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Research, part of a Special Feature on Convergent Science for Sustainable Regional Systems

Convergence research as transdisciplinary knowledge coproduction within cases of effective collaborative governance of social-ecological systems

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ABSTRACT. Successful collaborative governance (CG) of social-ecological systems (SES) involves multiple stakeholders convening iteratively over the long term to reach a commonly held vision. This often involves building knowledge for social learning processes induced to come to collective decisions about managing complex systems in flux. Because of the complexity of any SES in the Anthropocene, this coproduced knowledge is frequently transdisciplinary, using a convergence of applied and scientific knowledge from a variety of disciplines and stakeholders outside academia. We find evidence that these cases of effective SES CG involve both knowledge coproduction and convergence research. We evaluated seven case studies of CG across four continents using criteria (principles and methods) developed to facilitate and describe convergence research on SES and found them to be largely present. We also assess these CG cases using indicators of knowledge coproduction, and show that they all involved transdisciplinary knowledge coproduction, which can provide an informative lens for deepening our shared understanding of convergence and its application to complex adaptive systems. All the cases selected for this paper are examples of CG of SES in which research was conducted as part of a collaborative effort to improve the social-ecological conditions in a particular place, and several incorporate various forms of knowledge and ways of knowing. We suggest that these cases demonstrate both convergence research and knowledge coproduction because of the overlap and similarity of these concepts, providing a brief comparison and contrasting of these approaches to addressing sustainability problems collaboratively.

Key Words: *collaborative governance; convergence research; interdisciplinary research; knowledge coproduction; social-ecological systems; transdisciplinary research*

INTRODUCTION

The Anthropocene, characterized by rapid change as a result of unprecedented human impact to the Earth's climate and ecosystems, has brought about urgent challenges that require adaptive governance, and varied forms of collaboration to foster social and institutional learning and action (Schusler et al. 2003, Rockström et al. 2009, Berkes 2017, Schoon and Cox 2018, Rodela and Gerger Swartling 2019). Social-ecological systems (SES) are facing multifaceted problems, such as climate change, habitat loss, introduction of novel species, and shifting patterns of human utilization and pressure, which have the potential to impact the well-being of people at local, regional, and, potentially, global levels. Addressing these landscape-scale issues in equitable ways requires cross-cutting team science; adaptive, collaborative management; reflective practice; and coproduction of knowledge (Cockburn et al. 2020).

Transdisciplinary approaches, involving integration of disciplines and boundary-spanning across organizations (OECD 2020), have been recognized by science and policy platforms such as the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) as key sources for credible and relevant information needed for addressing complex social-ecological challenges (Tengö et al. 2017, 2021). Long-term perspectives from local knowledge systems can also be used to complement scientific observations (Schick et al. 2018) and capture local and context specific insights that are necessary for inclusive and long-term transformative actions (Tengö et al. 2021). Additionally, engaging stakeholders in management has positive spillover effects including the education of resource users while also improving the legitimacy of rules (Fujitani et al. 2017).

Convergence research is gaining momentum within the scientific community as an approach for producing knowledge addressing urgent social challenges (Peek et al. 2020). The National Science Foundation (NSF) of the United States aims to facilitate the acceleration of convergence research to help navigate pressing problems in society. According to the NSF, convergence research is solutions-oriented, driven by a specific compelling problem, shows deep integration across disciplines, and intentionally brings together intellectually diverse scholars to develop effective ways of communicating across disciplines (NSF 2024). Here, we adapt the definition of convergence research from Peek et al. (2020): an approach to knowledge production and action that involves diverse teams working together in novel ways—transcending disciplinary and organizational boundaries—to address vexing social, economic, environmental, and technical challenges to promote collective well-being.

Studies of convergence research have shown that the integration of experts from different disciplines pursuing a common research agenda can result in the emergence of new frameworks and paradigms (or even new disciplines), as these communities adopt shared language, methodologies, and theories from one another (Sundstrom et al. 2023). Although convergence is similar to the concept of transdisciplinary research, the latter explicitly bridges the "gap" between practice and science by involving actors from practice as well as science and policy. The NSF describes transdisciplinary research as "the pinnacle of integration across disciplines" (NSF [date unknown]). This process of knowledge coproduction, the collaborative production of knowledge among actors situated across the boundaries of science, practice, and policy (Wyborn 2015, Lemos et al. 2018), asks participants to

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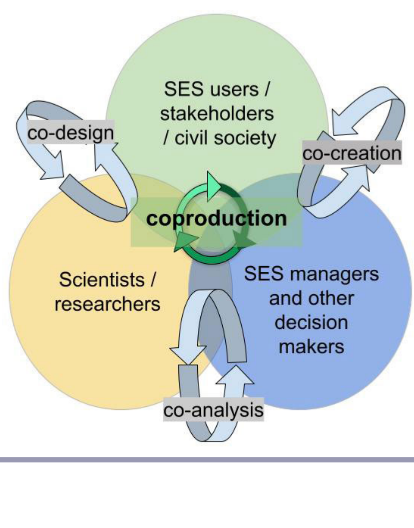
reconcile their diverse perspectives and coevolve their understanding of a social-ecological issue to generate new insights (Roux et al. 2017, OECD 2020). Although this is similar to processes described in convergence research (Peek et al. 2020, Moran et al. 2022), knowledge coproduction is not explicitly part of the definition of convergence.

Although there is literature on convergence research and its impact in addressing pressing social challenges, there are few studies exploring the connection between convergence research and other proven approaches to solving urgent social problems, such as knowledge coproduction or adaptive collaborative governance (CG) of SES. CG of SES is increasingly considered an effective approach to creating public value and improving outcomes, and knowledge coproduction is often part of the value creation process in CG arrangements (Wyborn 2015, Koontz 2019, Vignieri 2020, Chambers et al. 2021, Muhl et al. 2023).

Studies of socially engaged models of scientific inquiry suggest that knowledge produced collaboratively with practitioners has a much greater likelihood of having real impact on policy and practice (Beier et al. 2017, Arnott et al. 2020). This process of knowledge coproduction involves knowledge users and producers collaborating at every stage of a project's development and has emerged as a promising approach to producing new knowledge about and resolving social and environmental issues (Ostrom 1996, Lemos et al. 2018). Knowledge coproduction in the CG of SES can be understood as a cyclical, iterative process of codesign, cocreation, and coanalysis with managers and decision makers, scientists, and stakeholders (Fig. 1) where diverse practices, disciplines, and knowledge systems can be reconfigured to generate new transdisciplinary knowledge (Audia et al. 2021). All overlapping categories of collaborators can be involved in these three highlighted processes of coproduction (codesign, cocreation, and coanalysis), although some may be more suited to certain aspects than others, and these processes may have a temporal element to them, occurring mainly at certain stages in the process.

Fig. 1. Knowledge coproduction in the collaborative governance of social-ecological systems (SES) as a cyclical, iterative process of codesign, cocreation, and coanalysis with SES managers, decision makers, scientists, SES users, and stakeholders from civil society.



Because knowledge coproduction involves users in the creation of knowledge, or science, and CG includes stakeholders in the management of SES, knowledge coproduction is a logical component of CG, and offers an applied example of convergence research in action. CG of SES is a ripe field for illustrative cases that can inform the use of convergence research in the practice of managing SES. The CG context shapes the nature of research conducted, because of the imminent usage of the knowledge produced, the urgency of the need for the knowledge, the diversity of actors involved, and the disparate sources of funding. The presence of public agencies in many cases brings practical management experiences, resources, and a heightened potential for using the resulting science. The social learning inherent in the processes of codesign, coanalysis, and cocreation is necessary for collaborative natural resource management (Schusler et al. 2003, Berkes 2009a, Berkes 2017).

