communication, is shown as the hub of the wheel in Figure 1, and as multiple subdomains of Table 1. Specific communication skills and knowledge (bulleted items) are distributed throughout the review as they best fit, per the judgment of the INFEWS-ER team. The supporting literature for domains and subdomains are presented in the following sections.

domain: individual oriented (transdisciplinary readiness)

The focus of the INFEWS-ER project is on those who are early in their training to become researchers in a FEWS field and wish to develop interdisciplinary or transdisciplinary skills and knowledge. The domains and related skills and knowledge represent those that are helpful to facilitate a transition to interdisciplinary or transdisciplinary projects from a platform that is likely derived from a traditional disciplinary educational program. The subdomain areas

identified within the Individual Orientation domain are Scientific and Research Skills, Mindset, and Communication.

subdomain: scientific and research skills

Many of the essential characteristics and competencies of transdisciplinary scientists are no different than the core strengths of any successful scientist [8]. The items in this domain are important for transdisciplinary researchers, but are likely to be skills or knowledge developed in the course of traditional graduate education programs. The ways in which these competencies may differ or need expansion for inter- or transdisciplinary research are noted.

Some of the competencies related to this subdomain are:

- **Expertise**. Developing an academic area of expertise is a desirable prerequisite for and compatible with transdisciplinary research [20] [21]. The Integrative Graduate Research and Education Traineeship (IGERT) project, included a similar sentiment in the final report, "...that interdisciplinary knowledge is not meant to replace singular disciplinary expertise..." [17]. Eigenbrode and Martin [22] indicated that it was important for participants to gain rigorous disciplinary experience along with skills for collaborating with those in other disciplines. There have been programs that explored pathways in which students concurrently developed expertise in more than one disciplinary area [16] [23] as well as pursuing additional training outside of their discipline after that initial expertise is developed [24]. However, developing a disciplinary expertise along with capacity for collaboration appears to be the primary path for emerging inter- or transdisciplinary researchers.
- **Convergent research methods.** All scientists, transdisciplinary or otherwise, are expected to develop skills in research/study design, statistics, data structures, analysis, and interpretation [25]. Convergence research is considered similar to transdisciplinary research and is characterized by being problem-focused and including deep integration across disciplines [1]. This is not a comprehensive list of convergent methods, but rather, a brief overview of some commonly mentioned in conjunction with transdisciplinary research. These include action research, participatory research and mixed-methods research. Action research includes components in which scientists work with practitioners and/or communities to solve problems [26] [9]. Participatory methods are used to involve stakeholders in the research process as well as decision-making [27]. While these have disparate origins, they have evolved to be similar [28] and projects that use a participatory action research framework can be found. Transdisciplinary research, by nature, is meant to solve problems. As such, data and information needs to be contextualized and problem-focused. A review to identify best practices in transdisciplinary research identified mixed methods data collection as one of those [29].
- **Analytical Thinking.** Analytical thinking skills are essential for graduate students, especially as related to the development of the higher order thinking needed for innovative thought [30]. While analytical reasoning skills are important for graduate students, different aspects of analytical reasoning (e.g., "understanding, analyzing, and evaluating arguments" compared to "breaking down complex problems into simpler ones") were rated at different importance levels by professors in different disciplines

[31]. For transdisciplinary research, these differences represent an opportunity for a more robust mutual learning process. Stokols [9] conceived of transdisciplinary action research as requiring an analytical scope that includes biological, psychological, social/environmental, and community/policy levels.

subdomain: mindset

There are many traits identified in literature on transdisciplinarity; Augsburg [10] devoted a paper to describing the transdisciplinary individual. The items in this subdomain represent those that especially predispose a scientist toward participation in transdisciplinary research projects.

- **Committed to collaboration.** Transdisciplinary team members need to be committed to collective knowledge creation [7], value transdisciplinary collaboration [8] and possess an appreciation for team-based research [18]. They also need to accept scholars of other disciplines and those with experience-based expertise as equals [8] [32]. Implied in this commitment is that a researcher approaches collaboration with humility [10], inclusivity, openness to other points of view and will persist in the collaboration despite challenges [11] [33] [8] [34].
- **Creativity**. Augsburg [10] noted that creativity and transdisciplinarity are connected. [35] asserts that creativity is often a missing element in academia and that "creativity, complexity, and transdisciplinarity go together hand in glove." Critical and creative thinking was one of four key competencies identified by [36] for transdisciplinary learning.
- **Intellectual curiosity.** Transdisciplinary science requires people who are motivated and able to take responsibility for their own learning and can do so with little or even no guidance [7] [20]. Implied in this is curiosity, especially intellectual curiosity [17] [34] toward what other disciplines have to offer [8]. Transdisciplinary work especially requires intellectual risk-takers [10] [20] willing to push boundaries, enter new areas of thought and who believe those risks advance science [8].
- **Global consciousness.** FEW systems are complex and interconnected at a global scale, but are the result of decisions made at a local level. Understanding these connections requires global consciousness. The University of Illinois [37] identified this as one of their five undergraduate student learning outcomes. Similar terminology used in literature includes global competence [38] and global awareness [39]. Odame and Oram [40] explored transdisciplinary community service learning as a way to develop global consciousness. Steger [41] held up transdisciplinarity as a method to "globalize the research imagination" while recognizing the difficulties in challenging the disciplinary-based status quo of university structures.

subdomain: systems thinking

Systems thinking is a critical part of transdisciplinarity [42] [43] [44]. A survey of INFEWS-ER team members and participating students (unpublished, March 2019) revealed that "systems

thinking" was considered the most important skill for an individual on a transdisciplinary team to possess (n=19; tied with co-learning/ co-production) as well as the skill most often selected as necessary to be present on a transdisciplinary team (n=18). Zafeirakopoulos and van der Bijl-Brouwer [34] found that six of seven transdisciplinary professionals interviewed identified a desire to understand "the system" as a reason they pursued transdisciplinary approaches.

