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Analyzing knowledge integration in convergence research

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ABSTRACT

A pragmatic concern guides this perspective piece: How might researchers charged with leading convergence research better plan, design, implement, and evaluate the integrative processes and products of their research? We use a self-evaluation approach to assess the integrative processes and products of the first two years of a five-year National Science Foundation Growing Convergence Research project on addressing inland freshwater salinization. To examine the linkages between integration approaches and products, we analyzed the integrative qualities of fifteen research products and the collaborative processes used to generate these products. We found that large, heterogeneous teams with a broad mix of disciplines and professional expertise produced more interdisciplinary research products, but they relied on skilled integration by the leader, more intensive forms of collaboration, and inclusive problem framing. Teams that relied on deliberation by experts and used more consultative or cooperative mechanisms for engagement produced research that was more uni- or multidisciplinary. We consider the efficacy of the various knowledge integration approaches used in this research and share empirically derived recommendations for designing, implementing, and evaluating convergence research. Our findings and lessons provide researchers at the helm of large-scale convergence and transdisciplinary research projects that address complex socio-environmental problems guidance on: (1) the planning and designing of projects with the explicit goal of knowledge integration; (2) the selection and implementation of appropriate knowledge integration approaches and tools; and (3) how knowledge integration can be conceptualized and evaluated for socio-environmental problems.

1. Introduction

Convergence research is a problem-based Research, Development, and Innovation (RDI) approach inspired by the concepts of post-normal, mode-2, and triple helix science paradigms (Funtowicz and Ravetz, 1993; Gibbons et al., 1994; Etzkowitz and Leydesdorff, 2000). It has recently been embraced by funding entities such as the National Science Foundation (NSF) in the United States as an approach for resolving society's grand challenges (NSF, n.d.). Distinct from other problem-based RDI approaches, convergence research emphasizes integration of knowledge across disciplinary boundaries.

Knowledge integration across disciplinary boundaries is a foundational methodology for convergence research (Gajary et al., 2023; Bainbridge and Roco, 2016; Pohl et al., 2008). Knowledge integration has been defined as a multidimensional and interactive process that results in shared understanding and mutual learning (Cockburn, 2022; Pohl and Hadorn, 2007; Lang et al., 2012; Pohl et al., 2021), the synthesis and combination of diverse forms of knowledge, including academic and stakeholder knowledge (Gugerell et al., 2023; Pohl et al., 2021), and practice-oriented solutions (Hoffmann et al., 2017a; O'Rourke et al., 2016). Some scholars reason that there can be no universal model of knowledge integration because convergence research projects vary in scale, scope, purpose and mix of expertise involved, and operate in different cultural, governmental, academic, and industrial contexts (Klein, 2021; van Kerkhoff, 2005). Others have documented the significant structural, interpersonal, communication, and value-based barriers to integrating knowledge across disciplinary, cultural, professional, and sectoral boundaries that undermine the effectiveness of convergence research programs (Klenk and Meehan, 2015; Lotrecchiano and Misra, 2020; Obermeister, 2017; Stokols et al., 2008a).

While a number of scholars have enriched our understanding of the antecedents, principles, elements, methods, and processes of knowledge integration (O'Rourke et al., 2016; Misra et al., 2015; Rodela et al., 2017; Hoffmann et al., 2019; ; Pohl et al., 2021; Andrews et al., 2024) and the collaborative processes and outcomes of cross-disciplinary team science initiatives (Misra et al., 2009; Stokols et al., 2010; Misra et al.,

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2011; Misra et al., 2015), empirical studies that have systematically applied models and methods of knowledge integration and evaluated their intellectual and societal outcomes are still sparse (for exceptions see Hovelynck et al., 2010; Hoffmann et al., 2017a, 2017b; Pohl et al., 2019; Dannevig et al., 2020; Deutsch et al., 2021; Hoffmann et al., 2022b; Karrasch et al., 2022). There is a dearth of research-based, actionable guidance for researchers at the helm of large-scale convergence research enterprises that address complex socio-environmental problems concerning: (1) the planning and design of convergence research projects with the explicit goal of knowledge integration; (2) the selection and implementation of appropriate knowledge integration approaches that align with the realities and contextual circumstances of the projects; and (3) the impacts of knowledge integration and collaboration approaches on integrative processes, short term outputs or products, and long term intellectual and societal outcomes.

To address these gaps and extend the literature on knowledge integration in convergence research, we conducted a self-evaluation (Defila and Di Giulio, 1999; Späth, 2008) at the end of the first two years of a five-year National Science Foundation (NSF) Growing Convergence Research (GCR) project focused on inland freshwater salinization. Our objectives were to:

(1) Develop an analytical framework to examine knowledge integration processes and products that draws on and elaborates existing evaluation frameworks.
(2) Apply the framework to assess the knowledge integration processes and products during the first two years of an NSF GCR project using a self-evaluation approach.
(3) Distill and convey lessons learned that can inform the design and implementation of future convergence research endeavors by addressing the following research questions: How can we evaluate the integrative processes and products of convergence research? What are the linkages between integration approaches and integrative products? How are team composition (i.e., the size of the team, the breadth of disciplines and expertise involved), the level of engagement of actors, and the socio-cognitive framework used for collaboration linked to the integrative quality of research products?

In evaluation research, outputs refer to the immediate, tangible, and measurable results produced during the course of a research project, representing the culmination of specific tasks or activities (Rossi et al., 2018; Thomas and Campbell, 2020). Scholarly products are one type of research output. The quality and quantity of research products, such as scholarly articles, chapters, books, presentations, proposals, and boundary objects, are measured using quantitative assessments and predefined metrics (Misra et al., 2015). Outputs are closely aligned with the specific goals and tasks outlined in the project plan and serve as the direct results of the planned activities.