Effective CG of SES demands the integration of diverse forms of knowledge, transcending the traditional boundaries of disciplinary silos. In this context, the interactions between different ways of knowing, including tacit knowledge, traditional ecological knowledge, and local knowledge, with scientific knowledge have emerged as a critical area of study (Berkes 2009b). Tacit knowledge is embedded in the daily activities of communities, and its value lies in its practical wisdom and experiential insights. Literature on knowledge coproduction recognizes the need to tap into tacit knowledge by engaging local communities and practitioners to better understand the dynamics of social-ecological systems (Cash et al. 2003, Beier et al. 2017). Convergence research, which seeks to bridge gaps between disciplines and knowledge systems, can harness the potential of these various knowledge forms for CG, facilitating hybridization, adaptation, sustainability, and transformation (Angeler et al. 2020).

Here, we examined seven case studies of CG from various locations around the world and found evidence that these cases of effective SES CG involve both knowledge coproduction and convergence research. We evaluated these case studies using criteria (principles and methods) developed to facilitate and describe convergence research on SES and found them to be largely present. We also assess these CG cases using indicators of knowledge coproduction and show that they all involved transdisciplinary knowledge coproduction. All the cases selected for this paper are examples of CG of SES in which research was conducted as part of a collaborative effort to improve the social-ecological conditions in a particular place, and several incorporate various forms of knowledge and ways of knowing. We suggest that these cases demonstrate both convergence research and knowledge coproduction because of the overlap and similarity of these concepts, providing a brief comparison and contrasting of these approaches to solving sustainability problems collaboratively.

METHODS

We assess the presence of characteristic indicators of convergence research and knowledge coproduction in seven cases of collaborative SES governance using metrics designed to describe and identify convergence research and knowledge coproduction. The research design is descriptive, not testing a hypothesis or attempting to assign causality (Gerring 2017). Our purpose is not

Table 1. Case studies of collaborative governance of a social-ecological system involving convergence research.

Case study	Brief description of the case study	Scientific disciplines converging	How convergence research was used in practice in each case
Brazos River water security project in TX, USA	Siting green infrastructure for system resilience and water storage in the Brazos River, Texas	Remote sensing, flood modeling, reservoir engineering, socio-hydrology, economics	The corporate sector wanted greater water availability and storage and the potential for increased flexibility in water markets. An NGO partnered with interdisciplinary teams of ASU scientists and coordinated with Texas state and federal agencies to coproduce a research agenda for Brazos River system resilience
University-led rural revitalization in Hong Kong	Community, ecological, and economic revitalization in Lai Chi Wo Village, Hong Kong	Ecology, agroforestry, social science, economics	Centre for Civil Society and Governance from the University of Hong Kong facilitated ecological baseline studies of the area, and coled ecological, social, and economic revitalization efforts with the local community. The community took the lead in determining the social dynamics of the project. These practices formed the basis for the Centre's research, rather than the reverse scenario.
White Mountains Stewardship Project, USA	Forest restoration, wildfire prevention, and economic revitalization in eastern Arizona, USA	Ecology, forestry, conservation biology, environmental history, economics, environmental management	Multiparty monitoring board commissioned studies to inform restoration efforts, which ultimately required integration of ecological, historical, and economic knowledge to make management decisions
Serengeti's future land use change scenarios, Tanzania	Scenario planning of future land use and land cover change, biodiversity conservation, food production, and sustainable development at the Serengeti ecosystem, Tanzania.	Environmental science (forestry, wildlife management, paleoecology, biodiversity conservation), social science, veterinary science, archaeology, environmental history, road engineering	Pathways to desirable and sustainable futures developed with diverse stakeholders, strategizing solutions to local challenges including ongoing fragmentation of wildlife habitats, biodiversity loss,climate change impacts, and land degradation
Central Arizona Conservation Alliance, USA	CAZCA coordinates a system of regional natural open spaces throughout central AZ to coordinate conservation and habitat restoration using volunteer groups. Geographic scope includes a complex mosaic of land managers and land uses.	Botany, restoration ecology, conservation biology, natural resource management, social science	An applied collaborative conservation approach is key to the function of this network. The science team synthesizes the best available science for local habitat restoration (invasive plant monitoring and management, native plant production), and this is translated into action through public outreach and engagement, using teams of volunteers to monitor and restore natural areas throughout the region.
Water-Energy-Food Nexus, Switzerland	Identifying governance interventions (leverage points) to increase coordination between the different sectors (hydropower production, biodiversity, and agricultural irrigation) in Water-Energy-Food Nexus cases in Switzerland.	Hydrology, governance, economics, biodiversity	Different scientific disciplines were brought together to create a system understanding, and then workshops were held with decision makers from the Swiss Federal Offices for Energy, Agriculture, and Environment to improve understanding of the larger interlocking social and ecological systems, and to identify governance interventions.
Upper San Pedro Partnership, USA	Watershed partnership was formed to achieve sustainable yield of the Sierra Vista Subwatershed regional aquifer	Hydrology, biogeography, ecology, biology	Because of historical conflict about water, and the ecological complexity of the San Pedro watershed, there was a need for robust and neutral science that stakeholders could all agree upon. Based on this need, stakeholders have developed robust scientific understanding of water systems, provide policy recommendations for regional stakeholders. This information is now available to all through a website.

to compare the cases, but rather to look at them collectively, to add to the knowledge base about these emergent fields of research through the examination of how knowledge coproduction and convergence research show up in cases of CG of SES.

We included cases using two criteria: first, it must be a case of CG of a SES, and second, the case involved knowledge building and/or social learning in service of problem-solving (Trimble and Plummer 2019). The demand for knowledge and learning creates the opening for coproduction and/or convergence of knowledge. Experts with deep knowledge of particular cases of CG of SES were invited to contribute to this study. We worked together to agree upon the analytical approach to assessing the cases. Although we do not engage in investigations of relationships between variables, we are interested in what aspects of knowledge coproduction and convergence research tend to be present in cases of CG of SES.

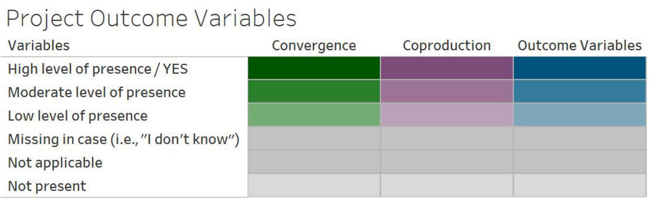
Table 1 lists the case studies, with brief descriptions about main goals and activities of CG, and the apparent usage of convergence research. All our cases included at least 3 scientific disciplines, including ecology, economics, forestry, hydrology, wildlife management, and botany. The cases are driven by governmental, NGO, and/or corporate actors.

To evaluate the levels of presence of the indicators (see Appendix 2) across the case studies, we used an ordinal scale (from high to absent), using a gradient of colors to present the degree of presence (see Table 2). Codes were assigned by the assessment of coauthors with expertise and/or direct involvement in specific cases, and reliability of codes were checked among coauthors through ongoing discussions during the coding process. Figures 3–11 show the coding of the convergence and coproduction metrics, with each column A–G representing a case study and each row a metric. As Figure 2 shows, darker colors indicate "high" presence and lighter

Table 2. Main categories of convergence research indicators and knowledge coproduction metrics. See Appendix 2 for a full list of all indicators assessed.

Convergence research indicators (adapted from Berkes 2009b, Roco 2016, Ahlborg et al. 2019)	Knowledge coproduction metrics (adapted from Wall et al. 2017)
Project Cycles	Inputs
Vision-inspired research	Process
Systems logic, ways of knowing, and problem solving	Outputs
Creating and applying cross-domain languages	Outcomes
	Impacts

Fig. 2. Color key for assessment of variables' presence in the cases.



colors indicate "low presence" of measures. White indicates "no presence" of a measure. Grey represents "not applicable," not relevant in a case, or "missing in case," suggesting that such information is not available to the case study expert.