Despite a wide acknowledgement of its importance, there are many definitions of systems thinking [45] and ambiguity on what it is [46] [47]. The competencies listed here are not meant to identify all the essential skills/knowledge needed to be a systems thinker. Arnold and Wade [48] published a "Complete Set of Systems Thinking Skills" that may serve as a detailed reference for that topic. The narrative for this subdomain focuses on some ways systems thinking helps team members contribute to transdisciplinarity.

- **Operationalize systems thinking.** [43] and [47] emphasized the need for educators to not only convey theory about systems thinking but to provide opportunities for students to apply it to real-world problems. One application of systems thinking is in developing a systems-oriented understanding of the problem [42]. Eelderink et al. [49] presented a case study in which systems thinking and participatory action research were used to engage in stakeholder-focused problem and solution framing. Systems thinking also has an important role in promoting dialogue and cooperation [50].
- **Navigate uncertainty**. When dealing with complex systems, team members need to be able to make decisions despite uncertain or ambiguous information [48]. In transdisciplinary research, finding ways to deal with uncertainty increases the effort needed to collect or validate data, but can result in a more realistic view of the system being examined [51]. Navigating uncertainty may require transdisciplinary team members to identify information needs, adapt, and iterate [52] as new data is gathered or circumstances change. Discovery skills for navigating uncertainty, such as making connections, questioning, root cause analysis, systematic experimentation and networking can be learned and practiced [53].
- **Manage complexity**. The need to assess, understand, manage or reduce complexity is included in multiple definitions of systems thinking [45]. Transdisciplinary approaches are regarded as a way to address complex systems and problems through ongoing collective dialogue, development of shared conceptual frameworks [54] and by overcoming knowledge fragmentation [51]. The challenge of complexity and transdisciplinarity is "...how to organize that information, turn it into knowledge, and use that knowledge wisely" [35]. Due to the complexity of transdisciplinary programs, team leaders and managers should be prepared for time lags and high start-up costs [11], establish a collaborative culture and systems thinking by using diagrams [55] or artifacts to articulate the problem space [56].

subdomain: communication

The communication skills and knowledge related to the individual oriented domain focus on communication skills needed to work across boundaries and understand other viewpoints and perspectives.

- **Cross-disciplinary communication**. The ability to communicate with other scientists, especially across disciplines, is essential for an interdisciplinary or transdisciplinary scientist [17]. This can be challenging because of a lack of platforms (i.e., journals) and the absence of a shared research framework [57]. Putting students or faculty from different disciplines together in a project, course, symposium or other setting is not enough. Situations which develop skills in cross-disciplinary communication need to be structured to bring about conversations on differences in terminology or methodologies as well as contrasting epistemologies [58]. These skills can be developed with short-term experiences but should be further cultivated through longer-term settings such as courses, internships, or similar offerings [58].
- **Empathy**. Transdisciplinary research requires cooperation among people representing a wide range of views and perspectives. Empathy in this context is about a person's ability to suspend their own point of view [10] and relate to those of fellow collaborators and stakeholders. A holistic understanding of complex issues requires genuine engagement through the use of empathetic communication skills [59]. Empathy was identified as one of five core values for developing participatory academic communities [60]. Empathy can be cultivated in students through deliberate and thoughtful incorporation into educational curriculum [59] [60].
- **Visual mapping or modeling**. When examining systems, we develop mental models which represent those systems [61]. In a transdisciplinary setting, it is very important for a team to synthesize their individual views of the system into a shared model, which can be accomplished through visual representations [56] [50]. A shared conceptual framework, in the form of a "jargon free visual schematic" is a best practice that allows all transdisciplinary team members to understand and agree on the research plan [29]. Mohammed et al. [62] described strong links between the similarity of team mental models and team performance.

domain: relationship oriented

Transdisciplinary teams need to represent both a breadth and depth of knowledge, work together to integrate existing and new knowledge, and translate knowledge for practical application. As such, relationships and connections all play an important role in transdisciplinary research. Transdisciplinary researchers should possess skills and knowledge around analyzing and cultivating these.

subdomain: networks, communities and stakeholders

Throughout history, humans have organized themselves in a variety of ways to achieve cooperative goals - tribes, hierarchies, and others, however "The network has become the favored unit of action for people who want to make nearly any sort of difference in the world" [63]. Networks are idealized as dynamic, completely "flat" and devoid of hierarchy. The practical reality of most human endeavors, including research, is that some level of governance and cohesion is necessary to maintain accountability and measure progress and impact. [64] advocated for a blended model in which a strong network (driver of innovation and awareness) is supplemented with temporary, negotiated hierarchies (for taking informed action).

Communities represent a subset of a network that is more closely connected and shares a sense of identity or purpose [65]. It is around these network-generated communities (workgroups, action teams, communities of practice, etc.) in which the key ingredients for transdisciplinary research can be found (desire to make a positive difference, commitment to collaboration, innovation, etc.) One of those key ingredients in transdisciplinary research is that non-academic participants, often referred to as stakeholders, are significantly involved.

Some skills or knowledge related to this subdomain include:

- **Network analysis**. Networks of any type "...are similar to each other, a consequence of being governed by the same organizing principles" and are subject to mathematical analysis [66]. Network analysis can provide insight for a project on the problem or system being defined [67] as well as leadership effectiveness [68] and connections between network patterns and outcomes [69]. It can also be used to identify gaps or tipping points [70], identify learning pathways [71], evaluate impact [72] or some combination of these [67]. Analyzing the strength and centrality of network ties also provides information on the level of stakeholder influence or marginalization, and can identify brokers [73].