Outcomes, on the other hand, focus on the broader, long-term, collective effects that multiple outputs or products have on stakeholders or the environment (Rossi et al., 2018; Thomas and Campbell, 2020; Gajary et al., 2023). Outcomes emphasize impact and change over time, representing the ultimate purpose of the project and its broader impacts on individuals, communities, or the environment. Because outcomes are related to the overarching goals and objectives of the project, measuring them requires a more comprehensive approach, combining quantitative and qualitative indicators.

This perspective piece is organized as follows. We first orient readers to convergence research and discuss the overlaps between convergence and transdisciplinarity (Section 2). Next, we provide background information about our convergence research project and conceptualize knowledge integration in the context of our research (Section 3). We then describe the analytical framework we developed to assess the efficacy of knowledge integration tools and approaches (Section 4) and apply it to our convergence research project to evaluate the integrative activities, processes, and products that emerged over the first two years (Section 5). Our results clarify the challenges and opportunities of knowledge integration approaches and the contextual circumstances that may influence their efficacy. We generate empirically derived recommendations that can be used to inform the design, implementation, and evaluation of convergence research projects by practitioners and funders.

2. Convergence research

The overlaps and distinctions between convergence research and other forms of cross-disciplinary research (e.g., multi-, inter-, and transdisciplinary approaches that aim to integrate knowledge across disciplinary, professional, and sectoral boundaries) remain elusive to both RDI funders and scholars (e.g., NASEM, 2019; National Academies of Sciences, Engineering, and Medicine, 2021). As recently as 2019, the National Academies of Science Engineering and Medicine, *Fostering the Culture of Convergence in Research* report, noted that "…significant overlap exists between the terms convergence, transdisciplinary research, and team science" (NASEM, 2019; National Academies of Sciences, Engineering, and Medicine, 2021). Drawing on older formulations and examples of convergence research (e.g., Roco, 2002; 2003), NSF (n.d.) disseminated the following definition of convergence research: "Convergence research is a means for solving vexing research problems; in particular, complex problems focusing on societal needs. It entails integrating knowledge, methods, and expertise from different disciplines and forming novel frameworks to catalyze scientific discovery and innovation." More recently, NSF provided the following elaboration of their definition to acknowledge the overlaps between convergence and transdisciplinary research, "…new frameworks, paradigms or even disciplines can emerge from convergence research, as research communities adopt common frameworks and a new scientific language. In this sense, convergence research is similar to transdisciplinary research, which is seen as the pinnacle of integration across disciplines" (NSF, n.d.). In line with the literature, we have elected to use the term convergence research in this paper, acknowledging its parallels with transdisciplinary research. This decision reflects the increasing prominence of convergence research in the United States, as evidenced by two National Academy of Science, Engineering and Medicine reports on the topic (NASEM, 2019; National Academies of Sciences, Engineering, and Medicine, 2021), as well as its specific appropriateness for this study, which was funded by an NSF Growing Convergence Research (GCR) grant.

3. Background - NSF GCR Project on Inland Freshwater Salinization

NSF's GCR program, one of the agency's "10 Big Ideas," is focused on solving vexing problems focused around societal needs through knowledge integration (NSF, n.d). The societal problem for our GCR project is inland freshwater salinization, which threatens ecosystems and drinking water supplies in streams, rivers, drinking water reservoirs, and lakes across the United States and globally (Bhide et al., 2021; Grant et al., 2022; Hintz et al., 2022). Apart from chronic and acute threshold concentrations for chloride set by the U.S. Environmental Protection Agency (230 and 860 mg/L, respectively), the regulatory regime for managing salt pollution in the United States is inadequate to prevent escalating impacts on human and ecosystem health (Hintz et al., 2022).

In lieu of, or as a complement to, top-down regulation, our GCR project focuses on bottom-up stakeholder-driven solutions to this environmental grand challenge. Specifically, we propose that freshwater salinization can be understood as a common pool resource problem, where the resource is the capacity of inland freshwaters to assimilate salt. Common pool resources differ from traditional public and private goods in two ways: (1) excluding users is difficult; and (2) the use of the resource by one user reduces its availability to other users. Inland freshwater salinization meets both criteria. Practically speaking, it would be difficult to prevent individuals from using excessive amounts of deicer on their driveways during winter or pouring salt-rich products down the sink in their homes—practices that add salt to streams and reservoirs, where they consume salt assimilative capacity. Furthermore, consumption of salt assimilative capacity leaves less available for other users in the watershed.

Our GCR project explores two hypotheses. First, given the absence of a strong regulatory framework, local management of inland freshwater salinization could take the form of collective action arrangements, along the lines of Elinor Ostrom's Social Ecological Systems (SES) framework for Common Pool Resources (Ostrom, 2007, 2009). The purpose of Ostrom's SES framework was, from her point of view, "to enable a diagnostic analysis of SES, from which a scholar would retrieve the variables from the framework that were needed to examine his or her particular case or type of case," thereby "focus[ing] on [the variables] most appropriate for the type of system under study" (Schlager and Cox, 2018, p. 237). Second, this bottom-up approach can be supported, or even possibly catalyzed, through convergence research around the barriers identified by applying Ostrom's SES framework to local conditions (Grant et al., 2022). In short, we propose to tackle inland freshwater salinization by adopting Ostrom's framework for bottom-up management of Common Pool Resource problems as our framework for catalyzing scientific discovery and innovation and integrating knowledge, methods, and expertise, in alignment with the goals of GCR at NSF.

In the context of our project, Ostrom's SES framework served multiple objectives, namely to (1) grasp the complexity of the problem of freshwater salinization; (2) facilitate holistic and systemic thinking through the contextualization of the problem; (3) organize ideas and perspectives on Common Pool Resource management across social sciences, natural sciences, and engineering disciplines; (4) diagnose whether salinization of a particular water body can be addressed through stakeholder-driven, or polycentric, collective action (Ostrom, 2010); and (5) more speculatively, to catalyze bottom-up management of freshwater salinization through focused convergence research around those second-level variables that might locally limit collective action on this issue.

