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Insight

Managing environmental knowledge networks to navigate complexity

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ABSTRACT. Environmental knowledge networks (EKNs) link research collaborators in a common purpose to produce data and knowledge to better understand social-ecological phenomena and address environmental challenges. Over recent years, as scientists have grappled with how to produce data and actionable knowledge for conservation and sustainability, more EKNs have been established. Although each network is founded for its own purposes and maintains its own goals and ways of operating, these networks are generally managed by scientists to produce knowledge to advance science and decision making. In this Insight article, we articulate key qualities and benefits of EKNs and shows how EKNs can address grand challenges that cannot be answered by a single team or institution, create a diverse, vibrant culture of science and community of practice, and provide innovative solutions and knowledge to society. We also discuss challenges of EKN governance, and how challenges may vary with a network's development. Finally, based on a synthesis of structured discussions about key issues in EKN management, we share recommendations and best practices, emphasizing management practices that are inclusive, reflexive, adaptive, and flexible, so that others may benefit from our experience leading EKNs.

Key Words: *assessment; convergence science; environmental research; evaluation; knowledge network; research network; social-ecological system; team science; transdisciplinarity*

BACKGROUND

The rise of environmental knowledge networks to address complex environmental challenges

Environmental knowledge networks (EKNs) are networks of researchers and their partners who collaborate to co-produce data and knowledge to address environmental challenges. EKNs can enable powerful, potentially transformative opportunities for collaboration across disciplines, also known as convergence science (Angeler et al. 2020). Activities include managing environmental monitoring and observation systems, conducting project-based and long-term research, cultivating partnerships and inclusive engagement activities, developing and promoting innovative solutions, creating opportunities for professional development of a diverse workforce, and providing useful information for policy makers (Feldman 2012, Mirtl et al. 2018, Metzger et al. 2019, Holzer and Orenstein 2023). EKNs usually engage in three types of activities: (a) collaborative research and information exchange, (b) engagement with stakeholders, and (c) network management (Creech and Ramji 2004, Feldman 2012). For some networks (the social web of people that collaborate and co-produce environmental knowledge), conducting basic and applied science constitutes a significant part of their mission. Some EKNs are formally conceived and empowered with significant funding and clear mandates whereas others are established less formally, to address a specific need or challenge.

The advent of "big science" in the 1960s (ambitious, long-term, sometimes multinational projects, which often led to breakthrough innovations that impacted various fields and sectors; Scarrà and Piccaluga 2022) preceded the rise of networked biological research programs (Hobbie et al. 2003, Aronova et al. 2010, Vermeulen et al. 2013, Barraclough et al. 2023). In the decades since then, several trends have emerged in ecological research as concerns about global climate change, biodiversity loss, ecosystem degradation, and the unsustainability of human activities have surged (Yu et al. 2021). These trends include transitions: (a) to include human activities in the study of nature; (b) from studying a single ecosystem to studying multiple, regional ecosystems; (c) from conducting small-scale to large-scale observations, network (multi-site and/or replicated) experiments, and model simulations; (d) toward greater focus on the integration of ecosystem components, processes, and scales; and (e) toward multidisciplinary studies (Yu et al. 2021). These scientific approaches to address so-called "grand challenges" have galvanized scientists and stakeholders to work in large, multidisciplinary teams (Stokols et al. 2008, Falk-Krzesinski et al. 2011, National Research Council 2015). In this paper, we focus on nine such environmental knowledge networks, including: ResNet, a network for monitoring, modeling, and managing Canadian ecosystem services for sustainability and resilience; the Nutrient Network (NutNet), a grassroots research effort to address questions about human impacts on ecosystems within a

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coordinated research network comprising more than 150 grassland sites worldwide; and Red SocioEcoS, which convenes different research groups dealing with social-ecological and sustainability issues in Mexico, among others.

Transdisciplinary science (research collaborations guided and/or conducted by scientists and non-scientists often intended to influence decision makers toward problem-solving) has increased substantially over the past 60 years, to address complex social-ecological problems and make knowledge more readily actionable (National Research Council 2015, Holzer et al. 2018a). The advent of transdisciplinary research, often articulated by Europe-based scholars since the turn of this century, has coincided with the shift from industrial to post-industrial economy, and with it the shift from "normal" to "post-normal" science, particularly regarding the need to address complex environmental challenges (Scholz et al. 2006:227). Transdisciplinarity has been defined as a process of mutual learning and joint problem-solving in which "scientists from different disciplines collaborate with practitioners to solve real-world problems" (Scholz et al. 2006:227).

By "complexity," we refer to problems with high levels of uncertainty, multiple perspectives, and multi-scale, interlinked processes (Apgar et al. 2009). Inherent in this complexity is the fact that environmental and sustainability problems typically involve value-based decisions "that require civic participation and the building of social legitimacy" for proposed solutions, leading to a call for the reconceptualization of "the role of experts, practitioners, and citizens in the production and use of scientific knowledge" (Popa et al. 2015:45). In a similar push to address complex societal challenges, in 2016, the U.S. National Science Foundation identified convergence research, "a means of solving vexing research problems, in particular, complex problems focusing on societal needs" (Angeler et al. 2020:97), as one of 10 "big ideas" for future NSF investments (Petersen et al. 2021). Convergence science expands on transdisciplinary research by aiming to "more fully and meaningfully integrate diverse and multiple fields of science into synthetic, high-level frameworks to solve complex problems and address complex intellectual questions," particularly by stimulating the emergence of something larger than the sum of its parts (Sundstrom et al. 2023).

Funders, driven by a desire to encourage greater policy relevance in research, have reinforced these trends, encouraging network science through their design of grant calls (Arnott et al. 2020a, Kaiser et al. 2022). Research funders increasingly emphasize research that leads to impacts on the ground and are creating funding models that require collaborative and transdisciplinary research approaches (Jones et al. 2018). Examples of funding requirements to support research deemed more useful and relevant to funding agency priorities include: mandates to engage and collaborate with stakeholders (e.g., NOAA National Estuarine Research Reserve Systems), encouraging citizen science and co-production (e.g., EU Directorate General for Research and Innovation, Horizon Europe), and evaluating products of funding based in part on evidence of knowledge adoption and implementation of innovations and solutions produced through the funded projects (e.g., U.S. Forest Service; Holzer et al. 2018b, Arnott et al. 2020a).