- **Stakeholder engagement**. Transdisciplinary teams value the participation of non-academics as equal to the academic contributions [15]. Long-term stakeholder involvement is desirable [12] especially from the beginning of a transdisciplinary project [74] and should include a role in shared problem framing [15]. Despite their importance, the selection of stakeholders is often ad hoc and has the potential to overlook important groups or bias results [75]. Methods for selection of stakeholders can be enhanced with stakeholder and social network analysis that identifies those with strong ties (trust, influence), weak ties (diversity), and centrality (potential brokers or intermediaries) [73]. Inclusivity is important to transdisciplinary projects but also leads to increased complexity [11].
- **Cultural competence.** Cultural competence exists as a spectrum with terms used across that spectrum including: cultural knowledge, cultural awareness, cultural sensitivity and cultural competence [76]. The definition of cultural competence varies, however [77] proposed one concise definition as "...the ability to understand and then effectively perform, communicate, and engage with others in a different cultural context." What seems to set cultural competence apart from the other terms is an action or operational component. Culturally competent people don't just know or believe, they take actions that are inclusive. Cultural competence can be applied to transdisciplinary research in multiple ways. Reich and Reich [78] compared disciplines to cultures and indicated that cross-cultural competence was essential to effective interdisciplinary collaboration. Harvard Catalyst [79] examined community based participatory research (CBPR), which shares many similarities with transdisciplinary research, and asserted cultural competence was a requirement for an effective process.

subdomain: communication (individual oriented)

The competencies in relationship oriented domain represent those which help individuals develop connections to people with different perspectives or from different knowledge systems.

- **Build a diverse network**. Purposefully cultivating cross-boundary interactions can lead to novel insights in problem framing, analytical methods, or knowledge integration and interventions [80]. One of the advantages of a network is access to diverse skill sets. As [77] note, diverse networks guard against a tendency to populate one's network with those who are similar to oneself or those with whom one spends the most time. Participants should cultivate ties with people of diverse backgrounds as well as diverse knowledge systems [81]**.** It should be noted that it is not necessary to cultivate strong ties (frequent communication) in all cases. "Diverse information and new ideas have been shown to travel best through weak ties" or infrequent communication [73].

- **Knowledge brokering.** Gray [68] described knowledge brokers as those who form connections between that which is otherwise unconnected or unrelated. Brokering can strengthen many different dimensions of knowledge, including creation, acquisition, assimilation, use, and dissemination [82]. It can be done by individuals, organizations or structures and serve to bring together academic knowledge with practice [83]. Vogel et al. (2014) [84] identified brokering and bridge-building as a main factor facilitating success in transdisciplinary research. Klerkx et al. [85] took the label a step further by describing innovation brokers as an important role to act as a systemic intermediary with a responsibility for building linkages.

domain: team oriented

The unique nature of transdisciplinary research presents some challenges that require additional skills and knowledge especially relative to the potential for large, complex teams addressing large, complex issues, the diversity of the teams, and the lack of available operational guidance [13].

subdomain: project leadership

Leadership for transdisciplinary research requires many of the same skills as those needed to lead any collaborative team. McGregor and Donnelly [86] conceptualized "transleadership" as a "...shift from leadership as solely an individual activity to a co-creative act." This subdomain is not an exhaustive list of qualities needed to lead a transdisciplinary research team, but instead focuses on some of the unique aspects of transdisciplinary leadership that may differ from non-transdisciplinary leadership. Eigenbrode et al. [13] developed *"Leading Large Transdisciplinary Projects Addressing Social-Ecological Systems: A Primer for Project Directors"* which provides additional depth on this topic.

Examples of competencies relevant to transdisciplinary project leadership include:

- **Team composition.** Recruiting a diverse and multidisciplinary team is a necessary step for transdisciplinary research, but "...mixing up people in the building will not of itself naturally create transdisciplinarity" [12]. Transdisciplinary research requires the "right" people who are interested in learning from each other, bridging epistemic differences and building capacity, among other characteristics [55]. The "right" people include team members that possess transdisciplinary competencies [12] and are able to undertake the communication and learning processes needed to collaborate with individuals trained in different disciplines [17]. It is important that participants recognize the amount of time and effort that will go into developing the relationships and trust needed for transdisciplinary work [11]. Transdisciplinary leaders need to have the professional credibility needed to recruit team members [87] and a diverse network to draw upon. Also mentioned was the importance of identifying, assigning and supporting roles within the team [11] [12] [52].

- **Collaborative leadership**. Leadership, especially for transdisciplinary projects, is increasingly seen as a shared responsibility and less as a top-down control structure. Using shared or collaborative leadership models promotes equality, open dialogue and trust [11] [55]. Multiple leaders (collaborative leadership) may especially be necessary with large, complex teams or those that are geographically distributed [68]. Collaborative leadership does not mean there is a lack of structure; clearly defined roles and responsibilities are important for building trust and cooperation [88]. Gray (2008) [68] identified three groups of tasks required of transdisciplinary collaborative leadership: cognitive (visioning, framing and judgment), structural (coordination and information exchange), and processual (constructive, productive interactions).
- **Promote effective collaboration**. Transdisciplinary leaders need to be persistent in efforts to foster collaboration [11]. Gray (2008) [68] identified "patience, tolerance, openness, listening, and conflict-resolution capability" as important qualities for building an environment for collaboration. Leaders should understand motivations and incentives for participation, "both tangible and intangible" [55] due to the diverse perspectives and knowledge assembled in a transdisciplinary team. Transdisciplinary projects require respectful communication that helps build a shared identity [89] as well as shared language and mutual learning [11]. Once those are established, transdisciplinary teams can begin to emphasize integration [90]. Using a co-creation framework promotes integration [91].