Our testbed, the Occoquan Reservoir, is a drinking water supply for up to one million people in Fairfax County and surrounding communities in Northern Virginia in the United States. It is also one of the first large-scale deliberate indirect potable reuse projects in the United States. That means the reservoir receives inflow from two watersheds, Bull Run and the Occoquan River, and treated wastewater from the Upper Occoquan Service Authority. While the Occoquan Reservoir has provided a reliable source of drinking water for nearly half a century, rising sodium concentrations in the reservoir are reaching levels that can adversely affect the taste of drinking water. If this trend continues, the

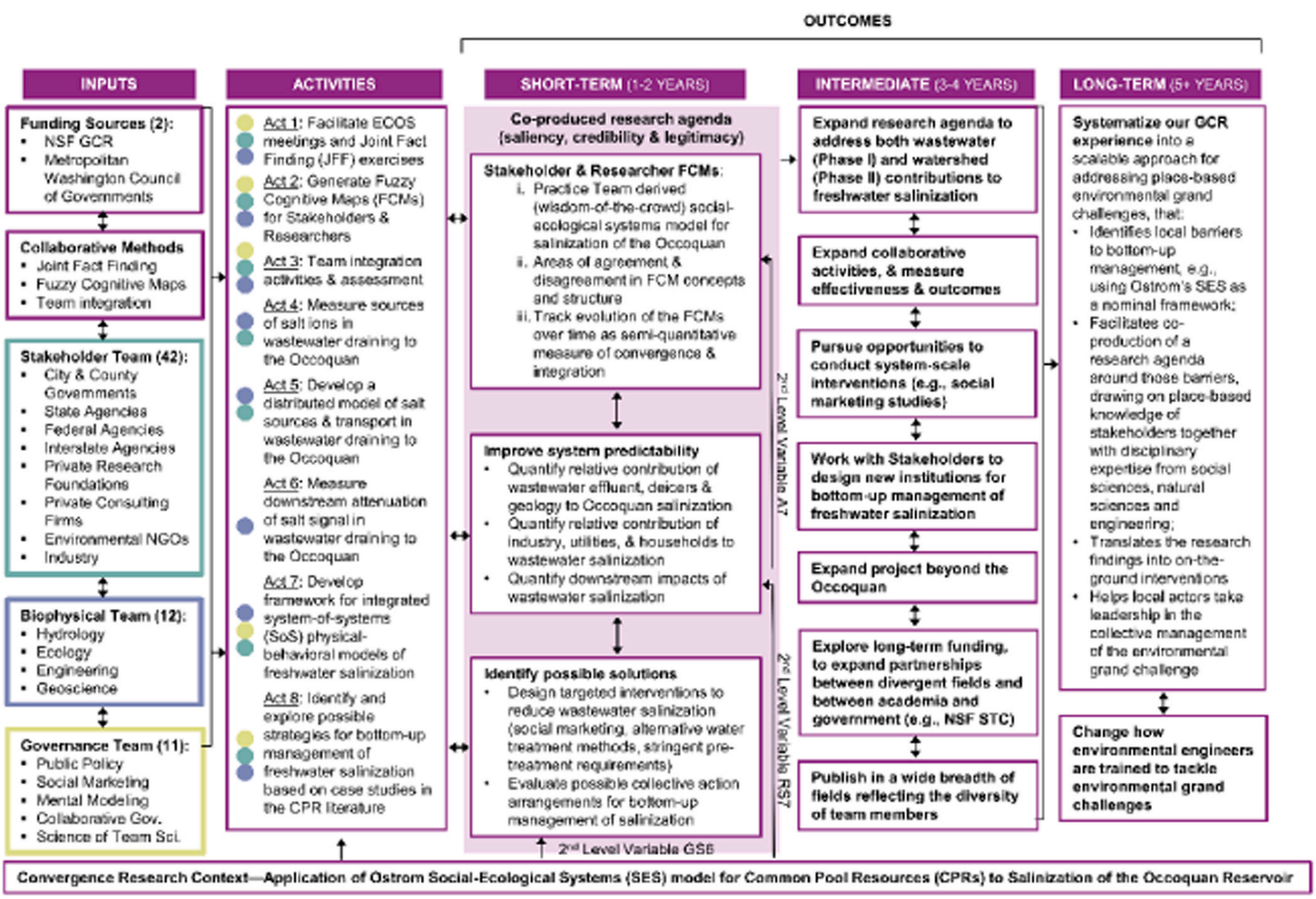

Fig. 1. The Logic Model for the NSF GCR salinization project. Inputs include NSF funding; a set of collaborative methods (including Joint Fact Finding and Fuzzy Cognitive Mapping); a Stakeholder Team consisting of 42 local experts (the Executive Committee on the Occoquan System, ECOS); a Biophysical Team with expertise in hydrology, ecology, engineering and geoscience; and a Governance Team with expertise in public policy, social marketing, mental modeling, collaborative governance, and the science of team science. Research activities are organized into eight "Acts." Colored dots indicate which teams participate in each Act. Most Acts involve two or more teams. The outcomes of Phase I, or "short-term outcomes" are divided into three categories, corresponding to three second-level variables in Ostrom's SES, including: assessment and tracking of stakeholder and researcher mental models; improved system predictability; and the formulation of possible solutions and collective action arrangements to manage salinization. The research agenda and research findings are continuously updated and co-produced with the Stakeholder Team, using joint fact-finding methodologies.

drinking water utility, Fairfax Water, might be forced to upgrade their treatment processes to, in effect, "desalinate freshwater." Such an upgrade could cost a billion dollars, not including brine disposal costs, energy and carbon footprint costs, and lost production capacity. Controlling sodium pollution at its source is the far better option and the focus of our project (Bhide et al., 2021). In Phase I (first two years), we examined sources of sodium in treated wastewater. In Phase II the project broadened its focus to include sources of sodium in the watershed as well.