Each case of CG was assessed for the presence of indicators of convergence research (Figs. 3–6) and knowledge coproduction (Figs. 7–11) by an author, who is an expert on the case study being evaluated, based on deep knowledge of the case as well as our collective reading, discussion, and development of the indicators selected and honed for this study. The coding was conducted iteratively, with discussion of the indicators, the cases, and the coding amongst the coauthors. Variable language was adjusted periodically for clarity or accuracy in representing the comparison of cases. For example, we clarified "who" conducts various coproduction measures by specifying the role of coordinating/leading resource manager, as this role is appropriate for our CG case contexts. Using communication strategies and best practices for reaching shared understanding, we reviewed the coding collaboratively (Raschke et al. 2023).

The convergence indicators were drawn from Roco (2016), which documents the fundamental principles and methods that facilitate convergence of disciplines and supplemented with indicators from SES literature (Ahlborg et al. 2019, Berkes 2009b, Whyte et al. 2016) to incorporate a diversity of ways of knowing, including indigenous ecological knowledge systems. In the system logic category, we draw from Berkes (2009b) and Whyte et al. (2016) to tailor convergence metrics to SES contexts. We incorporate the need for cross-domain language in bridging scientific and traditional knowledge in the collaborative process (Whyte et al. 2016), with the measure "using universal language" that connects across different domains of thinking, and "creating spaces of knowledge exchange and lines of communication." We also draw from the social-ecological-technical systems approach of Ahlborg et al. (2019) in which they highlight the ways in which technology mediates human-environment relationships by transforming human agency and power.

Coproduction of knowledge is assessed using the 45 indicators developed by Wall et al. (2017) to evaluate coproduced, usable climate science, drawing on a literature review on the theory and practice of coproduction, metrics used by federal agencies and NGOs, and insight from practitioners (see Appendix 2 for full listing). These indicators are divided into five categories: project context, process (including actions and activities throughout the project lifespan), outputs, outcomes, and impact, which measures the instrumental use of science information to inform decisions and policy actions.

Finally, we asked some key questions about the overall outcomes and impacts of each CG project (Fig. 12). These are presented in the same way as the previous indicators, but the difference is that these questions are answered using a 0–4 Likert scale multiple choice continuum, providing options indicating that conditions may have worsened or improved (see Appendix 3).

RESULTS

We present the results, grouped based on the main categories selected to represent convergence and coproduction metrics. Each subsection below covers one category of variables. See Appendix 2 for a full table of all the variables. Because of a greater interest in the variables across all cases rather than a comparison of the cases, we are not listing which case corresponds to which letter. This tells us more about the cases overall, in aggregate, and the variables individually, which is the aim of this study.

Convergence metrics: coding of the cases (A–G)

In general, there is a relatively high degree of reported presence of the convergence metrics across the cases of CG examined here, confirming their relevance to the field.

Project cycles (Fig. 3)

The project cycles category of variables includes high-level project management approaches, including assembling information through inclusive processes of data collection. "Assembling and integrating information" was present in all cases. Participatory design was common, with "cultivating vision-inspired research," "identifying and pursuing high-priority common goals," and "pursuing participatory design and governance" all frequently present among the cases. Least present in our cases was the use of broad-based science and technology platforms.

Vision-inspired research (Fig. 4)

Vision-inspired research encompasses establishing a shared vision and culture, assessments that may serve as the foundation for projects, and helping monitor their progress. Among these variables, "establishing a credible vision for what is desired" was highly present in all cases, which is notable, as this is a key factor of effective collaborative governance (Carr Kelman et al. 2023). Also "participatory assessments" was commonly present, while almost no reported presence of "reverse mapping and planning" was found.

Fig. 3. Case coding for project cycles category of convergence metrics.

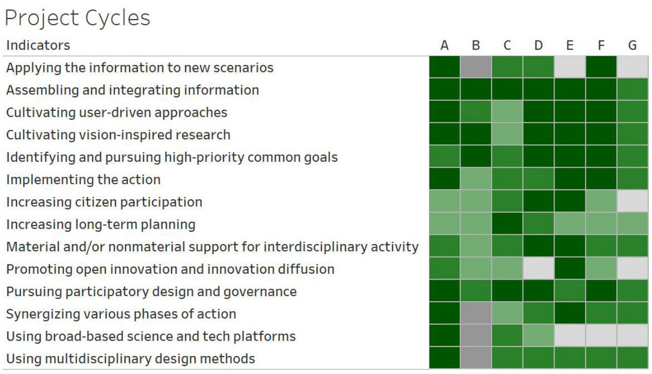
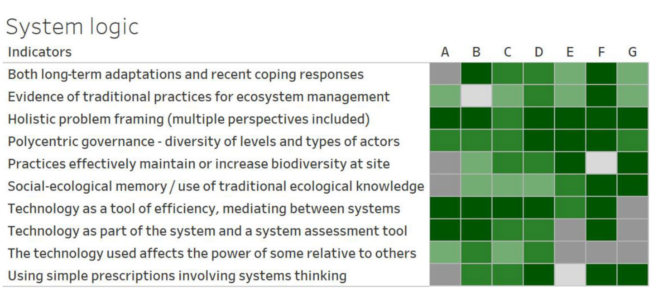


Fig. 4. Case coding for Vision-inspired research category of convergence metrics.

System logic, ways of knowing, problem solving (Fig. 5)
Across the system logic, ways of knowing, and problem-solving category, the indicators with the highest levels of presence involve incorporation of social-ecological-technical systems thinking. These include "holistic problem framing," "polycentric governance," and "technology as a tool of efficiency." Although technology contributing to the power of some relative to others was not commonly reported as present, this is still a feature of technologies that is difficult to avoid.

Fig. 5. Case coding for system logic category of convergence metrics.



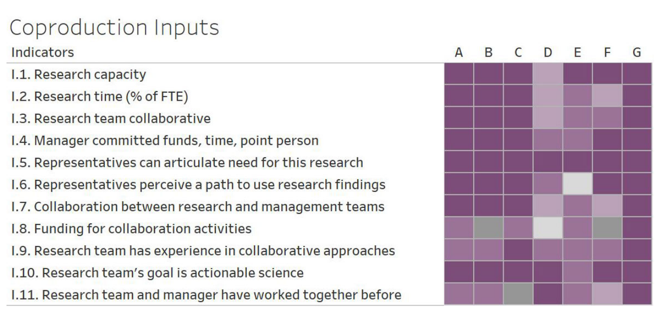
Creating and applying cross-domain languages (Fig. 6)
Because of the transdisciplinary nature of CG, cross-domain language is an important factor, as we can see from the high presence of these metrics in many cases, including establishing spaces for knowledge exchange, and lines of communication between formal research areas and public education. Agreeing on common meanings for cross-disciplinary communication was also highly present.

Fig. 6. Case coding for cross-domain languages category of convergence metrics.

Knowledge coproduction metrics: coding of the cases (A–G)
We also see generally high levels of presence of coproduction metrics across cases of CG, confirming that coproduction of knowledge is a common feature of CG. The input and process categories (Figs. 7 and 8) generally displayed a high level of indicator presence across cases. Also, process indicators were applied comparatively well across all cases, with only indicators P.1 and P.7 showing average application across. Output indicators (Fig. 9), on the other hand, were generally applied at moderate levels, while Outcome indicators (Fig. 10) were observed at levels ranging from moderate to high. Impact indicators (Fig. 11) exhibited even greater variation in the level of presence compared to all other categories.