The aim of transdisciplinary research to have direct societal impacts and immediate relevance for policy and action has led to novel evaluation approaches because frameworks commonly used for evaluating scientific research are not suited to multi-discipline, multi-sector collaborations with multiple objectives (Klein 2008, Holzer et al. 2018a, Schäfer et al. 2021, Van Drooge and Spaapen 2022). One study suggested that impacts of transdisciplinary projects can be analyzed in terms of first-order effects (direct effects within the scope and duration of a research project); second-order effects (effects beyond the project but close in spatial or temporal proximity to the project); and third-order effects (changes beyond the temporal or spatial context of the project; Schäfer et al. 2021). This is all to say that although there has been great enthusiasm for the potential of transdisciplinary approaches to facilitate collaboration and produce actionable, relevant knowledge, this type of research is challenging to lead and navigate, and evaluating its success has been an ongoing challenge, despite some promising, novel evaluation approaches (Walter et al. 2007, Carew and Wickson 2010, Buizer et al. 2015, Belcher et al. 2016, Steelman et al. 2021, Kny et al. 2023).

Despite limited robust evaluations of transdisciplinary projects, some recent studies hint that, when executed well, research projects employing transdisciplinary principles in their design and implementation can generate diverse contributions and have a greater breadth of influence than conventional research (Belcher et al. 2019). One study identified a 10-step approach to conducting transdisciplinary research, which included matching the research question and societal knowledge demand (steps 1–4), identifying disciplines and societal actors and planning who to involve, when, and how (steps 5–9), and reflecting about the impact and lessons learned throughout the previous steps (step 10; Pohl et al. 2017). Generally, evaluation criteria use process-based approaches, looking at elements such as integration or collaboration, or "process to outcome based criteria" (Steelman et al. 2021:643), such as relevance, credibility, legitimacy, and effectiveness.

Recent decades have also shown a trend in increased project grant size in OECD countries, leading to a concentration of funding in the hands of fewer researchers globally (Bloch and Sorensen 2015). Concentrating funds on larger projects and centers is seen as important for promoting collaboration and, often, research productivity (Bloch and Sorensen 2015). For example, the U.S.-based National Socio-Environmental Synthesis Center (SESYNC), with its mandate to collaborate across disciplines, with stakeholders and with the public, has cultivated knowledge networks focused on producing actionable science for sustainability (Palmer et al. 2016, Arnott et al. 2020a). EKNs, due to their collaborative nature, are well situated to maximize potential for knowledge integration and synthesis (Palmer et al. 2016).

With this paper we aim, through our collective experiences, to (a) articulate the benefits and added value of EKNs, (b) illustrate their complex and dynamic nature, and (c) discuss the implications of their dynamic nature for how we manage them and address challenges that arise. This paper is based on a series of structured discussions that aided a diverse group of EKN leaders to reflect on leading large-scale collaborations (van Breda and Swilling 2019, Freeth and Caniglia 2020, Black et al. 2023), helping the group to identify challenges, suggest solutions, and develop guiding questions for emerging EKN leaders. Viewing environmental knowledge creation and mobilization as polycentric and shaped by communities and networks (Søndergård et al. 2004), we build on analyses and insights of our own individual networks (e.g., Borer et al. 2014, Metzger et al. 2019, Bennett et al. 2021, Grove and Pickett 2021, Calderón-Contreras et al. 2022, Holzer and Orenstein 2023) to compare, contrast, and synthesize our experiences. We hope these reflections and recommendations can support the next generation of EKN leaders to benefit from our collective experience.

The EKNs represented among the co-authors share some common features that enabled vibrant discussions reflected in this article, including that each conducts a mix of long-term monitoring and basic and applied scientific research; is led by a network of researchers across research sites (Table 1); adopts a transdisciplinary, social-ecological system perspective, integrating multiple forms of scientific and local (stakeholder) knowledge; focuses on policy-relevant, actionable science; and has accrued several years of operational experience.

LEARNING APPROACH AND CONTRIBUTING CASE STUDIES

A series of structured discussions by leaders of environmental knowledge networks resulted in key themes and recommendations

Impetus for symposium and description of participating networks

The insights that contributed to this analysis were generated through a three-part virtual symposium. The impetus for the symposium was a series of challenges that arose in the Canadian research network known as “ResNet,” established to advance monitoring, modeling, and management of ecosystem services toward sustainability and resilience across Canada. These challenges prompted the desire to compare lessons learned across different EKNs. A three-part virtual symposium was organized by the first author in collaboration with ResNet colleagues (EMB, GMH, JB, KJW).

To recruit symposium participants, we used an informal snowball approach. Beyond the symposium organizers, we reached out to several ResNet co-leads who have also led other environmental knowledge networks. JMH reached out to her own professional contacts and professional contacts of EMB whom she knew held leadership positions in different EKNs. We aimed to convene between 10–15 founders and/or leaders (as well as individuals who might not self-describe as leaders but were privy to decision processes over time) in EKNs based in diverse settings around the world. We also included several early career researchers who were in positions to witness decision making and organizational changes of their EKNs. The authors represent 10 different EKNs found in North and Central America and Europe, and most of the authors were either a founder or a senior administrator of their EKN. A list of participating EKNs, their aims, origin stories, and other key details are included in Table 1.