Because our research agenda is co-produced with stakeholders, the project is in a constant state of evolution. Our project's logic model is presented in Fig. 1. Inputs include NSF funding; a set of collaborative methods, including Joint Fact Finding (JFF) (Karl et al., 2007) and Fuzzy Cognitive Maps (FCMs) (Aminpour et al., 2020); a Stakeholder Team consisting of 42 local experts comprising the Executive Committee of the Occoquan System; a Biophysical Team with expertise in hydrology, ecology, engineering, and geoscience; and a Governance Team with expertise in public policy, social marketing, mental modeling, collaborative governance, and the science of team science. The Occoquan system encompasses at least eight different utilities and government agencies working in very different sectors, including the local drinking water utility (Fairfax Water), the wastewater reclamation facility (UOSA), the state transportation agency (Virginia Department of Transportation, which manages deicer and anti-icer application on state-owned roads), and separate city and county departments in five jurisdictions responsible for winter road maintenance and municipal storm sewer systems, which discharge road salts to tributaries of the Occoquan Reservoir during storms (City of Manassas, City of Manassas Park, Prince William County, Fairfax County). In addition to these entities, our stakeholder team includes state and federal agencies, interstate agencies, private research foundations, private consulting firms, environmental NGOs, and industry representatives.

Phase I research divides into eight activities, or "Acts." As indicated by the colored dots in Fig. 1, most Acts engaged two or more teams. Short-term outcomes (Phase I) are arranged according to the three Ostrom second-level variables, including assessment of stakeholder mental models, improved system predictability, and co-developed solutions and collective action arrangements to manage salinization. The research agenda is co-produced with stakeholders using JFF methods. Intermediate outcomes (Phase II) include an improved understanding of wastewater and watershed salt sources, enhanced collaboration between academics and practitioners, development of interventions and salt monitoring approaches, sustained funding, and scholarship across a wide range of disciplines and fields. Long-term outcomes include a systematic approach for catalyzing bottom-up solutions to environmental grand challenges, along with an environmental engineering workforce that is holistically trained to tackle complex transdisciplinary problems, in alignment with American Society of Civil Engineers education goals.

4. Analytical framework for evaluating the integrative processes and products of convergence research

Three discourses of transdisciplinary integration (e.g., Bammer et al., 2020; Klein, 2023; Laursen et al., 2022; Laursen and O'Rourke, 2019; McDonald et al., 2009; O'Rourke et al., 2016; O'Rourke et al., 2019; O'Rourke and Crowley, 2013; Pohl et al., 2021) are relevant to convergence research. (1) Creation of new overarching frameworks that aim to reorganize the structure of knowledge. (2) Co-production of societally relevant knowledge with extra academic stakeholders where the focus is on "real world" problems. (3) Interrogation and critique of the limits of disciplinary boundaries and the dominant structures of knowledge. While scholars differ on whether the weight of cross-disciplinary integration in convergence research should fall on philosophical reflection, critique, or societal relevance, all three discourses highlight the heterogeneity and relationality of knowledge. Integration approaches of convergence research transcend interdisciplinary approaches because they are mindful of the epistemological origins, logic, and relevance of knowledge to addressing complex problems.

Drawing on O'Rourke et al.'s (2019) analysis of cross-disciplinary team science, we consider integration as both a product and a process. Integration processes give rise to acts of integration, that in turn and over time produce integrative cases and entities that enable or constrain further integrative processes. Furthermore, along a continuum of inputs, processes, and outcomes, the extent of integration may be assessed in terms of its scale (from local to global), the degree of conflict, and the extent of its comprehensiveness (O'Rourke et al., 2016). While integration processes and outcomes are intimately related, the relationship between integrative processes and outcomes remains poorly understood (O'Rourke et al., 2016). For example, little is yet known about intrapersonal dimensions that influence integrative processes, outputs, and longer-term outcomes of cross-disciplinary team science. Further, there is very little research on the qualitative attributes of research products emanating from the collaborative processes in science teams (Gajary et al., 2023; Misra et al., 2015).

Our analytical framework (see Table 1) focused on self-evaluating the processes and products of knowledge integration. That is, we evaluated: (1) specific cases of knowledge integration by assessing the integrative quality of the scholarly products that emerged from our research such as scholarly papers, reports, boundary objects, data, narratives, theories, conceptual frameworks, corresponding to the short-term outcomes in Fig. 1; and (2) the collaborative processes that generated those products. Collaborative processes included the communication and collaboration practices or methods that foster goal alignment, community or practitioner inclusion, and integrative knowledge generation for addressing wicked problems across disciplinary, sectoral, and ecological boundaries (Norström et al., 2020; Piso et al., 2016; Pohl and Wuelser, 2019). The criterion "perceived level of engagement of each actor" was used to describe the collaborative processes (consultation through collaboration) that generated each scholarly product. We also recognize four ideal types of *socio-cognitive frameworks* (Table 5) that research teams may use to organize their collaborations, reflecting the importance of socio-cognitive frameworks for facilitating knowledge integration in cross-disciplinary teams (see Hoffmann et al., 2017 and Hoffmann et al., 2019, based on work by Rossini and Porter, 1979).

To evaluate products of convergence research, we integrated Huutoniemi et al.'s (2010) typology and indicators for analyzing cross-disciplinary documents, Bergmann et al.'s (2005) approaches for transdisciplinary integration, and Misra et al.'s (2015) rating scale for the integrative quality of scholarly products to create two criteria for assessing the scope and type of integration in our research products. The *scope of integration* (Table 3) addresses the extent or range of integration in the research product; and the *type of integration* (Table 4) addresses the integrative depth of the research product. In Tables 2–5, we present details of our four evaluation criteria.

Our self-evaluation was conducted through a reflective and dialogic process that involved all members of biophysical and governance teams (see Fig. 1). Three project team leaders led the development of the analytical framework, evaluation of products, and the statistical

Table 1
Analytical Framework for Evaluating the Processes and Products of Knowledge Integration.