Inputs (Fig. 7)
Input indicators of knowledge coproduction refer to the efforts put into the project from the outset, including preparation, intentions, funding, planning, and preexisting conditions that may influence CG units to engage in coproduction and use of scientific knowledge. The results in Figure 7 show that Indicator I.5 was consistently present in all case studies, which is positive. Most of the CG cases indicate high levels of positive contextual factors to coproduce scientific knowledge (I.1, I.4, I.5, I.10), but there are other factors that indicate significant variations across cases including a clear path for communication and engagement (I.7), level of funding for projects (I.8), and the allocation of significant research time (I.2).

Fig. 7. Case coding for coproduction inputs category of metrics.

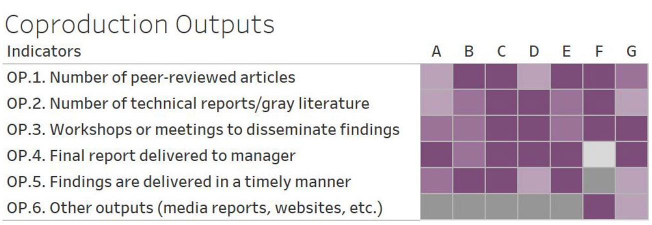


Process (Fig. 8)
Process indicators are about the quality and frequency of engagement and communication between stakeholders, and how early they were involved in the research process. Results suggest that most of our CG cases have a high degree of coproduction processes (P.2–P.6). Although most of the perceptual indicators such as researcher's satisfaction on levels of engagement (P.5), coordinating manager's satisfaction with levels of engagement (P.4) are high, we still see differences between cases such as researcher's awareness of how information is used (P.7) or the timing of resource manager's participation (P.1).

Fig. 8. Case coding for coproduction process category of metrics.

Outputs (Fig. 9)
Outputs are tangible results from research activities including workshops, reports, peer-reviewed publications, etc. Results suggest that although these are present, CG cases tend to have variation in the kinds of outputs coproduced such as technical reports (OP1, OP.2), and the timely delivery of such reports (OP.4; OP.5).

Fig. 9. Case coding for coproduction outputs category of metrics.



Outcomes (Fig. 10)
Outcome indicators include less tangible results including perceptions about goal achievement, legitimacy, and credibility of scientific research. Across measures, the CG cases tend to have high perceived outcomes in participant satisfaction on science credibility (OC.2), salience (OC.4), and process legitimacy (OC.5). But cases also tend to have less confidence on whether coproduction achieved stated goals (OC.1). These results suggest that although assessing individual stakeholder's satisfaction is one indicator of effective coproduction, achieving stated goals as a group is another important indicator to assess collaborative outcomes.

Impacts (Fig. 11)
Impact refers to the ways information is used and informs decision making. The most common uses of information across cases were understanding problems, learning what actions to take and how, checking factual veracity, and projecting future scenarios (IM.2, IM.3, IM.4, IM.6). There is more variation in strategic use of scientific information including political or confirmational use (IM.8, IM.5), but this is expected because these are some of the few indicators that may be perceived as negative. Scientific findings also do not necessarily contribute to successful actions in three cases (IM.10). These results suggest that CG cases tend to have different ways to use information that may have feedback effects on other stages of coproduction.

Fig. 10. Case coding for coproduction outcomes category of metrics.

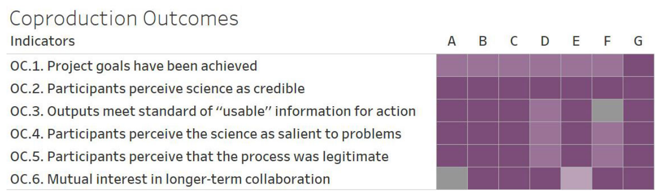
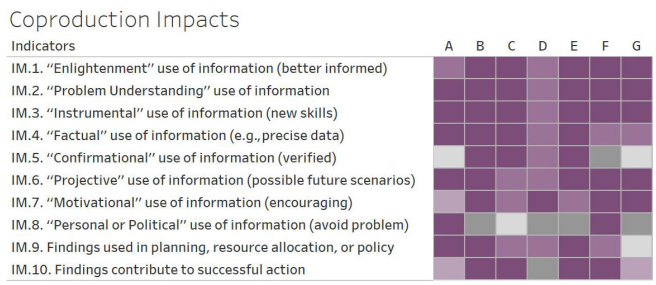


Fig. 11. Case coding for coproduction impacts category of metrics.



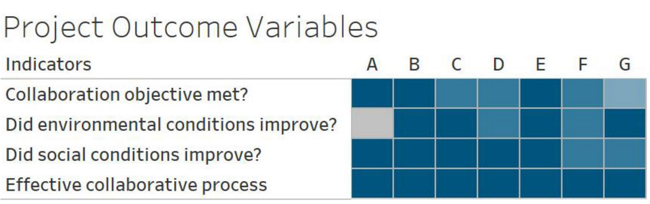
Project outcomes
Outcomes of the various case studies are summarized in Table 3 and assessed in Figure 12. Table 3 shows the specific SES management outcomes that the case studies achieved, demonstrating the diversity of project contexts and activities. Tangible positive outcomes of cases include technological tools, increased social capital and resilience, proof of concept for ecological restoration, policy entrepreneurship, and conflict resolution.

Environmental and social project outcomes of cases
Figure 12 shows how the cases were assessed regarding the four general outcome-oriented questions: whether each project (1) met its goals, (2) had positive or negative environmental outcomes, (3) positive or negative social/economic outcomes, and (4) whether the process was deemed effective by participants. The purpose of this was so that generalizations might be made regarding the effectiveness of the projects and their activities. On average, the cases were assessed positively regarding their results. Although more than half the projects did not fully meet their objectives, there were not any projects that did not meet any of their goals. Generally, both environmental and social conditions were improved, and the final outcome metric, that participants deemed the process effective, was scored positively across all cases.

Table 3. Social-ecological system (SES) management outcome descriptions of the cases analyzed.

Case study	Social-ecological system management outcome
Brazos River water security project in TX, USA	Decision-support tool that incorporated physical and social science metrics to show a range of water future scenarios to help government officials and private companies plan for current and future water use.
University-led rural revitalization in Hong Kong	An eco-production, agroforestry, and social innovation focus resulted in increased biodiversity, employment, and market opportunities. A culture of collaboration developed in the village, resulting in greater capacity in village governance, disaster awareness and recovery, and transparent decision making.
White Mountains Stewardship Project, USA	Community members and agency representatives worked with scientists to determine the best model for ecological restoration of the pine forests of eastern Arizona to prevent large forest fires. A forester was contracted to harvest the small-diameter trees that were causing the greatest fire risk, and about half of the designated area was thinned, reducing wildfires.
Serengeti's future land use change scenarios, Tanzania	Researchers designed and facilitated several multi-day workshops with local communities, in which non-academic stakeholders were involved in coproducing narratives of future land use and land cover change scenarios, which informed modeling of spatial outputs.
Central Arizona Conservation Alliance, USA	CAZCA funds and carries out ongoing, applied research (e.g., for implementation in agency management plans) to further its goal of conserving a network of ecologically functional natural areas in Maricopa County, and to coproduce solutions to emergent CAZCA partner needs (e.g., to inform the design of projects or address crises such as wildfire), building trust.
Water-Energy-Food Nexus, Switzerland	Scientists from different fields identified potential interventions in Swiss Water-Energy-Food Nexus, which they presented to experts from the Swiss Federal Offices. In several meetings and a workshop, the participants agreed on specific interventions, which led to policy recommendations, one of which was implemented a year later.
Upper San Pedro Partnership, USA	Scientific groups and policy makers collaboratively produced various outputs (peer-reviewed articles, reports to congress, etc.) and outcomes (mitigation of groundwater decline, water recharge projects). This project also facilitated conflict resolution among parties.