Prior to the symposium, participants filled out an online survey about their motivations and assumptions when getting involved in network science, as well as the surprises, challenges, and lessons learned as a result of their involvement in an EKN (see survey questions in Appendix 1). The first symposium meeting focused on the start-up phase of EKNs; at this meeting we discussed survey responses, focusing particularly on the challenges and best practices of network start-ups. At the second meeting, we discussed how to define, assess, and achieve network success. At the third meeting, we discussed how networks can create pathways for actionable knowledge. Our discussions were structured as a reflexive process. Transdisciplinary research has been associated with an increase in reflexivity (Marg and Theiler 2023). The importance of reflexivity and periodic self-assessment on the part of leaders of transdisciplinary science has been well-recognized (Popa et al. 2015, Ruppert-Winkel et al. 2015, Knaggård et al. 2018). Reflexivity usually refers to ongoing reflection on the part of the individual researcher to process and reflect upon the research and the social and societal context in which science is conducted. This may include reflecting on the research framing and its social relevance, the values and understandings that contribute to real-world problem-solving, and the commitments and orientations of the people involved, and their influence on making changes in society (Pope et al. 2015). It may also refer to a sense of constant mental flexibility, openness, and questioning of one’s own position (Marg and Theiler 2023).

Goals and visions for environmental knowledge networks

Although the EKNs represented in our discussions have many common elements, they differ in substantial ways, including their mission, the breadth and diversity of goals and objectives, intended longevity, funding structure, and cultures of science (Table 1). They also vary on the spectrum from basic to applied science. For example, some EKNs, like ResNet and eLTER, aim to promote transdisciplinary science in specific regions, to draw general lessons across a variety of cases (Bennett et al. 2021). Other networks, like NutNet, conduct experiments using identical protocols to test hypotheses arising from ecological theory relevant at local and global scales, and to understand condition-dependence of responses (Borer et al. 2014). Symposium participants articulated the desire for their networks to cultivate social capital and collaboration, to expand capacity to scale data and conduct cross-site research, and to optimize the application of research to policy and action. Participants hoped their networks would promote research integration and action-oriented research, and produce reliable, long-term data for decision making. A representation of the similarities and differences among the networks is illustrated by Figure 1. The tree root system represents motivations, assumptions, and goals shared by the participating EKNs, the trunk representing core common characteristics shared by these EKNs, and the branches represent elements of divergence and difference among the networks.

RESULTS AND DISCUSSION

Four themes emerged from a “critical reflection” process (Black et al. 2023), which characterize the group’s collective focus and insights regarding environmental knowledge networks: (a) the benefits and added value of conducting projects in the context of a network, (b) complexity and dynamics of networks, (c) overcoming challenges in network management, and (d) managing networks smarter moving forward. There was also significant interest in the idea of EKNs moving through common

Table 1. List of environmental knowledge networks represented by the co-authors and network key aims. See Appendix 2 for greater detail.

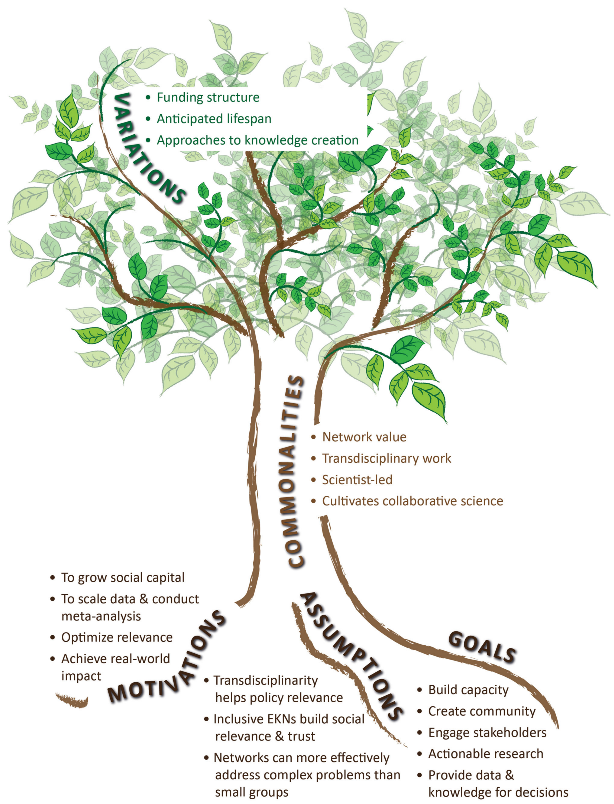
Network name	Key aims of the network	Network origin story
Alternet, Europe-founded; now international	To foster the science-policy interface on biodiversity and ecosystem services in Europe.	The network was formed in 2004 through funding from the European Union under the Framework Programme 6 as an EU Network of Excellence. When the project ended in 2009, Alternet continued with 22 of the original partners. A Council and Management Board facilitate the activities of Alternet, which has grown to 33 partners from 19 countries.
eLTER RI (Integrated European Long-Term Ecosystem, Critical Zone, and Socio-Ecological Research Infrastructure), Europe	To provide evidence-based knowledge and ecosystem observation data across the European continent for addressing complex sustainability challenges (e.g., climate change, biodiversity loss, soil degradation, pollution, and unsustainable resource use) over spatial scales from the local to the global, and over the long-term; To catalyze scientific discovery and insights through a state-of-the-art research infrastructure, collaborative working culture, and transdisciplinary expertise.	LTER - Europe, or "eLTER," evolved out of a European-funded Network of Excellence, Alternet (see row 1). It is comprised of 26 formal national LTER networks in Europe. In 2018, eLTER was added to the European Strategy Forum for Research Infrastructures (ESFRI) and has since been engaged in cross-country harmonization of activities and institutionalization of its research and data observation infrastructures. Thus, what started in a highly distributed manner has evolved into a complex system of related communities, projects, services and research sites.
ESCom (Ecosystem Services Community), Scotland	(a) Align Scottish ecosystem services research, to maximize benefits, identify synergies, and avoid duplication; (b) Work with policy and practice to gain better understanding of user needs, provide relevant research, and achieve impact; and (c) Organize and promote events to support knowledge exchange through a dedicated website.	Substantial Scottish Government and EU research funding for ecosystem services research (with some overlapping objectives) prompted researchers from four institutes and one university to identify synergies and opportunities for collaboration. They agreed to establish a community for ecosystem services research, decision-making and natural resource management in Scotland.
LTAR (Long Term Agroecosystem Research network), U.S.	Create a vibrant and inclusive agricultural economy supported by evolving scientific knowledge that enables farmers and ranchers to achieve production, environmental, and societal goals sustainably.	LTAR was initially established by the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA) to build the knowledge required for sustainable intensification of agriculture, increasing yields from the current agricultural land base while minimizing or reversing agriculture's adverse environmental impacts.
LTER (Long Term Ecological Research Network), U.S.	LTER envisions a society in which exemplary science contributes to the advancement of the health, productivity, and welfare of the global environment that, in turn, advances the health, prosperity, welfare, and security of our nation. Thus, the LTER network mission is to provide the scientific community, policy makers, and society with the knowledge and predictive understanding necessary to conserve, protect, and manage the nation's ecosystems, their biodiversity, and the services they provide.	The LTER Network was founded in 1980 by the U.S. National Science Foundation with the recognition that long-term research could help decipher the principles and processes of ecological science, which frequently involves long-lived species, legacy influences, and rare events.
NEON (National Ecological Observatory Network), U.S.	(a) Continental-scale environmental data and archival samples. (b) Infrastructure for ecological research studies. (c) Educational tools to work with large data.	The Earth and its ecological processes are changing at unprecedented rates due to human activity; the effects of these changes are uncertain. To address this uncertainty, the science, education, computing, and engineering communities provided input to NEON's design, with the shared goal of creating a long-term ecological observatory that collects and provides a diverse suite of comparable and consistent ecological data at multiple spatial and temporal scales.
NSERC ResNet, Canada	Support Canada's capacity to monitor, model, and manage its working landscapes and seascapes (and all the ecosystem services they provide) for the long-term shared health, prosperity and resilience for all Canadians through community-engaged research.	EMB wanted to build a network of scientists focused on multi-scale ecosystem service monitoring and modeling to improve environmental governance in working landscapes.
NutNet (Nutrient Network) U.S.-funded; international in scope	(a) To experimentally test specific hypotheses about elemental nutrient supply and herbivory arising from ecological theory; (b) To build on single site theory tests and meta-analyses by generating data using identical methods at every site and experiments replicated under many conditions to understand generalities and biotic & abiotic contingencies in responses; and (c) To develop a new, distributed experimental approach to testing ecological theory.	NutNet was conceived by a few early career scientists with the goal of overcoming the limitations of meta-analysis for testing ecological theory.
Red SocioEcoS, Mexico	Red SocioEcos aims to convene different research groups dealing with social-ecological and sustainability issues in Mexico. Since there is a wide array of institutions and research groups focusing on social-ecological research in Mexico, Red SocioEcos was designed to convene research groups and identify common interests to create a platform for knowledge exchange, collaboration, transdisciplinary research, outreach, and funding opportunities.	Red SocioEcos was created in 2014 as a "network of networks." The original idea was to identify and gather research groups in Mexico with common social-ecological interests and a focus on sustainability research. The proposal was supported by the National Council for Science and Technology, and it provided the means for a first thematic gathering of nearly 80 representatives of the different networks involved in social-ecological and sustainability research, outreach, and teaching.