Dimensions of knowledge integration	Evaluation criteria
Knowledge integration process	• Perceived level of engagement of actors • Socio-cognitive framework for facilitating knowledge integration
Knowledge integration products	• Scope of integration • Type of integration

Table 2
Perceived Level of Engagement of Each "Actor" in the Research Activity that Generated the Research Product (Bennett and Gadlin, 2012; Bennett et al., 2018; International Association for Public Participation, n.d; Nabatchi and Leighninger, 2015; Tebes and Thai, 2018).

Consultation: The purpose of consultation is for researchers to invite practitioners, community members, and/or policy makers to provide input or feedback on ideas, findings, or questions.
- It is a one-way form of communication (one group offers their perspective and others receive and act on it).
- There is limited give and take when providing input or feedback. Information, ideas, and perspectives are placed in the hands of researchers with the power/authority to do something (or nothing) with it.
- Some exchange of information is possible in the form of questions or feedback. Ultimately, however, researchers are left to determine the outcome of consultation.

Cooperation: The purpose of cooperation is to obtain mutual benefit by sharing or partitioning work.
- Cooperation involves providing active assistance for a portion of a research project or process.
- It is characterized by frequent consultation and knowledge sharing between team members with clear roles.
- It requires mutual trust, respect and acknowledging the mutual benefit of working together.
- Team members may work or act together for a common purpose, but interaction between team members is not essential to accomplish tasks.
- Cooperation does not involve recursive processes.

Coordination: The purpose of coordination is to avoid gaps and overlaps in individuals' assigned work and accomplish objectives efficiently and effectively.
- Coordination requires mutual understanding of research and team objectives.
- It requires team members to understand "who needs to do what by when" as well as the proper ordering of tasks and how they interrelate.
- It often includes problem resolution mechanisms.

Collaboration: The purpose of collaboration is to achieve collective goals that participants would be incapable of accomplishing if working alone.
- Collaboration involves working with others to achieve a shared purpose.
- It involves open communication, mutual trust and respect.
- It uses a recursive process, where people or organizations work together to realize shared goals.
- It is more than the intersection of common goals seen in cooperation. A sense of urgency, commitment, and deep, collective determination to reach an identical objective is evident.
- Collaboration involves creative endeavors that leverage complementary, diverse skills and knowledge.
- It necessitates knowledge sharing, learning, and building corroboration and consent.

analysis. One of these leaders has expertise in evaluation of the collaborative and integrative processes and products of cross-disciplinary research, one leads studies on the sources, fate, and transport of salt ions in the Occoquan system, created our stakeholder team (the Executive Committee on the Occoquan System) and interfaced with our stakeholders, and the third project leader was responsible for leading studies that characterized stakeholders' understanding of the social ecological system through fuzzy cognitive mapping. All three project leaders also served as boundary spanners (Klein, 2021) and were closely involved in all project activities making them good candidates to rate the intellectual and integrative qualities of the scholarly products that resulted in the first two years of our project.

In the first stage of self-evaluation, each project leader reviewed and rated fifteen scholarly research products based on the *perceived level of engagement of each actor* in the activity that generated them (Table 2) as well as their *scope of integration* (Table 3), *type of integration* (Table 4), and *socio-cognitive framework* (Table 5) using the definitions and criteria described in Tables 2–5. The three leaders then discussed the similarities and differences in their individual ratings and came to an agreement about how each scholarly product should be classified according to our evaluation criteria.

The following rules were used to select scholarly products for inclusion in our analysis. First, the product must be archived and retrievable. For posters and presentations, only those that had accessible, peer reviewed abstracts were included. Second, the product had to be directly related to our NSF GCR activities. That is, products that cited the grant but did not result from consultative, cooperative, coordination, or collaborative activities with other project team members or practitioners were excluded. Third, the product must be related to inland freshwater salinization. Collaborative papers with other project team members on topics not related to freshwater salinization were not included.

For each scholarly product (publication, poster, conference presentation, or book chapter), project leaders only counted team members and practitioner stakeholders as "actors" if they were listed as authors or mentioned in the acknowledgements, or if they actively shaped how the study was conducted. Any individual who was classified as an "actor" was assigned a disciplinary or professional expertise based on their self-reported expertise or disciplinary affiliation.

We employed agglomerative hierarchical cluster analysis to identify groups of research products with comparable collaborative processes with respect to the number of participating actors or disciplines, the socio-cognitive framework employed, the scope and type of research integration, and the level of engagement (package FactoMineR, R Core Team version 4.4.0; Lê et al., 2008). Tied ranks were computed for all numerical variables (e.g., number of actors, number of disciplines). Variables with categorical levels (for instance, level of engagement - consultation, cooperation, coordination, and collaboration) were recast as ordinal (e.g., 1, 2, 3, 4) prior to analysis. Euclidean distance was estimated for the normalized ranks of all variables, and clusters were determined using the farthest neighbor (complete) linkage (Davis and Sampson, 1986). Scree tests and the gap statistic were used to identify the optimal number of clusters (i.e., the number of groups of research products with distinct collaborative processes) (Tibshirani et al., 2002).

5. Findings of self-evaluation of knowledge integration processes and products

First, the results of our self-evaluation revealed that the early phases of a convergence research initiative can involve a variety of research approaches and products from team-based unidisciplinary work to interdisciplinarity (note the variety of cross-disciplinary types evident in Fig. 2). These approaches and integrative quality of the products can be expected to shift and evolve as team members get to know each other and each other's work, begin to develop an understanding of the potential contributions of different disciplines, build relationships and trust with stakeholders, develop integrative skills and capacity, and advance systems, target, and transformation knowledge relevant to the

Table 3
Scope of Integration (Adapted from Huutoniemi et al., 2010).

Narrow cross-disciplinarity: Research products that synthesize theories, methodologies, or approaches of closely related or compatible disciplines (e.g., physics and mathematics) usually dealing with the same level of analysis (e.g., molecular biology and genetics).