Fig. 12. Overall project outcomes: environmental and social results of CG cases (see Appendix 3 for full listing of the questions and Likert scale options).



DISCUSSION

The seven cases presented here are from four different continents, but there are striking similarities in the approaches across these projects, despite their varied objectives and contexts. According to both convergence and coproduction metrics, all cases had a clear vision and strong motivation to coproduce actionable science. Coproduction processes were present at a high degree in all cases, taking place in the context of knowledge exchange and communication between researchers and the greater public. Coordinators and participants agreed that these processes had a high degree of legitimacy. Many of the case studies' outputs and outcomes directly influenced the management of different SES (Table 3, Fig. 12 and Appendix 1).

Our findings point to the relevance of applied convergence research for addressing sustainability problems, as well as the importance of genuine knowledge coproduction that incorporates the knowledge users from the outset in designing the research (Beier et al. 2017; Kellner and Martin 2023). That said, there is no one-size-fits-all or prescribed approach to apply convergence research or implement CG of SES. It is just one tool, and much of the writing and funding for convergence research, especially from NSF, seems to be geared toward engineering and STEM fields. Although SES management involves STEM fields, it also integrates social sciences, and CG is necessarily transdisciplinary. In some ways, convergence research may seem limiting to those involved in the CG of SES.

We can also learn about the metrics themselves from how they were coded for the seven cases, which variables tended to be present or absent, and where they diverge. In Tables 4, 5, and 6, we list the variables that were consistently present, absent and highly divergent in the cases assessed in this article and discuss what can be learned from this.

As listed in Table 4, elements of codesign were strongly present across all the cases, with a strong baseline of knowledge integration, visioning, and problem framing as measured in convergence research. In general, participants were satisfied with the levels of engagement and the knowledge coproduced, and the collaborative processes were deemed effective. These are elements of coproduction and convergence that CG of SES are already doing well.

Table 4. Variables with high overall presence in the cases.

Category	Variables with HIGH overall presence in these collaborative governance (CG) cases	Positive?
	Convergence Research Metrics	
PC	Assembling and integrating information	Yes
V	Establishing credible vision for what is desired	Yes
SL	Social-ecological-technical systems thinking and holistic problem framing	Yes
CDL	Creating spaces of knowledge exchange / lines of communication between areas of research and education with areas of application	Yes
	Knowledge Coproduction Metrics	
Inputs	Resource manager can articulate a need for this research	Yes
Process	Resource manager is satisfied with the level of engagement	Yes
Process	Researchers are satisfied with level of engagement	Yes
Outcome	Participants perceive science as credible	Yes
Impacts	"Problem understanding" use of information	Yes
Impacts	"Instrumental" use of information	Yes
	Overall Environmental and Social Results of CG Cases (Project Outcome Variables)	
#4	Effective collaborative process	Yes

In Table 5, the variables with low overall presence show a different pattern and can be put into three categories. First, there are some variables that are less relevant for CG of SES than some other uses or applications of convergence research. These have to do with technology and innovation, which play a role in some cases of CG of SES, but not many. These convergence indicators are geared more to fields like engineering. Another type of variables are those that could be negative, and therefore a lower presence is potentially preferable, such as the "personal or political" use of information, or technology affecting the power and agency of some relative to others. Finally, there are those indicators that may be helpful to try to raise to higher levels in future CG of SES projects, such as increased anticipatory assessments, long-term planning, and funding. These are the areas that we suggest that CG of SES could improve, a point we return to below. We recommend that decision makers involved in such projects focus on the bold indicators in Table 5 (low presence in cases but have relevance to CG of SES) and Table 6.

Table 5. Variables with low overall presence in the cases (bold indicates areas for improvement in collaborative governance [CG] of social-ecological systems [SES]).

Category	Variables with LOW overall presence in these CG cases	Relevant?
	Convergence Research Metrics	
PC	Using broad-based science and tech platforms	Maybe
PC	Applying the information to new scenarios	Maybe
PC	**Increasing long-term planning**	**Yes**
PC	Promoting open innovation and innovation diffusion	Maybe/ No
V	**Anticipatory assessments**	**Yes**
V	**Reverse mapping and planning**	**Yes**
SL	**Evidence of diversity of local / traditional management practices**	**Yes**
SL	The technology used mediates human relationships, affecting the power and agency of some relative to others	Maybe
	Knowledge Coproduction Metrics	
Inputs	**Total funding for project compared to total amount allocated**	**Yes**
Impacts	"Personal or political" use of information	Maybe / No

There are also differences between the cases. Some variables received divergent responses (see Table 6), meaning either there were two clusters of high and low presence, or there were responses ranging from low to medium to high. For example, the wide variation in presence of system logic indicators across cases shows that some cases were using a wide variety of forms of knowledge, including some local and traditional knowledge, while others did not. Some of the variables in this category were confusing to coders of cases (such as "adaptive assessments"), while others may hold important clues regarding what could be improved in some projects (such as those about how the findings of research were used). Variables like adaptive assessments and increasing citizen participation are positive elements for managers of SES to incorporate.

Additionally, there were three variables that were coded as having "medium" presence in most cases: Using multidisciplinary design methods (PC.11); Research team has training or experience in collaborative research approaches (I.9); and Project goals have been achieved (OC.1). This seems to illustrate that these are variables that are difficult to fully accomplish.

Figure 13 presents a generalized model of the process of CG of SES, in stages that incorporate the specialized convergence of expertise in codesign, cocreation, and coanalysis, which may be adjusted to suit the specific needs of a particular SES. These results may be informative for academia as well as policy and practice. For practitioners, these metrics offer a way to take stock of CG programs, while keeping in mind that these are not meant to be prescriptive or one-size-fits-all. Although these lists may be helpful to improve CG, they do not constitute a blueprint nor offer a standardized model, as each SES is unique. For researchers, the metrics may offer new tools to assess CG cases, as well as a reminder that engagement with practitioners should occur even before a research project exists or is funded. For SES managers, it should also be advantageous to involve researchers in a CG process from the beginning.

Along with the case study findings, similarities between convergence research and knowledge coproduction were also found by comparing their respective metrics (Table 7). Looking at the elements within coproduction loops of codesign, coanalysis, and cocreation (Audia et al. 2021), one can see similarities to the convergence metrics (Roco 2016). Convergence research and knowledge coproduction both include support for interdisciplinary activity, vision-inspired research, common meanings for cross-domain communication, and share many common steps in collaborative project cycles. More specifically, convergence and coproduction both emphasize the coframing of issues, coanalysis, and codevelopment of policy scenarios (Table 7), which are key processes facilitating social and institutional learning and knowledge building, the activities that form the bedrock of transdisciplinary knowledge coproduction in collaborative processes.

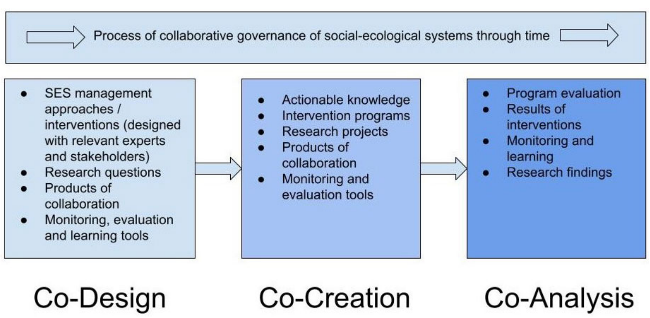
Ultimately, scientists working with SES managers and stakeholders is an expansion of the basic concept of convergence research that incorporates other ways of knowing including tacit knowledge and traditional ecological knowledge. Some convergence research is already taking this transdisciplinary step into inclusion and participation of user communities, without calling this coproduction (Moran et al. 2022, Sundstrom et al. 2023). The richness of diverse perspectives that is of the essence here is a result of the inclusion of stakeholders from policy and practice sectors to compliment scientific knowledge. Therefore, this contributes to the conversation regarding who are producers of knowledge and who are users of knowledge, disrupting this dichotomy and showing that many knowledge users are also knowledge producers (Ostrom 1996, Wehrens 2014).