subdomain: mutual learning

Scholz (2000) [92] identified mutual learning as a basic principle of transdisciplinarity. Zscheischler et al. (2018) [93] surveyed researchers and practitioners that had participated in transdisciplinary projects and identified mutual learning as an important criteria in the "success profile" of a transdisciplinary project. [94] also found that interdisciplinary team members defined success beyond the traditional measures (citations, grant funding, etc.) and included process-based outcomes such as relationships and capacity building in their description of success. A common theme in literature on transdisciplinary research was that leaders and team members should be persistent and patient in cultivating mutual learning and a collaborative culture [11] [95] and consider different types of team interactions, including informal ones [55] [96].

Competencies relevant to this subdomain include:

- **Contribute to high performance teams.** High performing teams (HPTs) distinguish themselves from real teams especially through "strong personal commitments to each other's growth" and also demonstrate strong commitment to the mutual cause, shared leadership, interchangeable/complementary skills, and extended team effect (members feel empowered to act but still check with other team members) [97]. Mercado et al. (2017) [98], drawing upon [99], described six attributes of HPT: 1) common vision, purpose, goals and operating procedures, 2) shared leadership, 3) individual and mutual accountability and high level of caring, 4) high trust, 5) commitment to innovation, stretch thinking, and conceptual breakthrough, and 6) clear and effective two-way

communication. Rozovsky (2015) [100] examined teams at Google for two years and identified five characteristics of successful teams 1) psychological safety, 2) dependability, 3) structure and clarity, 4) meaning of work, and 5) impact of work. Other descriptions of HPTs exist in literature but many include accountability, trust, commitment to the work and each other, and shared vision in some fashion. Regardless of which characteristics a team aspires to or the phrasing they use, HPT requires frequent reflection and assessment to ensure uptake and progress [96] [101].

- **Recognize strengths/limitations of disciplines**. Interdisciplinary or transdisciplinary researchers should be able to recognize the strengths and limitations of multiple disciplines, including (and perhaps especially) their own [17] [15] [56] [34]. This awareness "...is essential for the integration of disciplinary approaches that is fundamental to transdisciplinary research" [56] and can reduce prejudices and increase acceptance of approaches originating outside of one's own discipline [15].

subdomain: communication (team oriented)

The competencies related to communication as part of the team oriented domain focus on those that especially need to be demonstrated by those in leadership in transdisciplinary teams.

- **Visioning and sensemaking.** One of the most important tasks for a leader is to bring about shared understanding and purpose for a transdisciplinary team. "While sensemaking charts a map of what is, visioning produces a map of what could be…" [102]. Visioning by transdisciplinary leaders includes imagining how the contributions of team members overlap in a positive way to create new knowledge, and can communicate that vision to team members [68]. Sensemaking can be thought of as a precursor to visioning as it allows for a team to understand the current context and situation. Sensemaking is especially important when bringing together people with diverse, and sometimes opposite, viewpoints in which team members may be confronted with information that is novel or contradictory to what they already possess. Sensemaking was identified by [86] as one element of "transleadership". Survey data [102] indicated that sensemaking may be more important than visioning for leadership effectiveness.
- **Develop shared language and understanding**. Transdisciplinary teams need to develop effective, two-way communication across disciplines [17] [97] as tacit knowledge in one discipline may not be known (or may be doubted) in another [15]. Teams should avoid jargon [36] and instead use lay language [18] to facilitate team communication as well as external communication. Derry and Fischer (2005) [7] recommend the use of boundary objects and developing "a system of examples, analogies, illustrations and other representational artifacts that can help make major ideas in one's specialty comprehensible to specialists in other fields." [18] also supported using analogies, metaphors and lay language. This process can be time-consuming and should be ongoing throughout the life of a project or program [11].
- **Formulate transdisciplinary questions.** This phase, if done well, provides specificity and clarity that allows interdisciplinary research goals to move toward transdisciplinarity [12] [15]. Ciesielski et al. (2017) [80] assert that diverse perspectives and cross-disciplinary interactions help researchers frame better and novel research questions.

Formulating the research question is also important to ensure the scope of the project is appropriate [103]. Carajales-Dale et al. (2020) [104] emphasized that Food-Energy-Water Systems (FEWS) research questions are greatly affected by multiple scales, the physical and human processes occurring within those, and the data and tools available. Pohl and Hirsch Hadorn (2008) [105] noted that transdisciplinary research questions should be situated in the three forms of knowledge (systems, target and transformation) in order to bring implicit assumptions to light so that they become explicit tasks.

domain: task oriented

"In our experience classical project management methods are not well-adapted to complex transdisciplinary research projects" [106]. Transdisciplinary projects, by definition, will include methods, outputs, approaches or knowledge that is unique or novel. This may require management techniques or tools that are also innovative.

subdomain: project management

Project managers need to be able to develop workflows and select tools and technologies that can support transdisciplinary work.