Broad cross-disciplinarity: Research products that bridge theories, approaches, or methodologies of widely disparate disciplines (e.g., history and biology) at different levels of analysis (e.g., immunology and psychology)

Table 4
Type of Integration (Tress et al., 2005; Huutoniemi et al., 2010; Misra et al., 2015; Bergmann et al., 2005, Rosenfield, 1992; Klein, 2007; Stokols et al., 2008a; Stokols et al., 2008b; NRC, 2014; Gajary et al., 2023; Lotrecchiano and Misra, 2018; NASEM, 2019).

Definitions	Type of integration in the research product
Unidisciplinary collaborative research: Participating actors are scholars or researchers from a single discipline or field who work together to address a common research problem through a singular disciplinary lens.	***Unidisciplinary*** research products include one or more of the following: • Integration between disciplines and fields does not occur. • A research group with closely related or overlapping interests from the same or closely related disciplines or fields. • Topics or themes from the same or closely related fields or disciplines are brought together to address a common research problem. • Disciplinary concepts and methods are retained. • Work occurs independently or sequentially. • Expertise with the same or closely related fields is modularized to produce new knowledge. Interaction between actors is mostly technical (i.e., research tasks are externalized to different expertise within the same discipline or field), after which findings are aggregated. • Interaction between actors is coordinated rather than dialogic.
Multidisciplinary collaborative research: Participating actors are scholars or researchers from two or more disciplines or fields who work independently or sequentially and come together periodically to share their perspectives and achieve a broader-gauged analysis of a common research problem. Actors remain conceptually and methodologically anchored in their respective fields - multiple actors in a collaboration may share research goals, but the problem is fundamentally examined by each actor through a singular disciplinary lens.	***Multidisciplinary*** research products include one or more of the following: • A coordinated plan for transferring knowledge between different disciplinary modules. • A diverse research group with related interests but minimal intellectual interaction or synergy between topics or themes. Work occurs independently or sequentially. • Topics or themes from different fields or disciplines are brought together, but not combined (i.e., they are applied to different research questions. Disciplinary concepts and methods are retained). • Expertise in different fields is modularized to produce new knowledge. Interaction between fields is mostly technical (i.e., research tasks are externalized to different fields), after which findings are aggregated. • Interaction between fields is coordinated rather than dialogic. • Theories or concepts are borrowed from one field and applied to another. • Intellectual interaction between fields is limited to the problem context. • The research or societal problem is cross-disciplinary, but concepts and goals are only shared at a general level without advanced synthesis at the level of hypothesis generation, operationalization, or application. • Methodology or findings are not integrated across disciplines.
Interdisciplinary collaborative research: Participating actors are scholars or researchers from two or more disciplines or fields who engage in an interactive and collaborative process aimed at integrating information, data, methods, tools, concepts, or theories, drawing on their own disciplinary perspective in order to address a complex question, problem, topic, or theme. Communication across knowledge boundaries is essential to interdisciplinary research, although actors remain anchored in their respective fields.	***Interdisciplinary*** research products include one or more of the following: • Data integration from different fields to investigate relationships between phenomena. • Evidence from different disciplines is used to test hypotheses, address a research question, or produce new knowledge for policy makers. • Research is hypothesis driven and posits causal links between constructs. • Reanalysis of existing datasets within a new integrative context.
Transdisciplinary and convergence collaborative research: Participants engage in problem-oriented research that crosses the boundaries of academic, public, and private spheres by engaging researchers, scholars, practitioners, and community members in knowledge co-production. Transdisciplinary research aims to generate overarching synthetic conceptual and methodological frameworks that transcend disciplinary worldviews. A high degree of collaboration between actors and communication across knowledge boundaries is essential to build a common set of concepts and metrics as well as shared understanding about goals.	***Transdisciplinary*** research products include one or more of the following: • Translation of societal problems into research questions or hypotheses that are jointly formulated. • Comparative analyses of concepts, theories, or models from different fields that spur development of new theories. • Integrative method development that involves the elaboration of unidisciplinary methods. • Shared understanding of concepts and theoretical frameworks across disciplines. • Content that creates generic links between fields. • Content that creates a new territory of knowledge, or paradigm of inquiry. • Triangulation of two or more methodological approaches in order to develop a comprehensive understanding of a problem or phenomenon, or a new methodology. • Assessment procedures that synthesize criteria from different disciplines and professional perspectives. • Methodologies that are developed and combined in a novel way (not merely juxtaposed or borrowed) so that they constitute a harmonious whole. • The development of models or applications that link theory and practice. • Creation of boundary objects that foster mutual understanding across cognitive and normative boundaries.

Table 5
Socio-cognitive frameworks used by teams or sub-teams to organize collaborative activities to generate research products (Rossini and Porter, 1979).

Socio-cognitive framework	Definition
Common group learning	Integrative processes occur through reflection and dialogue among the entire research team resulting in shared understanding
Modelling	A conceptual framework or model is created by one or a few team members. Other team members contribute information or apply the conceptual framework or model to address questions or generate findings.
Deliberation/negotiation among experts	Integration takes place during one or more rounds of exchange among two or more team members (including practitioners and researchers)
Integration by leader	A team leader acquires composite knowledge and performs knowledge synthesis through one-on-one interactions with team members (including practitioners and researchers)

socio-environmental problem they are tackling (Pohl and Hadorn, 2007).