Table 7 illustrates a key finding of this paper, that there is significant overlap between the concepts of convergence research and knowledge coproduction. Although the key difference is the requirement of transdisciplinarity, with the inclusion of stakeholders and decision makers, we note that some examples of convergence research do seem to be somewhat transdisciplinary as well (e.g., Moran et al. 2022). Additionally, we found indicators that both of these practices for solving sustainability problems were present in all of the cases of CG of SES that we looked at, across several global

Table 6. Variables with Divergent overall presence in these collaborative governance (CG) cases (bold indicates areas for improvement in CG of social-ecological systems [SES]).

Category	Variables with DIVERGENT overall presence in these CG cases	Positive?
	Convergence Research Metrics	
PC	Applying the information to new scenarios	Maybe
PC	**Increasing citizen participation**	**Yes**
V	**Adaptive assessments**	**Yes**
SL	**Social-ecological memory through recurrent land-use and observation**	**Yes**
SL	**Practices created within context of project effectively maintain or increase biodiversity at site-scale and/or landscape scale**	**Yes**
SL	Using simple prescriptions involving assessment of a large number of variables	Maybe
SL	The technology used mediates human relationships, affecting the power and agency of some relative to others	No
CDL	**Using shared databases and establishing convergent languages**	**Yes**
CDL	**Monitoring and benchmarking using indicators to understand the health of the system are in place for two or more domains of research or practice**	**Yes**
	Knowledge Coproduction Metrics	
Inputs	Total funding for project compared to total amount allocated	Maybe
Inputs	Research team and resource manager have pre-existing working relationship	Maybe
Process	Researchers are aware of whether/how information was used or not used by resource manager	Maybe
Outputs	Number of technical reports / grey literature	Maybe
Outputs	**Findings are delivered in a timely manner**	**Yes**
Outputs	Other outputs	Maybe
Impacts	“Confirmational” use of info	Maybe
Impacts	“Personal or political” use of info	Maybe
Impacts	**Findings from study are used in resource manager planning, resource allocation, or policy decision**	**Yes**
Impacts	**Findings contribute to successful action**	**Yes**
	Overall Environmental and Social Results of CG Cases (Project Outcome Variables)	
#1	**Collaboration objective met?**	**Yes**

Fig. 13. Generalized stages of collaborative governance (CG) of social-ecological systems (SES) project incorporating convergence research.



regions. We believe it is worthwhile to further investigate whether there is a relationship between these practices and the success or effectiveness of CG initiatives to solve sustainability issues within SES.

Our findings suggest that CG of SES might be improved by giving more attention to cultivating some of the following elements in the codesign, cocreation, and coanalysis of such projects, as they were found to be less present in the cases assessed:

- Increase long-term planning
- Include anticipatory and adaptive assessments
- Integrate reverse mapping and backcasting from shared goals into planning
- Include evidence of diversity of local / traditional management practices in planning and management
- Increase citizen participation
- Social-ecological memory through recurrent land use and observation
- Create practices within context of the project to effectively maintain or increase biodiversity at site-scale and/or landscape scale
- Use shared databases and establish convergent languages
- Monitoring and benchmarking using indicators to understand the health of the system are in place for two or more domains of research or practice
- Deliver findings in a timely manner
- Use findings in resource planning, allocation, or policy decision

Several of the above metrics can enhance SES management projects in general. More citizen participation will also incorporate more kinds of knowledge. From a policy perspective, it may be most fruitful to work on bringing out the untapped potential in existing approaches, where we already have policy and practice in place, rather than attempting to craft new approaches, which is a slower and often contentious process (Garmestani et al. 2019).

Simultaneously, we note the limitations of convergence research, which tends to use opaque language, despite their call for shared language, and tends to be geared toward use in technology and engineering sciences. To use their metrics, we had to use

Table 7. Selected similarities between steps in coproduction (Audia et al. 2021) and convergence metrics (Roco 2016) in social-ecological systems (Berkes 2009b).

Convergence metric categories	Coproduction loops		
	Codesign	Coanalysis	Cocreation
Project cycles	Joint framing of issues and questions Identifying and pursuing high-priority common goals Pursuing participatory design and governance Using multidisciplinary design methods	Analysis and modeling	Joint development of policy scenarios Increasing long term planning
Vision-inspired research	Establishing credible vision for what is desired Promoting culture of convergence on common goals		Reverse mapping and planning
Systems logic, knowing, problem solving	Social-ecological-technical systems thinking and holistic problem framing	Using simple prescriptions involving assessment of a large number of variables Technology as a tool of efficiency, mediating between human and environmental systems Using broad-based science and tech platforms	Polycentric governance
Creating and applying cross-domain languages	Unifying theories or goals for different situations Simplicity approach in problem description and decision making	Using shared databases and establishing convergent languages	Simplicity approach in problem description and decision making

interdisciplinary interpretation and adapt the language, even supplementing some of the technology-centered language with metrics that were more geared toward SES. Funding for convergence research also seems to be geared toward engineering fields, with little sense of inclusion of social sciences or other sciences, somewhat ironically.

CONCLUSION

The discovery of overlap between convergence research and knowledge coproduction can provide an informative lens for deepening our shared understanding of convergence and its application to complex adaptive systems. The convergence research that we observed in these case studies of CG of SES is characterized by transdisciplinarity through coproduction of knowledge with local stakeholders and scientists (e.g., Kellner 2023). There is no way to apply these findings as a panacea because a key finding is that contextual knowledge is key. Because the very concept of CG of SES is meant to involve stakeholders who have many forms of knowledge (tacit, local, indigenous, traditional, varied scientific), this incorporates a diversity of ways of knowing and perspectives, while ensuring that the outcomes of the research are actually being applied, in an attempt to address a real social need in a particular context.

Increasingly we are seeing studies and SES projects that intertwine ways of knowing and attempt to converge upon shared language and concepts (e.g., Whyte et al. 2016). Thus, CG of SES offers a rich field to learn more about convergence research and knowledge coproduction in practice. More available funding opportunities for action-research on CG of SES would provide more resources for both the implementation and the study of CG. Of particular value would be funding that incentivizes projects that are indigenous led, to make progress in decolonizing research and practice.

Because all the cases had relatively positive environmental and social outcomes, and we found evidence that in general, CG of SES that involve knowledge building seem to utilize elements of both knowledge coproduction and convergence research, we suggest that it is worthwhile to look into whether these practices are causally associated with the positive outcomes and if so, which practices in particular yielded the most positive outcomes. Future research can elucidate whether and how the coproduction of knowledge using interdisciplinary research and local and tacit knowledge can improve social and ecological components of CG processes and outcomes.

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Candice Carr Kelman: writing, editing, managing, case study, methodology; Jaishri Srinivasan: metric development, methodology, case study; Theresa Lorenzo Bajaj: writing, making tables, editing, case study; Aireona B. Raschke: writing, editing, case study; R. Nana Brown-Wood: writing, analysis; Elke Kellner: writing, editing, case study; Minwoo Ahn: writing, case study; Rebecca W. Kariuki: writing, case study; Michael Simeone: figures; Michael Schoon: guidance, editing.

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Data/code sharing is not applicable to this article because no data and code were analyzed in this study.

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Appendix 1. Case study descriptions.