developmental stages during their “life cycle” (Imperial et al. 2016, Jones et al. 2018), and that each stage may be characterized by different phenomena, needs, and management challenges.

The benefits and added value of environmental knowledge networks

The core benefits of EKNs relate to their capacity to leverage collaboration and social capital (“a set of relationships and shared values created and used by multiple individuals to solve collective problems”; Ostrom 2009:22) toward shared aims. Participants mentioned benefits such as the ability to conduct multidisciplinary and transdisciplinary, macro-level science across multiple sites and scales, the ability to build capacity and research infrastructure, the ability to address problems and questions that cannot be sufficiently addressed by a single team or institution, and the ability to access a greater range of opportunities, such as stakeholder engagement and funding opportunities, reflective of the idea of an epistemic community (Haas 1992) or community of practice (Metzger et al. 2019).

Fig. 1. A living environmental knowledge network. This tree graphic represents key comments from co-author survey responses and symposium conversations. The tree root system represents motivations, assumptions, and goals shared by the environmental knowledge networks (EKNs) represented by this study; the trunk represents core common characteristics shared by these EKNs; and the branches represent elements for which there is greater variation among networks. Graphic: Ronit Cohen-Seffer.



The overarching benefits of EKNs are to address complex questions that can only be addressed by integrating multiple perspectives and evidence from multiple fields, to create a vibrant culture of science, and to provide useful and transformative information and knowledge to society (Turner et al. 2016, Holzer et al. 2019, Bennett et al. 2021, Burch et al. 2023). This assertion is in line with past research that has shown how, under the right conditions, large, multi-partner collaborations can encourage learning across sites and scales as individuals directly engaged in the partnership bring learning into their respective organizations and their insights permeate outward beyond the core set of collaborators (Vinke-de-Kruijf and Pahl-Wostl 2016). However, the extent to which these benefits are realized within EKNs may depend on the presence of particular enabling conditions, as we discuss below.

Addressing complex science questions requiring multiple disciplinary perspectives combined with stakeholder knowledge, a transdisciplinary approach, often refers to research that collects and uses diverse data and knowledge across multiple temporal and spatial scales. EKNs provide resources and tools such as ideas, datasets, human resources, physical infrastructure and equipment, and ongoing case studies that can be more easily accessed with the social capital that accompanies EKNs (Hicks et al. 2010, Hampton and Parker 2011).

Creating a vibrant, diverse, and inclusive culture of science includes developing a shared vision, values, and working relationships around researching and addressing complex problems. Networks create opportunities for interaction that encourage the development of intellectual community and knowledge mobilization among their participants (Burch et al. 2023). Connecting diverse and physically distant groups of researchers to promote the sharing of ideas, expertise, and resources can be energizing and stimulate research productivity. Interdependencies cultivated by network relationships can foster access to resources, such as data sets, mentoring, and professional development opportunities. Networks can particularly serve as platforms for development of early career scientists and increasing diversity in scientific communities. Diversity on teams is important for enhanced performance and impacts (Urionabarrenetxea et al. 2021). Diversity enhances the team’s decision making, fosters innovation, and improves overall performance by bringing together a wide range of skills, experiences, and perspectives. It also helps better meet the needs of diverse stakeholders, thereby strengthening public trust and gaining a competitive advantage. As discussed during the symposium with examples from our own networks, diverse teams, when coupled with an inclusive environment, can lead to better outcomes and help teams remain productive and innovative (Urionabarrenetxea et al. 2021).