Examples of competencies relevant to project management include:

- **Co-develop project governance**. In the 'project leadership' subdomain, the emphasis was on achieving a shared vision, alignment and mutual learning. For the purposes of project management, this shared vision needs to be documented as goals, objectives, timeline, policies (including data, attribution and intellectual property) and expectations [56] [107]. Goals, outcomes [12] and policies [108] should be collaboratively negotiated and developed as a team. As transdisciplinary teams respond to changing priorities and circumstances, it is inevitable that adaptations or iterations will need to be made to team composition, policies, objectives and more [89] [108] and governance documents need to reflect those changes, made as transparently as possible.
- **Organizational savvy**. In a transdisciplinary project, there are likely many different institutional or organizational entities working together. Knowledge of diverse reporting and control structures, rules, and competitive interests of these entities is beneficial, as is the ability to navigate contracting arrangements in differing environments [11] [109].
- **Manage disparate data**. The core of any scientific research project is in its data. Transdisciplinary research is likely to provide significant challenges in integrating data from a variety of sources that may have very different collection or management protocols, and include mixtures of quantitative and qualitative data [106] and be complex, difficult to attribute, or be difficult to interpret [110]. It is important that a transdisciplinary team develop a shared vision for the data management plan, document it

[108] [110] and provide for long-term access [111]. Researchers in Australia [110] [112] echoed the value of data management plans and utilized work teams focused on integrating, managing, analyzing, and publishing data from disparate sources for use in meta-analyses or for future projects. The challenges mentioned also offer an opportunity - that of enhancing data collection and analysis through interdisciplinary collaboration [111] and the ability to generate new knowledge by re-examining old data [110].

- **Utilize adaptive management.** Traditional project management includes the up-front development of a detailed plan that spans the entire project. Transdisciplinary projects are often formative and build on information or data gathered at each step which lends itself to adaptive management. [113] described two important principles of adaptive management as iterative decision making and strategic flexibility. Gustafson and Wolcott (2017) [108] recommends regular reviews to determine if project objectives or milestones continue to remain relevant. [106] utilized agile management, a type of adaptive management in which short, intense periods of collaboration (sprints) are used to achieve specific project objectives. Project managers in complex environments need to pay attention to relationships and be able to understand, motivate and communicate with people involved in order to make needed changes as a project evolves [114].

subdomain: communication (task oriented)

The communication competencies related to project taskwork and managing the process of transdisciplinarity are included in this subdomain.

- **Support cross-boundary communication.** Transdisciplinary teams need to communicate across many different boundaries including experiential, methodological, spatial-temporal, technological, institutional, social, and political/ethical as well as consider that transdisciplinary teams evolving through different stages may require changes in their communication processes [115]. Wang et al. (2019) [116] developed a communication framework for transdisciplinary teams that offers topics for communication and indicators of successful communication (subdivided into relationship development and solution development) at each stage of team formation and performance. One feature of the workflow should be *regular and ongoing* (emphasis added) communication [98]. Transdisciplinary teams are often separated spatially and these will require virtual communication tools in addition to face-to-face time [7]. A feature of successful transdisciplinary research is an interdependence of tasks [89] and the communication for a project should especially focus on the “interfaces where the work of one participant is necessary for the work of another and participants can collaborate effectively” [117].
- **Conflict Management**. Transdisciplinary projects, by design, bring together a diversity of viewpoints and perspectives. This makes disagreements more likely to occur than

would in other scientific endeavors, and these can interfere with success [68]. Siebenhüner (2018) [118] identified four categories of conflict in transdisciplinary work: differing values, conflicting (economic) interests, dissimilar claims of legitimacy, and diverse knowledge claims. Divergences may occur in defining the problem due to differing values while conflicting interests and questions of legitimacy can lead to situations where participants are not equal in terms of influence or interest, making conflict a strong possibility [15]. To manage conflicts, prioritizing clear and effective communication is a necessity [98] and discussions should take a problem focus, which can de-personalize the dialogue [119]. Transparency was at least a portion of the remedy for three of the four conflict categories identified by [118]. An additional recommendation for managing conflict in transdisciplinary projects is the use of co-design and co-production to provide a shared sense of ownership [12] and improve engagement of stakeholders in decision making [120].

domain: results oriented

Transdisciplinary research can result in the development of products as well as a process [121]. Even though there is an emphasis on application to practice, multiple authors noted that integration into the scientific body was also an important product of transdisciplinary research [12] [6]. Identifying and evaluating outcomes is not an activity for the end of a project, but should be something discussed by the team from the beginning and iterated throughout the project [90].

subdomain: outputs and outcomes

Outputs and outcomes are not the same, but are often conflated when discussing scientific projects. Koontz and Thomas [122] defined outputs as "the plans, projects, and other tangible items generated by collaborative efforts" and outcomes as "the effects of outputs on environmental and social conditions." These are different than impacts which are generally defined as a broader or longer-term result attached to project outcomes [123] and are more difficult to directly connect to the competencies of project team members.

Competencies related to transdisciplinary outputs and outcomes include:

- **Develop capacity.** In the context of building innovation capacity [124] noted that capabilities combine to develop capacity and that this process is done at the individual, organizational, project, network and system levels. This provides opportunities (and challenges) for assessing capacity development at multiple levels. Matschoss et al. (2020) [125] emphasized communication and networking skills of individual participants to increase the capacity of stakeholders and researchers to work together. Walter et al. [126]

indicated that transdisciplinary research has both scientific and societal effects, and that one important societal effect is the increased decision-making capacity of stakeholders. At the same time, they acknowledged that attribution of this increased capacity to a single transdisciplinary project is difficult. Interviews of team members for a large transdisciplinary project identified two constructs of success including purpose driven (measurable outputs or deliverables) and capacity-building [94]. Within the latter construct they identified two themes, knowledge capacity and relational capacity, and noted that capacity building has not been a traditional measure of success in research.