Brazos River water security project in TX, USA

The Brazos River Water Security Project was a collaboration between multiple disciplinary groups at Arizona State University (ASU) and Texas A & M (TAMU), the non-profit organization Earth Genome, and as well as federal, state and local agencies and private companies. The goal of the project was to assign more water to growing industry sectors while ensuring resilience of the Brazos River through a variety of approaches including water markets and preferential siting of green infrastructure to increase water storage. ASU had social science and physical science research teams, the latter of which collaborated with physical scientists at TAMU. The social science team researched market instruments and interviewed stakeholders at optimal green infrastructure siting locations; the resulting stakeholder preferences were utilized by the physical sciences team to develop modified siting characteristics. The end result was a decision-support tool that incorporated both physical and social science metrics to show water futures in a range of scenarios that would help both government officials and private companies plan for current and future water use.

University-led Rural Revitalization in Lai Chi Wo, Hong Kong

The Centre for Civil Society and Governance (CCSG) from the University of Hong Kong spearheaded the economic, ecological, and community revitalisation of Lai Chi Wo Village in northeastern Hong Kong, in partnership with local non-governmental organizations, other academic departments, government agencies, a private funder, and the villagers. Through the project, CCSG aimed to define a community-based and collaborative rural revitalization model (Center for Civil Society and Governance, 2023). External stakeholders provided key resources such as manpower, knowledge, and skills, while the villagers co-managed resources in Lai Chi Wo and passed on their traditional knowledge. There were three broad stages throughout the nine-year project: farmland revitalisation, indigenous villager capacity building and collaboration with new settlers, and experimentation of socio-economic innovations (Center for Civil Society and Governance, 2023). All partners were broadly aligned regarding their vision for the agricultural revitalisation of the village and the protection of the surrounding environment (Policy for Sustainability Lab, 2023). Although the project produced traditional academic outputs such as publications, reports, and workshops to disseminate knowledge, the majority of outputs were directed towards the Lai Chi Wo community members and the greater Hong Kong society. These included organizing an annual village festival, establishing an academy delivering courses on rural revitalization, a hackathon for innovative rural solutions, incubating rural startups and a funding scheme for rural projects involving co-creation (Policy for Sustainability Lab, 2023). Overall, an eco-production, agroforestry, and social innovation focus resulted in increased biodiversity, employment, and market opportunities. A culture of collaboration developed in the village, resulting in greater capacity in village governance, disaster awareness and recovery, and transparent decision-making. The nine-year project has subsequently been recognized in Hong Kong government policy and strategy documents as an exemplary model of rural revitalization.

White Mountains Stewardship Project, USA

The US Forest Service (USFS) is charged with managing the health of US National Forests, which requires restoration, adaptive management, and the balancing of many, differing stakeholder perceptions on how to manage public land resources. The US Forest Service hosted the first Stewardship Contract in the White Mountains of eastern AZ to determine a way forward with stakeholders. A Multiparty Monitoring Board built on the work of a previous, stakeholder working group, and developed enough trust for collaborative work on the combined issues of increasingly intense and frequent wildfires, and forests overgrown with low-value small-diameter trees. The group commissioned studies in forestry, ecology, and economics to find plausible solutions. For example, they worked with scientists at Northern

Arizona University to choose clusters of large trees interspersed with meadows as the most fire-resilient model of landscape for restoration. They also used funding from the USFS to contract a forester to harvest the small-diameter trees that were causing the greatest fire risk, and find markets for this wood. Scientists and economists conducted studies that found the completed work to be ecologically and economically beneficial, and this served as a model for future USFS Stewardship Contracts.

Serengeti ecosystem in northwestern Tanzania

Researchers from the Adaptation and Resilience to Climate Change (ARCC) project sought to use longer-term historical perspectives to co-produce scenarios of future land use and land cover change for the greater Serengeti ecosystem and to assess their implications for conservation, agricultural production, and development. The project engaged 54 stakeholders from academic, governmental, nongovernmental, local communities, and community-based organizations in several multi-day workshops between 2018 and 2020 (Kariuki et al., 2022). The researchers designed and facilitated the workshops, while the non-academic stakeholders were involved in co-producing narratives of future land use and land cover change scenarios, which informed modeling of spatial outputs. The land use and land cover change scenario outputs from the workshops reflected the interests and expertise of the participants, and the environmental and political context of the Serengeti ecosystem. Outcomes from the workshops, such as social learning, collective addressing of common social-ecological challenges, and establishing networks depended on the diversity and expertise held by the participants. The workshops provided an enabling environment for participants to learn the interests and activities of others and the organizations they represented. Knowledge exchange with environmental historians and archaeologists provided better understanding of drivers of environmental change. Given that most participants had not been involved with horizon scanning before, the workshops also provided raining on visualizing the future and participatory scenario development approaches.

Central Arizona Conservation Alliance, USA

The Central Arizona Conservation Alliance (CAZCA) is an ongoing collaborative initiative located in Maricopa County, Arizona, USA; it includes more than 60 partner organizations ranging from federal, state, county, and municipal agencies, academic institutions, and non-profits. It is focused on the collaborative creation and ongoing management of a regional system of "open spaces" or natural areas that creates ecological connectivity and equitable access to nature across the urban-rural gradient that is evident in this region. Due to rapid development, population growth, a shift from agriculture to residential land use, and climate change impacts, among others, continual and innovative knowledge production is necessary to accomplish this long-term outcome. A convergence research strategy has been successfully used by CAZCA to fill knowledge gaps and address emergent challenges. Research and knowledge production carried out by CAZCA has been informed by both long-standing challenges in the region, as well as emergent and pressing needs as delineated by land managers, land owners, scientists, and members of the local community. Co-production and implementation of solutions has built trust and improved social conditions and begun to accomplish the Alliance's long-term environmental goals.

Water-Energy-Food Nexus, Switzerland

Water-Energy-Food (WEF) Nexus cases are complex social-ecological systems which often face conflictual trade-off situations between mitigation goals of the Paris Climate Agreement and Sustainable Development Goals. Two WEF nexus cases in Switzerland show a coordination gap between the different sectors and that not all sectors were considered equally (Kellner, 2023; Kellner and Martin, 2023; Kellner and Brunner, 2021). This has led to a prioritization of energy production over water-bound biodiversity and food production. To address this problem and to identify potential governance interventions leading to a more balanced coordination between different sectors resulting in the sustainable and equitable provision and utilization of WEF resources, a transdisciplinary project was started. Scientists from different fields such as governance, hydrology, biodiversity, and economy identified first potential interventions, based on the understanding of the dynamics in the current WEF nexus cases. Second, the results were presented to 14 experts from the Swiss Federal Offices. The experts and scientists discussed first the dynamics of the current WEF nexus case and subsequently the suggested governance interventions and their potential impact to transform the WEF nexus cases. In several meetings and a workshop, the participants agreed on specific interventions which led to policy recommendations. One of the recommendations was implemented one year later.

Upper San Pedro Partnership, USA
The Upper San Pedro Watershed basin presents complex scientific, social, administrative, and ecological problems that span across jurisdictional boundaries in Southeastern AZ, USA. Since the mid-1990s, tensions have arisen in this area on issues including the connection between surface and groundwater, the impact of groundwater pumping on the river, and the boundaries of groundwater systems. To address these vexing problems, a group of stakeholders formed the Upper San Pedro Partnership in 1998. Convergence research has played a key role in reducing tensions, enhancing comprehensive understandings of the water systems, and implementing key groundwater management strategies. Different scientific groups – hydrology, vegetation studies, riparian system research, soil erosion, stream flow – have worked together in the partnership, along with policy-makers, and their work has resulted in various outputs (peer-review articles, reports to congress, and other outgrowth research projects) and outcomes (mitigation of groundwater decline, water recharge projects). This convergence research also supported conflict mitigation among parties, through moderated communication flows that acknowledged group dynamics and facilitated discussions with less misunderstandings. USPP successes have gained recognition from the U.S. congress, financial support, and have demonstrated the tangible and intangible benefits of partnership engagement.