Providing useful and transformative information and knowledge to society is the most acute need for actionable science to deliver (Arnott et al. 2020b). Networks can conduct policy-driven science co-produced with decision makers, stakeholders, and the public. Because of the expertise, interests, and resources represented by a network, they are well-suited to investigate and address complex problems. EKNs are particularly suited to provide physical and intellectual infrastructure for the investigation of unexpected events, e.g., sites with ongoing monitoring programs can quickly detect and characterize extreme weather events such as windstorms or floods, helping managers to respond more quickly. Perhaps most powerfully, creating communities among scientists, stakeholders, rightsholders, and interested and affected parties can stimulate creativity and innovation, leading to new ideas and unique knowledge products that can challenge conventional thinking.

Box 1: Five narrative examples illustrate the value of environmental knowledge networks.

Addressing complex science questions requiring multiple disciplinary perspectives combined with stakeholder knowledge

Spotlight on U.S. LTER

A group of researchers from the U.S. Long Term Ecological Research network sites wondered, "Why do urban, suburban, and exurban areas across the U.S. all look the same, with a consistent mix of grass, trees, shrubs, and impervious surfaces?" (Groffman et al. 2017). What are the ecological implications of this vast conversion of heterogeneous native ecosystems into homogeneous residential ecosystems? What are the prospects for improving the biodiversity and environmental quality of this macrosystem (Larson et al. 2022)? Addressing these questions required interactions between social and biophysical scientists and is a good example of how EKNs can facilitate transdisciplinary science that addresses important basic and applied questions.

Creating a vibrant, diverse, and inclusive culture of science

Spotlight on NutNet

EKNs can effectively mobilize scientists within the global scientific community. By including and empowering early career scientists, female investigators, and investigators from countries where ecological science is poorly funded to contribute to collaborative knowledge production, EKNs can broaden the demographic and cultural base of knowledge producers. In the Nutrient Network (NutNet), this effort has meant that more than 50% of network papers have been led by graduate students and postdocs and 37% have been led by non-native English speakers (Borer et al. 2023). The inexpensive site-level infrastructure paired with attention to clear, inclusive communication has enabled equal participation by scientists even in countries with little funding for ecological research and regions underrepresented in the ecological literature (e.g., Argentina, Brazil, Colombia, Ecuador, India, Iran, Mongolia, South Africa, Tanzania). Importantly, this egalitarian collaboration benefits the scientists and the science (Urionabarrenetxea et al. 2021, Sundstrom et al. 2023). Because of its inclusive approach, NutNet is asking new questions and results are being interpreted from novel perspectives with relevance to developed and developing nations.

Spotlight on eLTER

Through a combination of bottom-up motivation and top-down requirement (e.g., from funders or government agencies), the European Long-Term Ecological Research Infrastructure (eLTER RI) exemplifies how EKNs can effectively institutionalize their values. Having been accepted into a European consortium of research networks known as the "ESFRI roadmap," eLTER RI secured two large Horizon Europe grants to transform what had been a loosely knit network of ecosystem scientists and research sites into a highly harmonized, pan-European research infrastructure. This transformation required new operational protocols, including a strategic plan, a gender equality plan, and ethical guidelines pertaining to every aspect of the RI operation. When combined with eLTER RI's emphasis on policy-relevant, stakeholder-integrated research, eLTER RI is establishing an institutional culture that engages in sustainability research and pays particular attention to how research is done and how the RI is managed. In this way, the RI hopes to increase trust in science, strengthen ecological literacy, and magnify its sustainability impact across the communities in which it works (Holzer and Orenstein 2023).

Providing useful and transformative information and knowledge to society

Spotlight on ESCom

The Ecosystem Services Community Scotland (ESCom) was a community of practice that brought science, policy, and practice together to facilitate shared learning about the concepts of ecosystem services and natural capital at a time when these concepts were beginning to be embedded in Scottish policy (Metzger et al. 2019). Events including workshops, conferences, and a study brought together over 600 individuals from diverse constituencies to share experiences and learn from each other. In 2017, the Scottish Government explicitly requested that its research institutes collaborate with ESCom in developing their strategic research program. A manager from the government nature agency, NatureScot, explained in a feedback interview: "ESCom did what no other platform was doing at the time in Scotland. It challenged, demonstrated, supported and researched approaches to strategies, plans and decision-making that shone a light on, and captured the contributions that nature makes to our prosperity and well-being. ESCom helped to 'kick-start' a movement that has now led to a more natural capital-focused agenda."

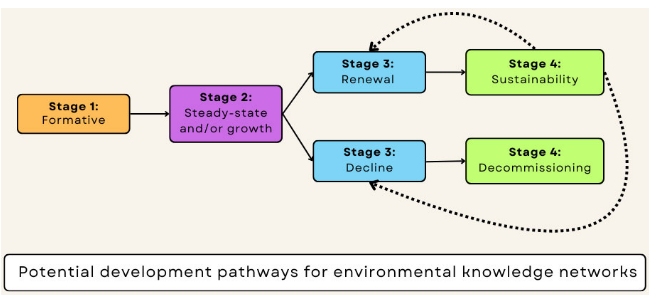
Spotlight on LTAR

Goodrich et al. (2022) demonstrated the advantage of network science, such as the Long-Term Agroecosystem Research network, through its ability to conduct transformative transdisciplinary science across multiple spatial and temporal scales and implement cross-location data collection, synthesis, modeling, and forecasting to address complex issues related to sustainable agriculture. Accomplishments have included the development and validation of cross-scale conservation management practices for agroecosystems, determining water use and plant development as impacted by climate variability, forecasting future responses to climate in managed systems through long-term data synthesis across 18 sites in the U.S., and calibrating sensors for different regions in the U.S. Another outcome is the open data platform that allows the scientific community and stakeholders to access data and develop novel solutions.