- **Develop integrated knowledge (Co-create knowledge).** The process of integrating knowledge draws upon multiple sources in order to develop solutions or lead to outputs such as new methods, insights, or other innovations. Integration does not happen all at once; it is an iterative process [111] that requires transparency [90]. Jacobi et al. [127] highlighted the importance of co-creating knowledge with stakeholders with more empowered participation coming from those involved early in the process. [91] also indicated that stakeholder involvement in knowledge production increases the usability of knowledge resulting from research. One challenge of multidisciplinary collaboration is in overcoming potential questions of scientific credibility that may occur because of different epistemologies, terminology, and approaches or methods [6]. Integration requires careful attention to many aspects of mutual learning such as a shared vision, common language, and joint framing of the problem [91].
- **Re-integrate results.** The production of [integrated] knowledge is necessary for transdisciplinary research but not usually the ultimate goal; rather it is the use of that knowledge to bring about change or improve a situation [121]. Traditional research publications or reports can lack adequate signal for practitioners relative to implications for their practice [128]. [6] advocated for approaches that go beyond knowledge transfer and instead re-integrate results into societal (as well as scientific) practice. Outputs of transdisciplinary research may be developed at different stages of the project, utilized at different times by different people, suggesting “multiple impact pathways” [127]. Assessment of transdisciplinary research should recognize societal as well as scientific use of knowledge and address the multitude of ways the information may be used.
- **Contribute to boundary objects.** An early definition of boundary objects, proposed by [129] is “those objects that are plastic enough to be adaptable across multiple viewpoints, yet maintain continuity of identity.” Boundary objects can represent the integrated knowledge produced in interdisciplinary collaborations [130] and be a means for re-integrating results into practice or scientific knowledge. Akkerman and Bakker [131] asserted that dialog occurring at and across boundaries of domains or communities aids in learning and communication, but to be successful, the resulting artifacts (boundary objects) must encompass multiple perspectives and meanings. [7] also noted the dual role of boundary objects as a means to facilitate communication or negotiation within a team

and as tangible products useful to a wider audience. Mollinga [132] identified boundary objects as a necessity in inter- and transdisciplinary work by serving as "devices and methods that allow acting in situations of incomplete knowledge, nonlinearity, and divergent interests…" Some examples of boundary objects include meeting notes, models, skills inventory (INFEWS-ER experiences), frameworks, procedures, protocols, matrices [132], ideas, standards, products, or designs [7], among others.

subdomain: assessment and evaluation

In transdisciplinary research, both the process and the product (outputs, outcomes) have value. The ability to assess both aspects is needed to demonstrate the value of transdisciplinarity in forming relationships and building capacity as well as impacting policies, practice, behaviors and knowledge.

Competencies related to transdisciplinary assessment and evaluation include:

- **Process evaluation.** In many projects, the focus of evaluation is on the products or outputs. In transdisciplinary research, evaluating the process is critically important as more investment is being made in this type of work [133] and knowledge on how to conduct transdisciplinary research is limited [111]. Bess et al. [134] recommended the use of both qualitative (observation, interviews) and quantitative (surveys, content analysis) to better understand how and why decisions were made as well as describe the relationships and experiences of the participants. Process evaluation can also be used to determine if an unsuccessful project was a bad idea or if it was implemented poorly [135].
- **Impact Evaluation.** One difficulty in evaluating impact is that it may require long periods of time, possibly even decades to determine [133]. There have been several efforts to define criteria for evaluation of transdisciplinary science, but none have become established or generally accepted [93]. Most projects measure success (or lack thereof) using their own criteria, and differing perspectives and views by individual team members add to the complexity [90]. Some suggested criteria for evaluation have included impacts on practice and policy, scientific integration, collaborative behaviors, professional validation and communication of outcomes [133]. Lang et al. [6] developed a conceptual model of ideal transdisciplinary research which included societal practice (useful results), research process (re-integrate and apply created knowledge), and scientific practice (new insights, questions, etc.) Four principles were identified by Belcher et al. [136] including: relevance (social significance and applicability), credibility (integration, reflexivity, scientific rigor), legitimacy (inclusion and fair representation of stakeholder interests), and effectiveness (contribution to problem solving and societal change).

subdomain: communication (results oriented)

When reaching the outputs and outcomes portion of a project, communication not only includes internal team communication and stakeholder interactions, but expands to include external audiences.

Competencies in communication related to the results (process and product) of a project include:

- **Knowledge translation**. Linear technology transfer approaches have not succeeded in bringing about desired practice changes related to complex problems; transdisciplinary approaches that include a focus on translating theory into practice have great potential for fostering innovations [11]. Knowledge translation is about "closing the gaps from knowledge to practice" and is an active, iterative approach in which knowledge needs to be contextualized, made useful, and monitored for impact [137]. To do this, a researcher must be able to explain: their own contributions, how their discipline relates to the research, and the contributions of others - academic and non-academic alike [15]. There are many models for knowledge translation, but a commonality among those identified by [138] is that they rely on a deliberate effort to foster connections and co-creation from the beginning. Gamse et al. [17] reported that outreach activities and related efforts, such as industry internships, improved the ability of graduate students to communicate with non-academic audiences.
- **Strategies for dissemination.** When discussing outreach for research results, the terms diffusion and dissemination tend to be used interchangeably, but, when looking more closely, dissemination is regarded as the more active process [128]. The scientific channels by which results are disseminated will be different for inter- or transdisciplinary research than for disciplinary research [15]. Hoffman et al. [71] envisioned transdisciplinarity as an iterative process in which multiple synthesis products may be produced for targeted audiences. Future Earth Ireland [12] also recommended the production of targeted outputs for different audiences, however [33] caution against products that are compartmentalized and do not reflect the integrated knowledge produced. Dissemination requires knowledge of the audience and their characteristics as well as contextualizing and framing the information for maximum receptivity [128].
- **Information Visualization**. Visualizations are a proven way to help make sense of complex knowledge by uncovering relations, relevance, or structure [139] [140] and for engaging with non-scientists and decision-makers [141] [142] especially when developed in a participatory environment [143]. Visualizations can serve as a boundary object. They can provide a mechanism for transdisciplinary teams in mutual learning, developing a problem-focus [143] and developing interdisciplinary skills in students [144]. Visualizations are an effective and efficient way to engage with stakeholders [141]. They

can be well-received as an outreach product especially when the visualization is designed to quickly convey baseline information and allow the learner to intuitively access greater depth of information if they wish [111] [141]. When possible visual representations used to describe systems should use standard conventions, e.g. there is a commonly accepted way to draw a causal loop or a stock/flow diagram [145].