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Appendix 2. All indicators for categories of convergence research and knowledge coproduction listed in Table 2 of paper.
Indicators of convergence research (adapted from Berkes 2009b, Roco 2016, Ahlborg et al. 2019).

Category	Aspect
Project cycles (PC)	Cultivating vision-inspired research
	Identifying and pursuing high-priority common goals
	Pursuing participatory design and governance
	Assembling and integrating information
	Implementing the action
	Cultivating user-driven approaches
	Synergizing various phases of action
	Using broad-based science and tech platforms
	Material and/or nonmaterial support for interdisciplinary activity
	Applying the information to new scenarios
	Using multidisciplinary design methods
	Increasing long-term planning
	Increasing citizen participation
	Promoting open innovation and innovation diffusion
Vision-inspired research (V)	Establishing credible vision for what is desired
	Promoting culture of convergence on common goals
	Anticipatory assessments
	Participatory assessments
	Adaptive assessments
	Reverse mapping and planning
System logic, ways of knowing, & problem solving (SL)	Evidence of diversity of local/traditional practices for ecosystem management
	Both long term adaptations and recent coping responses
	Social-ecological memory through recurrent land-use and observation
	Practices created within context of project effectively maintain or increase biodiversity at site scale and/or landscape scale
	Using simple prescriptions involving assessment of a large number of variables
	Social-Ecological-Technical Systems thinking and holistic problem framing
	Technology as part of the system and a system assessment tool
	Technology as a tool of efficiency, mediating between human and environmental systems
	The technology used mediates human relationships, affecting the power and agency of some relative to others
	Polycentric governance - diversity of levels and types of actors involved in decision-making
Creating and applying cross-domain languages (CDL)	Unifying theories or goals for different situations
	Using universal language for productive communication across disciplines
	Simplicity approach in problem description and decision-making
	Using shared databases and establishing convergent languages
	Creating spaces of knowledge exchange / lines of communication between areas of

	research and education with areas of application
	Monitoring and benchmarking using indicators to understand the health of the system are in place for two or more domains of research or practice

Knowledge Coproduction Metrics (adapted from Wall et al. 2017)

Components	Indicators (note, "agency" refers to implementing/ land manager organization)
Inputs	I.1. Necessary scientific disciplines are included on research team
	I.2. Significant research time is devoted to project
	I.3. Research team works collaboratively among themselves.
	I.4. Coordinating/Leading Resource manager indicated commitment through contribution of services, funds, time, and a specific point person.
	I.5. Coordinating/Leading Resource manager representatives on the project can articulate a need for this research
	I.6. Coordinating/Leading Resource manager representative perceives a path to use/application of the research findings
	I.7. Proposal includes a clear plan for communication, engagement, and/or collaboration between research and management team
	I.8. Total funding for project compared to total amount allocated for engagement/collaboration activities (if discernable). (green = high, yellow = medium, red = low)
	I.9. Research team has training or experience in collaborative research approaches.
	I.10. Research team's motivations for participating in the project (i.e., their goal is actionable science).
	I.11. Research team and Coordinating/Leading Resource manager representative have preexisting working relationship.
Process	P.1. Point at which host/Coordinating/Leading Resource manager entered or participated in the project: (green = vision and research question articulation, yellow = between research design and analysis, stages, red = from results to testing)
	P.2. Frequency and medium of communication between research and management teams.
	P.3. Participants perceive they had equitable opportunities to participate in project meetings, workshops,
	P.4. Coordinating/Leading Resource manager representative is satisfied with the level of engagement.
	P.5. Researchers are satisfied with the level of engagement.
	P.6. Challenges within project are resolved in mutually agreeable ways.
	P.7. Researchers are aware of whether/how information was used or not used by Coordinating/Leading Resource manager
Outputs	OP.1. Number of peer-reviewed articles
	OP.2. Number of technical reports/gray literature
	OP.3. Workshops or meetings to disseminate findings
	OP.4. Final report is delivered directly to Coordinating/Leading Resource manager representative(s) or made easily accessible via another format
	OP.5. Findings are delivered in a timely manner
	OP.6. Other outputs
Outcomes	OC.1. Project goals have been achieved
	OC.2. Participants perceive science as credible
	OC.3. Findings/outputs meet the standard the Coordinating/Leading Resource manager applies to ‘‘usable’’ information for action

	OC.4. Coordinating/Leading Resource manager participants perceive the science as salient to their needs/problems
	OC.5. Participants perceive that the process of producing the science was legitimate
	OC.6. Mutual interest in longer-term collaboration
Impacts	IM.1. ‘‘Enlightenment’’ use of information (Coordinating/Leading Resource manager representative perceives self to be better informed about an issue).
	IM.2. ‘‘Problem Understanding’’ use of information (more specific than Enlightenment, better comprehension of particular problems).
	IM.3. ‘‘Instrumental’’ use of information (Coordinating/Leading Resource manager representative finds out what to do and how to do something; gained new skills).
	IM.4. ‘‘Factual’’ use of information (provision of precise data, for example).
	IM.5. ‘‘Confirmational’’ use of information (previous information was verified).
	IM.6. ‘‘Projective’’ use of information (Coordinating/Leading Resource manager gained better understanding of possible future scenarios).
	IM.7. ‘‘Motivational’’ use of information (encouraged someone to keep going (or not) on search for information).
	IM.8. ‘‘Personal or Political’’ use of information (helped a person gain control of a situation or avoid a bad situation).
	IM.9. Findings from study are explicitly used in Coordinating/Leading Resource manager planning, resource allocation, or policy decision.
	IM.10. Findings contribute to successful action.

Appendix 3. Outcome variables used to measure social and ecological impacts and effectiveness of CG case study projects.

OUTCOME 1: Collaboration Objective Met?

Are all of the collaboration objectives met (or is the collaboration meeting its core objectives)? This includes whatever is specified in the collaboration mission or goals statement. In your opinion, have the collaboration objectives been:

(0) Not at all met
(1) Somewhat met (many remain unmet)
(2) Mostly met
(3) Completely met
(98) If missing in case
(99) If N/A

OUTCOME 2: Did Environmental Conditions Improve?

As a result of the collaboration (or at present if ongoing), did the environmental conditions improve? These environmental impacts of the project or side-effects may be somewhat separate from the outcomes of the project itself or whether it met its goals.

In your opinion, as a result of the collaboration, have the targeted environmental conditions…

(0) Substantially worsened
(1) Somewhat worsened
(2) Neither improved nor worsened
(3) Somewhat improved
(4) Substantially improved
(98) Missing in case
(99) N/A

<u>Social, Political or Economic Outcomes</u>

OUTCOME 3 Did social conditions improve?

As a result of the collaboration (or at present if ongoing), did local social (including issue awareness; community well being; economic outcomes; etc.) conditions improve?

These social, political or economic impacts of the project or side-effects may be separate from the outcomes of the project itself or whether it met its goals.

In your opinion, as a result of the collaboration, have local social conditions…

(0) Substantially worsened
(1) Somewhat worsened
(2) Neither improved nor worsened
(3) Somewhat improved
(4) Substantially improved
(98) Missing in case
(99) N/A

OUTCOME 4 Collaborative Process

As a result of the collaboration (or at present if ongoing), was the process of collaboration deemed effective by stakeholders?

Collaboration can be an end in itself, regardless of the outcome of the collaboration. Here we ask whether the process of collaboration is seen as effective by the individuals participating.

In your opinion, as a result of the collaboration, has the process of collaboration been deemed effective by stakeholders?

(0) Ineffective
(1) Somewhat ineffective
(2) Neither effective nor ineffective
(3) Somewhat effective
(4) Effective
(98) Missing in case
(99) N/A