Complexity and dynamics of environmental knowledge networks

Developing an EKN, determining its mission and goals, and learning how best to manage the network will rarely be linear or predictable, but at the same time, we would expect certain patterns of development that lead to either growth and stability or to development that culminates in the end of the formal network (Kline 1985, Imperial et al. 2016; Fig. 2). It can be constructive to think about four stages of network development: formative (Fig. 2, Stage 1), steady-state and/or growth (Stage 2), decline and/or renewal (Stage 3), and sustainability and, possibly, eventual decommissioning (Stage 4; Creech and Ramji 2004, Imperial et al. 2016), themes that arose in discussions about the nature of change in our own networks over time. Using these stages as a guide, we are reminded that our research networks are dynamic, evolving in response to internal and external stimuli, and that although surprises may occur, it may also be possible to identify patterns in network development. Although these stages may be reminiscent of perspectives that conceptualize governance systems as part of a larger, interconnected, social-ecological system (e.g., Holling and Gunderson 2002), the focus here was limited to the dynamics of network governance (Imperial et al. 2016).

Fig. 2. Stages of evolution (adapted from Creech and Ramji, 2004 and influenced by Imperial et al. 2016) of an environmental knowledge network represented as an unfurled spiral. Stages include: (1) Formative; (2) Growth/status quo; (3) Decline and/or renewal; (4) Sustainability (or decommissioning). This is a sketch of a dynamic, nonlinear, highly iterative process, both within stages and between them. In certain cases, the lifespan of a network runs its course, and after a period of strength, begins to decline and is eventually decommissioned (Imperial et al. 2016).



Different networks get their start in different ways. Some may form in response to a funding opportunity (e.g., Alternet, ResNET) or a specific knowledge need (e.g., NutNet formed to address the need to collect consistent data from a broad range of sites to allow direct comparisons of environment-productivity-diversity relationships). eLTER RI emerged in the early 2000s as the European regional component of a then-developing international network of long-term observation sites (ILTER) initiated in the U.S. in the 1980s. This network aimed to fill a gap in data collection for studying long-term ecological, and later social-ecological, phenomena at local to global scales (Mirtl 2010). Some would argue that the U.S. LTER network emerged in response to the realization that ecosystems are complex entities that change slowly, or sometimes suddenly, over time and therefore require long-term data collection. NEON, the U.S.-based National Ecological Observation Network, was also designed by ecologists and funded by NSF to provide open-access ecological data in response to the need for more consistent, coherent, and publicly available long-term data than could be provided by the more research-focused LTER network (Schimel et al. 2007). The Red SocioEcoS was first funded in 2014 to convene existing networks working toward the common objective of informing Mexico's environmental policies. As a network of networks, it soon became clear that its objective had evolved, to illustrate that place-based research had the potential to inform global sustainability (Balvanera et al. 2017).

The formative period (Fig. 2, Stage 1) is when members get acquainted, work, and create new knowledge independently, with little collaboration (Creech and Ramji 2004). In the ResNet network, coordination in the formative period required creating a coherent shared vision of the goals of the network and each person's role in achieving those goals. The shape taken by the network may be influenced by individuals' reasons for becoming involved. Survey responses showed that co-authors got involved in their respective networks for various reasons: "joining [my EKN] was a fundamental part of my research program"; to "broaden my collaborations, connect with others, and access skill sets that I know I lack"; "to create a sense of community"; "I wanted to challenge myself to do something more complex (but did not want to go into administration)."

In the steady-stage and/or growth stage (Stage 2), some of the benefits of coordination begin to bear fruit, with greater collaboration, but some members may also drift away from the network as research priorities, alignment, or capacity to engage evolve (Harvey et al. 2019). These shifts can come from any "side" of the partnership, with network focus evolving away from the initial focus as a result of personal and professional influences or simply as the formative phase subsides. Examples of such changes include staff turnover (in networks with institutional membership) or institutional affiliation/responsibilities (in networks with individual membership) or identification of new knowledge needs (Harvey et al., 2017). Learning that occurs within the network (or through network members' other spheres of activity) can also catalyze evolutions in individuals' practices within the network, the network's structures and norms, or even the values or principles around which it operates (Newig et al. 2010). In the decline and/or renewal stage (Stage 3), networks may experience slowing, stagnation, or failure, and, in some cases, a significant reduction of activities to basic information-sharing across the network with real collaboration limited to a core group (Creech and Ramji 2004). At this stage, either renewed excitement and activity arises from a shift in direction or identification of new opportunities, or the network leadership moves toward decommissioning (Fig. 2).

We suggest that the added value of a network may differ depending on its stage of development. Planning from the outset for this arc of development will help with intentional leadership through the stages. Cultivating awareness and reflection of a network's natural progression through these developmental stages may inform understanding and decisions about priorities and areas to emphasize or deemphasize. For example, Alternet experienced a brief decline phase following a 90% decrease in income after funding from the European Union ended, but grew in membership by 50% over the following decade. There were many possible contributory factors to this growth, but openness to participation by those outside the network likely played a key role, allowing others to experience the value of joining.

Overcoming challenges in environmental knowledge network management

Although EKNs can help society address problems in complex systems, they are themselves complex systems that can be challenging to manage. Network leaders may benefit from understanding challenges experienced by the nine EKNs represented by our group and recommendations for addressing them. The challenges we discussed generally fell into the following, often interrelated, categories: lack of cohesive vision and goals for the network, difficulties in coordination and communication, lack of suitable scientific approaches or methods, lack of member diversity, competing for members' attention, and perhaps most universally, funding issues (Table 2). An overarching challenge is sustained retention and/or recruitment of effective network leaders. Addressing most of the challenges listed below is greatly facilitated by leadership that encourages input, but also drives the group toward consensus, or in the absence of consensus, the best possible solution.