Second, the results of our cluster analysis indicate that larger and more heterogeneous teams with a broad mix of disciplines and professional expertise produced more interdisciplinary research products

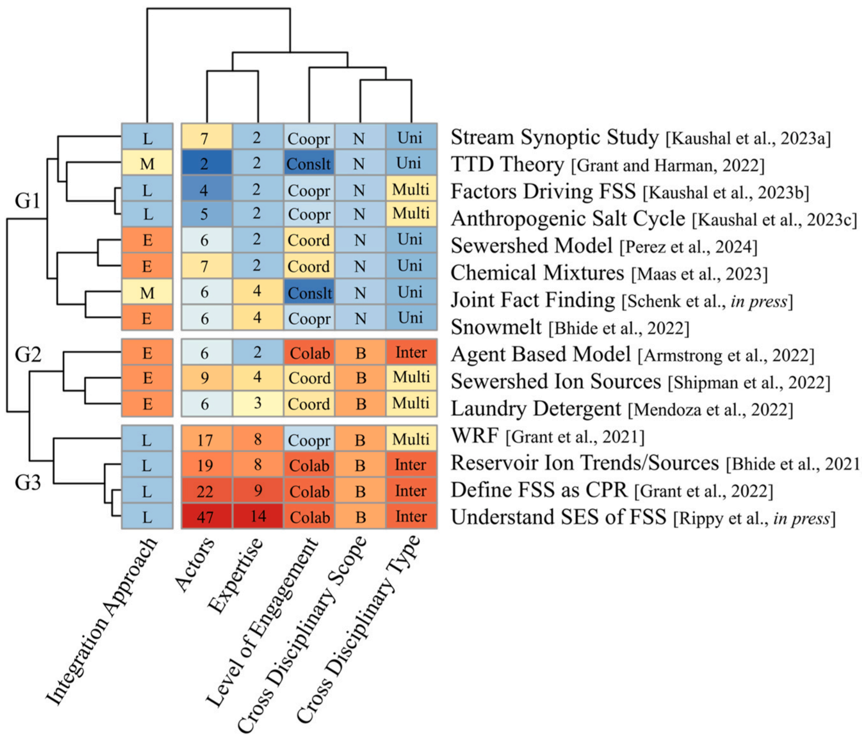

Fig. 2. Fifteen research products are clustered into three groups based on an assessment of knowledge integration across multiple dimensions (see G1-G3 on the left dendrogram; groups are separated by white horizontal lines). The dendrogram on the top illustrates associations among evaluation criteria, with "integration approach" separating out from the rest (white vertical line). Evaluation criteria are reported on the *x*-axis and individual research products are reported on the *y*-axis. Cell color indicates the rank of each evaluation criteria (low = blue; high = red), and cell labels indicate the specific category or number (e.g., type of integration, number of actors) each variable takes on for each product. Categories for type of integration include: L – integration by leader, E – deliberation by experts, and M – modeling. Categories for level of engagement include: Colab – collaborative, Coopr – cooperative, Coord – Coordination, and Conslt – Consultation. Categories for cross-disciplinary scope include: B – broad, and N – narrow. Categories for cross-disciplinary type include: Inter – interdisciplinary, Multi – multidisciplinary, and Uni – unidisciplinary. The following abbreviations are used for research products: TTD – Transit Time Distribution, FSS – freshwater salinization syndrome, WRF – Water Research Foundation, CPR – common pool resource, and SES – social ecological system (Bhide et al., 2022; Grant and Harman, 2022; Grant et al., 2021; Hoffmann et al., 2022a; Kaushal et al., 2023c; Kaushal et al., 2023a; Kaushal et al., 2023b; Maas et al., 2023; Mendoza et al., 2022; Perez et al., 2024; Rippy et al., in press; Shipman et al., 2022; Thompson et al., 2017; Schenk et al., 2024; Armstrong et al., 2022).

(compare G3 to other clusters, Fig. 2). These teams relied on skilled integration by a single team leader, intensive collaboration, and inclusive problem framing to generate products that were interdisciplinary. Smaller sub-teams that had a narrower range of disciplines or expertise were more likely to rely on deliberation by experts as their socio-cognitive framework (this was particularly evident for G2 projects, Fig. 2). They also tended to use consultative, cooperative, or coordinative mechanisms for engagement, in lieu of collaboration, and were more likely to produce research products that were unidisciplinary (see, for instance, G1; Fig. 2).

In preparation for kicking off Phase II (years 3–5) of our research project, the three project leaders organized a two-day workshop that involved all research team members, where the preliminary results of our self-evaluation were shared and discussed. The primary goal of the workshop was to build team cohesion by reflecting on our research activities, discussing areas for improvement, and proposing changes to further promote cross-disciplinary and cross-sectoral knowledge integration. Team members' reflections on the implications and meaning of these results are discussed in the next section.

6. Conclusions and recommendations for convergence research initiatives

A central challenge for project leaders at the helm of large-scale team science initiatives is selecting the most effective organizational set up for knowledge integration (Arpin et al., 2023). Some questions leaders often grapple with include: (1) Should we keep our team structure integrated by forming one big group to work toward our shared goals shoulder to shoulder, or should we differentiate tasks by breaking work into its components assigning the pieces to subgroups? (2) Should tasks be specialized so that trained specialists perform a smaller repertoire of tasks more expertly? (3) How large should subgroups be so that the span of control for a single leader is not overwhelming? (4) Should decision making authority be centralized or should authority be delegated? (5) What kinds of collaborative arrangements best foster knowledge integration across disciplines, sectors, worldviews, and orientations? (6) At the same time, how can convergence and divergence be balanced in convergence research? Our self-evaluation approach resulted in dialogue, reflection, and critical assessment of the collaborative processes, organizational structure, scholarly products, and longer-term outcomes of our research project. The analytical framework and assessment process described here and the insights we have generated have practical implications for a wide variety of cross-disciplinary teams addressing complex research problems.

Our first recommendation is that teams should pay attention to the composition (size, disciplinary expertise represented, and the integrative capacity and orientation of the leaders and members) of project subteams focused on specific aspects of the larger project early in their research project (Boon et al., 2014; Lux et al., 2019; Pärli, 2023). In our case, we found that if the team addressing the problem or question is large and heterogenous (that is, includes wide variety and breadth of disciplines and expertise), it is more likely that the problem or questions will be framed inclusively at the outset. However, contextual conditions, such as the integrative capacity of the leaders and the collaborative mechanisms used to facilitate research are important moderators of the relationship between team size and composition and the integrative quality of products. Furthermore, conceptualizing problems and questions too narrowly at the outset can hinder cross-disciplinary integration.