domain: growth oriented

A set of interviews with seven transdisciplinary professionals revealed a "clear feedback loop" in which a person engages in continuous learning that begins because of personal values and which is never complete [34]. Wolcott [87] noted, "You will rely frequently on those traits that you possess naturally; cultivate those for which you have aptitude; and be aware of and learn to compensate for those that do not come easily." In other words, one person does not need to be great at everything to be a competent transdisciplinary researcher, but should know themselves and their collaborators well enough to mix and match strengths with roles and responsibilities in a project.

subdomain: continuous learning (professional development)

There are many connections between this subdomain and those in the Individual Oriented domain, especially the Mindset subdomain. The Mindset domain focused on skills or knowledge that are common in those interested in transdisciplinary research. The Continuous Learning domain emphasizes skills and knowledge needed to further their development as a transdisciplinary professional, take on leadership roles, and/or to teach future transdisciplinarians.

Competencies related to continuous learning and professional development include:

- **Display a growth mindset.** A growth mindset refers to an attitude in which people believe that through hard work and effort they can increase their abilities, while a fixed mindset refers to those who believe their talents are innate [146]. Especially relevant to transdisciplinary teams, growth mindset behaviors include "sharing information, collaborating, innovating, seeking feedback, or admitting errors" [146]. Reid and Ferguson [147] assessed first-year engineering students and found that an open-ended design project reduced (or eliminated) a drift toward a fixed mindset that was otherwise observed in that group. Titone [148] identified a growth mindset as a critical characteristic of teachers and administrators in order to facilitate innovation. The concept of growth mindset has led to controversy, especially in regard to research that attempts to link mindset with academic achievement. The originator of the concept pushed back,

"...mindset theory is a theory about responses to challenges or setbacks. It is not a theory about academic achievement in general and does not purport to explain the lion's share of the variance in grades or test scores" [149].

- **Demonstrate contextual intelligence/competence.** Contextual intelligence applies to those "that understand the limits of their knowledge and are able to adapt that knowledge to a context different from the one in which it was developed" [150]. Kutz and Bamford-Wade [151] identified contextual intelligence as a leadership model for a "knowledge economy" that helps individuals understand why a solution may work in one situation but not another (among other outcomes). In most literature reviewed, both phrases were defined in very similar terms. In one instance where a direct comparison was made, Motamedi [152] identified contextual intelligence and contextual competence as important for handling uncertain situations, but noted that contextual competence has a greater action component. Atman et al. [153] recognized that engineering design requires more than technical knowledge and that other factors (people, places, events and socioeconomic systems) play a role in developing solutions; they developed an assessment for contextual competence for students that includes a design task, self-assessment, and assessment of the student's perception of the importance of context.
- **Develop processes for reflection.** It has been well-documented that reflection is a critical part of learning and growth. Esler et al. [42] utilized regular student reflections in a program designed to develop interdisciplinary skills. [6] assert that the iterative nature of transdisciplinary projects requires reflection and presented a case study in which reflection led to improved outcomes in the second phase of a transdisciplinary project. While often thought of as an individual exercise, reflection is also valuable as a collective (group) process [111]. Di Giulio and Defila [15] identified well-structured reflection as an integral part of developing transdisciplinary competencies. Mauser et al. [91] noted the importance of reflection in integrating knowledge. Some literature on transdisciplinarity emphasizes reflexivity in addition to reflectivity. Reflexivity is a more intensive process that includes introspection [154]. The New Zealand Primary Innovation Programme identified the role of reflexive monitors as critical for helping a transdisciplinary team develop trust and shared understanding [11].

subdomain: transdisciplinary pedagogy

Structuring transdisciplinary learning experiences can take many forms including: interdisciplinary courses [17], joint field trips [42] [155], colloquia or seminars [42] [17] [155]. Also mentioned was the co-development of outreach products [42] [17].

The competencies for integrating transdisciplinarity into educational curricula include:

- **Identify principles and challenges of transdisciplinarity.** Di Giulio and Defila (2017) [15] stressed the importance of an understanding of the theoretical foundation of

transdisciplinary research in order to prevent haphazard or random approaches. There is not one agreed-upon set of principles for transdisciplinarity, but there are common themes including diverse sources of knowledge, co-creation, and a desire to put the new knowledge into practice [6] [12] [156] [157]. Designing effective transdisciplinary learning experiences also requires knowledge of potential challenges in order to avoid or to cope with them. One challenge mentioned was the longer-than-expected time needed for developing shared language, trust, and mutual learning [11] [42] [55]. By the very nature of transdisciplinary research, people of different perspectives and backgrounds are brought together which creates opportunities for conflict and disagreements [11] [15] [9]. Timeline and conflict potential are important for educators to address by emphasizing team building and communication early in the learning experience [155]. An additional challenge mentioned is the difficulty in obtaining academic recognition for transdisciplinary research [84].