Lack of cohesive vision and goals for the network

Challenges: Difficulty developing and effectively communicating a clear vision and goals for a research network can hinder participation and collaboration. It can be challenging to frame the network mission inclusively for diverse participants, especially because they may have different research agendas and goals for their participation in the network. Without a clear strategic plan or clear protocols for collaboration, the integrity of the network can falter. One symposium participant noted, "The goals are not the same for all. There is a lack of a unifying vision, and a tendency to conflate this vision with the management objectives of the network. The 'added value' of the network is not always clearly made to members, which weakens buy-in to the network. Further, the majority of collaborating researchers are time-poor and therefore struggle to find space for active participation. Together this leads to a lack of shared ownership of the network, its vision, and its purpose ..." Another participant articulated challenges in a cohesive vision as the lack of a "clear strategic plan, agreement between sites on goals and methods to accomplish these goals, resources (financial, land, instrumentation), expertise, as well as labor or student shortage."

Recommendations for addressing these challenges: A fundamental recommendation here is to jointly create a shared vision and goals for the network that is dynamic and responsive to changing needs. For more formalized EKNs (e.g., eLTER RI), the preparation and publication of a strategic plan helps provide focus and a reference point for future collaboration. In the case of eLTER, the document was prepared by a broad group of network members, and is by definition a dynamic document that is periodically revisited and revised as necessary (Nikolaidis et al. 2021). Another suggestion that arose in our discussions was to manage the network "as a complex system, in contrast to a complicated system." The best institutional structure for dealing with complex and uncertain policy environments is decentralized, dense networks of institutions and actors that can nimbly relay information (Newig et al. 2010). Applying this logic could involve a "team of teams" approach where a central/administrative team has the role of envisioning and coordinating collaboration among research teams with diverse, but complementary goals. In this way, redundancies and resilience (the ability of a system to retain its structure, functions, feedbacks, and identity in the face of shocks; Walker et al. 2006) can begin to form, which can foster cross-fertilization of ideas. Because of the power of thought diversity among members, we also caution against letting meetings and processes become siloed, and encourage network leaders to foster evolution and branching, rather than seeing divergent approaches as "bad."

Difficulties in coordination and communication

Challenges: Challenges in coordination and communication include the lack of formal training in research network management and a lack of clear engagement protocols for how research teams should engage with each other and with partners. One participant said, "In general, the flexibility of the network and ability of network partners to do things in their own way is both a strength and has probably slowed collaboration down significantly, at least in this beginning stage." Another cited the difficulty of prioritizing voluntary collaboration.

Recommendations for addressing these challenges: We suggest incorporating a transdisciplinary approach at the highest level of network administration, like building stakeholder requirements into grant calls or writing a transdisciplinary approach into strategic goals. We also emphasize creating training opportunities for network leaders that would build skills in transdisciplinary collaboration and network-building and management, to create a "pipeline" of individuals well-equipped to lead EKNs, and also to create incentives for taking on leadership roles. Based on experience, participants suggested to be "proactive, in contrast to reactive, about training." In addition, EKNs can consider recruiting collaborators with professional skills such as group facilitation and management of diverse and complex groups.

Lack of suitable scientific approaches or methods

Challenges: It can be particularly challenging to develop protocols for a network with multiple, diverse goals. If the goal is primarily to coordinate experiments (e.g., NutNet), this can be more straightforward, but if the network ranges from computer modeling to engaged social science research (e.g., ResNet), it can be challenging to know where to start, as with many transdisciplinary collaborations.

Recommendations for addressing these challenges: Creativity may be a necessity here. One network leader offered the following example from NutNet: "We have implemented 'add-on' studies where people from any site can opt-in to collecting a particular new response variable (using identical methods at all sites). So, we have 'core' and 'add on' datasets -- core at all sites, add on just at a subset where investigators had interest and bandwidth to contribute. We have an additional option, which is a 'site' subplot where, e.g., students can do a focused study at a single location. This does not take advantage of the network, but takes advantage of the infrastructure and provides flexibility for small, very focused studies." A similar process is taking shape in eLTER RI, where sites are graded according to the extent to which they can collect network-wide observational data sets, allowing for participation of sites that cannot commit to collecting variables at a high level of spatial or temporal resolution.

Table 2. Categories of challenges that arose from the symposium, examples of these challenges, and suggested solutions.

Challenge theme	Challenges	Recommendations
Lack of cohesive vision and goals	Difficulty framing the network mission inclusively	Collaboratively write a dynamic strategic plan (i.e., one that is revisited periodically and revised as necessary)
	Lack of strategic clear plan	Manage the network as a complex system
	Lack of engagement protocols for member collaboration	Use a team science approach
	Members each have their own goals and research agenda	Encourage evolution and change in the network if it strengthens collaborative potential
		Strive for consensus while maintaining flexibility
		Recruit leadership that encourages input but also drives the group toward consensus (or the best possible direction)
Difficulties in coordination and communication	Challenging for members to prioritize voluntary collaboration	Embed transdisciplinarity in network administration by creating strategic network goals and research expectations
	Challenging to know where to start with transdisciplinary collaboration processes	Proactively create training opportunities for network leaders
Lack of suitable scientific approaches or methods	Challenging to know where to start with transdisciplinary collaboration processes	Be creative; develop novel methods and protocols
		Metrics of success should capture the diversity of network activities and change as the network evolves
		Find ways to evaluate: the flow of information from science to society, career development, diversity and inclusion (as defined by the network), and change in the network's culture of science
Lack of member diversity	Can be difficult to attract and / or retain diverse scientists to voluntary networks	Promote online participation
		Offer multiple membership types
		Cultivate an inclusive culture
		Communicate benefits of contribution that map onto the career motivations of members /potential members
		Encourage the development of early career opportunities, offer outreach and educational programming for under-represented groups, and engage in active member recruitment
Competing for members' attention	Voluntary membership can become a barrier to sustaining member commitment	Understand that different objectives apply to different individuals / projects (e.g., tenured academics versus academics without job security)
	Can be challenging to define relationships with similar networks and projects	Be flexible and responsive to changing needs
	Leaders may fail to articulate the added value of the network to members	Ensure network expectations align with member career needs
Funding	Commitment to the network declines when funding ends	Articulate and actively disseminate the value of EKNs for research and for addressing societal challenges, including by engaging in science-policy activities
	Securing long-term funding to sustain the network	Aim to identify ongoing financial support soon after network establishment
	Existing program evaluation methods usually do not account for much of the added value of EKNs	Explore alternative funding models and diversify funding sources
	Funder/s may develop a strong influence over network structure and function	

Another challenging area can be setting standards of success and determining evaluation methods for measuring research and societal impact. Participants suggested that as network aims evolve over time, measures of success should also evolve. There was agreement in response to the statement, "we are pretty good at evaluating scientific impact; publications, citations, etc. We need to do better at evaluating the flow of information from science to society, career development, diversity and inclusion, and the evolution of scientific culture."