Second, the question of who integrates is an important one. While knowledge integration is conceptualized as “shared understanding” and a team-level phenomenon in the literature, the reality, at least in the case of this initiative, is quite different. Highly integrative products were linked to skilled integration by a single leader or small group of members under conditions of intensive collaboration and inclusive or broad problem framing. While consultation, coordination, or cooperation can be appropriate or even necessary modes of engagement in a convergence research project, they may not result in highly integrative and transformative research products. In the early stages of our project, we found that team members differed with respect to their transdisciplinary orientation (Misra et al., 2015), collaborative readiness (Stokols et al., 2008a, 2008b), and levels of engagement, commensurate with funding realities and resource constraints, coordination challenges of remote collaborations, and the time needed to build trust among team members who do not have a history of collaboration. We found that the majority of integrative insights emerged through intensive dialogue within small groups of team members or reflection by a single member, rather than team-wide deliberations. This suggests teams should build in time for small group reflective activities focused on generating integrative insights since they are likely to be particularly beneficial in the early stages of convergence projects and result in higher levels of cross-disciplinary integration (Roux et al., 2010). In line with a growing body of research that calls for legitimizing the role of integration experts (Hoffmann et al., 2022b) and boundary spanning leadership (Taylor et al., 2021; Kaufman and Boxshall, 2023; Andrews et al., 2024), we find that skilled integrative leadership and capacity is critical for creating collaboration opportunities, easing power imbalances between academics and practitioners, and facilitating mutual learning and community building (Mattor et al., 2014; Obermeister, 2017; Kareem et al., 2022; Jacobi et al., 2022).

Our reported findings and recommendations must be considered in light of certain limitations. First, our analytical framework is limited in that it focuses only on knowledge integration products and processes, and not longer-term outcomes. Second, while all research team members reflected on the findings of the evaluation and provided input for recommendations, only three project leaders were involved in rating of the products and processes based on our analytical framework. Our team of professional stakeholders did not participate in this intermediary self-evaluation process. While these three project leaders had different domain expertise that represented the scholarly products generated by our team and were trained to evaluate cross-disciplinary research, it is possible that the findings would be more robust if other team members and stakeholders rated the integrative scope and depth of each scholarly product and the collaborative processes that generated them. Stakeholders may be more capable of assessing the future societal impact of scholarly products as compared to researchers. They may have different perspectives on the collaborative processes and socio-cognitive frameworks that generated the scholarly products. We are addressing some of these limitations through a summative evaluation study that incorporates stakeholders’ perspectives of knowledge integration. That larger ex-post evaluation study will also incorporate the experiences and perspectives of graduate students and postdoctoral scholars on the project and include other measures and metrics of knowledge integration beyond scholarly products, such as social learning and changes in researchers’ transdisciplinary orientation (Misra et al., 2015) over time.

Limitations notwithstanding, our analytical framework together with our self-evaluation process provide one approach that convergence research practitioners can use to review and appraise their own research processes, reflect on how they may facilitate or constrain relationships between academics, practitioners, and community members, and engage in double-loop learning (Klenk and Meehan, 2017; Lux et al., 2019; Verwoerd et al., 2020). The four criteria for evaluating knowledge integration processes and products, namely, perceived level of engagement of actors, socio-cognitive framework for facilitating knowledge integration, scope of integration in scholarly products, and type of integration in scholarly products, along with the associated indicators (Tables 2–5) synthesize a large body of literature on evaluating cross-disciplinary team science and are applicable to wide variety of settings, contexts, problems, and teams. Our approach provides one way to link integrative and collaborative processes to the integrative quality of products, thereby addressing a gap in the research on the linkages between knowledge integration processes and products. It is, however, exploratory and intermediary, since it does not incorporate the linkages between knowledge integration processes, concrete products, and the longer-term individual, community, and environmental outcomes of convergence research projects.

Our self-evaluation approach has advantages and limitations. First, the advantages. Self-evaluations, both intermediary and ex-post, can be valuable in encouraging double-loop learning (Cosens et al., 2021; Argyris, 1977) potentially improving individuals’ and teams’ capacities for designing and managing convergence research projects. The reflective and dialogic process central to self-evaluations can facilitate sharing of experiences and perspectives, constructive self-criticism, and course corrections if necessary. Self-evaluations are often feasible when the resources for larger scale external evaluations are lacking. They can also help to make the specific procedures and conclusions of evaluation transparent to team members, reviewers, and funders. Given that self-evaluation is less demanding, it is more likely that team members apply what they have learned through the process. Self-evaluations can be tailored to the specific normative aspects of a particular research project along with aspects of knowledge integration processes, products, and even longer-term outcomes resulting in more robust evaluation criteria and indicators. Finally, self-evaluations can be the starting point for more discursive forms of evaluation of convergence research projects. They can shape decisions about future phases of long-term projects, new research, and inform strategic recommunication of project results (Defila and Di Giulio, 1999; Späth, 2008).

Time, effort, and expertise are key limiting factors for self-evaluations. Although they are less resource intensive than external evaluations, they remain demanding and challenging to conduct. They require team members to be open to engaging in deep reflection and dialogue and, if not facilitated well, they can lead to unproductive conflict. Team members may disagree on the evaluation criteria and indicators. Members may be susceptible to social desirability bias, overestimate their competence and performance, disagree with the conclusions, and resist change to address limitations. Seeking input from members beyond the core research team, for instance, an advisory board or stakeholder team, could help address some of these limitations. We recommend that teams devote time to this kind of self-examination, especially early on in their project, aimed at generating insights into the nature of boundary spanning work, assessing the relevance and intellectual and societal impacts of their research, and evaluating how they might better plan, design, and implement their research with the explicit goal of knowledge integration.

CRediT authorship contribution statement

Stanley B. Grant: Writing – review & editing, Visualization, Validation, Resources, Project administration, Investigation, Funding acquisition, Formal analysis. **Megan A. Rippy:** Writing – review & editing, Visualization, Validation, Project administration, Investigation, Funding acquisition, Formal analysis. **Shalini Misra:** Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Data Availability

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

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