- **Implement experiential learning**. Students not only need to learn about the skills necessary for transdisciplinary research, but also need opportunities to practice those skills. This may involve setting up student cohorts with interdisciplinary responsibilities, and involved in producing outputs [22] including joint outputs [17] [155], engaging students in project-based experiences [158] [36] or developing case studies [32] [159]. This approach does have a downside - the time commitment can be considerable. Guided, community of practice based 'apprenticeship models' are demanding for both students and faculty [7]. The INFEWS-ER cohort challenges were structured to have a similar workload as a three-credit course (semester system) but participants indicated that the time spent on the challenge exceeded that. Inability to incorporate this extra-curricular workload into their program, shifting levels of work as a new semester started, or interference with other responsibilities were cited by students who did not complete the challenges.
- **Enable student leadership.** In transdisciplinary learning, students are at the center of the experience and are part of collaborative decision-making from start to finish [36]. Students need opportunities and leeway to choose topics [15] [155] and educators can support them by encouraging them to find projects of personal interest, which is connected to making the commitment required for transdisciplinary collaboration [158] [34]. Essential to this is providing feedback on authentic tasks resulting from scaffolded performance on activities like grant writing and project management [7].
- **Utilize multi-mentoring.** Having interdisciplinary teaching tandems [18] or teams [15] is recommended. In New Zealand, it was noted that pairing experienced Mode 2 researchers with Mode 1 researchers can assist in transitioning to the Mode 2 paradigm [11]. Eigenbrode and Martin (2017) [22] recommend defining and designating mentorship/co-mentorship roles, which may require training on effective mentoring. Mentors and educators are encouraged to leverage existing partnerships and networks in

providing options for projects/problems and sources of expertise to support student efforts [155].

subdomain: communication (growth oriented)

At the current time (2022), there are few avenues for achieving academic recognition as a transdisciplinary professional [84], resulting in the need for such professionals to actively promote their skills and build connections with others interested in the same type of work.

- **Build a transdisciplinary [professional] brand.** In addition to developing some of the skills and knowledge listed in this review, it is important to be able to communicate those to potential collaborators or employers. This requires deliberate and frequent self-assessment [160]. A common way for academics to gain notice for their expertise is through participation in a community of practice (CoP) which are typically organized around a particular knowledge domain of interest [161]. It is possible to nurture and participate in transdisciplinary CoPs [51]. In a digital world, students and young professionals should be instructed on how social media use, including personal use, impacts their professional identity [162]. Novakovich et al. [163] agreed that operational and strategic social media use is important for students to learn, but recognized that psychological barriers should be considered by allowing students to "determine their level of online exposure" rather than mandate participation.
- **Flexible facilitation.** The process of transdisciplinary research is a formative one in that new information or insights have the potential to drastically alter the actions that follow. It can be an uncomfortable process for those who prefer to have a pre-planned course of action or pre-determined set of outputs. Friend [164] highlighted flexible facilitation as a way to support developmental decision-making. Team-based projects are often used to practice transdisciplinary skills (see the experiential learning competency) and [165] emphasized that facilitators of such efforts should be flexible and adjust to student input and anticipate potential problems. Students that participated in an intensive transdisciplinary short course noted that flexible facilitation leads to individual assistance, provides for structured as well as unstructured time together, and allows for adjustment when each new cohort participates in the short course [166]. Rasmussen [167] provided an example in which a facilitation team needed to change their methods after recognizing that their first approach was not working.

discussion

The review of over 160 papers related to transdisciplinary education and the lessons learned from the INFEWS-ER project reiterated our initial belief that transdisciplinary education and research is a complex undertaking that requires a wide range of skills and knowledge. It should be noted that the authors do not advocate that individuals can expect to develop competency in every item presented in this review, but rather, that these skills should be considered when assembling a team for transdisciplinary research. Throughout the course of the review, it was noted that transdisciplinary competencies were often presented and discussed from the perspective of one or more of six orientations: the individual, relationships and connections, team, process, outputs and outcomes, and growth. These were designated as the domain areas for our competencies.

Communication competencies were repeatedly identified as critical to the success of transdisciplinary research and one that cut across all of the domain areas. As such, communication is a subdomain within each of the six domain areas with communication-related competencies sorted where it was decided they best fit. The importance of communication is reinforced in the “Competencies Wheel” (Figure 1) in which communication is presented as the hub.

The competencies presented in this review can be utilized in multiple ways. For example, the individual oriented domain could be used to develop surveys to identify students that may be interested or inclined to get involved in transdisciplinary research. These students could be directed toward courses, research projects or cross-disciplinary experiences that provide opportunities to develop competencies for this work. The competencies in several domains can be connected to educational modules, curriculum or other activities in which students or early career professionals can earn badges or certificates that allow them to promote their skills on their curriculum vitae and in other ways. A faculty member interested in developing inter- or transdisciplinary courses can review the growth oriented domain (and the transdisciplinary pedagogy subdomain in particular) as they develop the course.

One of the more challenging parts of developing this set of competencies was in deciding which domain or subdomain an individual competency should reside. Many of the competencies are connected to multiple domains/subdomains and an argument can be made for moving them around or listing them in more than one place. We present this review as a starting point for discussion, recognizing that others may be working with different target audiences, outside of FEWS fields, or with a different context than these. We encourage others to use these as a starting point and add to future discussions.

This review begins to fill an important gap in literature on transdisciplinary graduate education by identifying, defining, and organizing the current understanding of the skills related to transdisciplinarity in scholarship and real world problem-solving. It is clear from the descriptions presented that no skill listed functions in isolation from the others. A next step is to develop a deeper understanding of the connectedness between these skills and how each of the domains and their subdomains interact to create true transdisciplinary thinking. Additionally, a separate review of how these skills are taught and assessed is needed to better inform educators and researchers in their efforts to promote transdisciplinarity within their institutions.

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