Lack of member diversity

Challenges: Participants agreed that it can be difficult to attract and/or retain diverse scientists from underrepresented backgrounds to voluntary networks, as it is in the natural sciences generally. Yet diversity of thought, experience, and approaches is one of the greatest strengths of an EKN. One participant said, "We have a need to diversify our group of scientists. It is hard to attract individuals from underrepresented groups into science in general, and into ecosystem ecology in particular." At an institutional level, these networks are nearly always initiated by institutions based in North America and Europe.

Recommendations for addressing these challenges: The first suggestion to encourage international participation in a network is to promote online participation (as was done in Alternet summer schools). A second suggestion (per the Mexican social-ecological systems and sustainability network Red SocioEcoS) is to offer multiple membership types. Red SocioEcoS offered one membership type to students and academic researchers and another type of membership to civil society organizations, NGOs, and community members. Different membership types are linked to different roles within the network organization and support a transdisciplinary approach, which is an important value of the network. As a result, research groups started paying more attention to including non-academic members in research projects design, and improving their outreach efforts. This effort allowed the network to appeal to a more diverse audience and attract the attention of international research organizations that, in turn, triggered deeper collaborations (see Calderón-Contreras et al. 2022).

Another suggestion (per the LTAR network), is to be intentional in recruiting underrepresented individuals and entities and to create a culture of belonging where everyone is valued. Based on the LTAR experience, specific recommended actions include: ensuring low membership costs, reaching out to people with knowledge that will advance the network's goals, and clearly articulating the benefits to each member in terms of their career needs. EKNs can also engage in targeted programming (e.g., outreach, educational activities, access grants) to connect with underrepresented communities.

Competing for members' attention

Challenges: Related to above mentioned challenges, it can be difficult to sustain member commitment, especially if membership is voluntary, collaborations are not well-defined, or network leaders fail to articulate the added value of the network to members. In the formative stage of the NSERC ResNet network "... it is also hard to get people to do what they said they were going to do ... PI's [primary investigators'] interests chang [e] and then it is hard to make sure there is participation from that landscape or theme in the same way." This can also be true if a network is seen as competing with other, similar initiatives. In the ESCom network, competition with other new initiatives crowded out the availability of community members to support ESCom, which sometimes duplicated the types of products and events previously provided by ESCom. This generated what has been labeled as "coopetition" (combining cooperation and competition; Tsai 2002). In addition, tensions may exist between academic members, for whom grant funding is an extension of their income, and members from research institutes, who rely on soft money for their incomes. The latter group may have far less flexibility and capacity to remain committed to an unfunded project or network. On the other hand, the decentralized (i.e., polycentric) nature of these networks means that the dispersion of members' attention can also create opportunities for cross-pollination of learning if avenues are created for this to happen, i.e., that "distraction" is not always a negative if it can be harnessed productively (Newig et al. 2010).

Recommendations for addressing these challenges: The main recommendations to address these issues were to understand that all objectives may not be relevant for all individuals or projects, and to remain flexible and responsive to changing needs of members.

Funding challenges

Challenges: In most cases, networks developed to be long-term ventures. However, securing long-term funding to sustain the network is a key challenge. When funding ends, commitment to the network usually declines. A related challenge is that, often, existing program evaluation methods do not account for much of the added value of EKNs. An example from the ESCom network illustrates these points: "Obtaining institutional commitment to support funding for the network ended with research funding. There are great strengths in ESCom's grassroots origins, its organic development, and its inclusive and open nature, but we should, arguably, have been more aware of the importance of the complex institutional context to secure longer-term support. For example, funding support for a network manager is necessary to galvanize and maximize voluntary contributions and would provide excellent value for money."

Recommendations for addressing these challenges: Communicating the value of EKNs is often important to engage continued support of the network from funding agencies and to recruit additional funding. In addition, activities that promote engagement between researchers and policy makers, including those with links to funders, can help to identify funding opportunities. eLTER RI, for example, is trying to overcome these problems by securing the long-term financial commitment of government agencies and academic institutions, in addition to seeking grant funding. However, this solution demands a very high level of institutionalization, which necessitates trade-offs, like committing to rigid criteria that can impede flexibility and may be too daunting for some networks.

Managing environmental knowledge networks smarter moving forward

In response to the above challenges and strategies to address them, several overarching recommendations emerged. We recommend that EKNs (a) develop simple, flexible, transparent, and clear objectives for the network; (b) invest in an inclusive governance structure and leadership team; (c) find ways for people to contribute according to their ability and provide benefits to diverse constituencies without undue burden; (d) articulate priorities for balancing time and effort dedicated to conducting science vs. engagement and advancing the public good; (e) create communication, engagement, and data-sharing plans at the outset so members understand expectations for their interactions in the network; (f) meet, listen, and be patient (important for developing knowledge, credibility and trust). Members have a host of complementary strengths and their priorities will inevitably conflict; these issues take time to sort out.

To frame our reflections as advice for leaders of new and emerging EKNs, we developed the following 10 questions for reflection and action by EKN leaders, which may be particularly useful in the formative stage of building a network (Box 2).

Box 2: 10 Questions for reflection and action

1. What is our network's personality? Be true to the real reasons you set up the network.

2. What are we really trying to do? Have our core aims and activities changed since our network began (or since we last reflected)? Have new members/ partners/ funders/ users caused our aims and activities to shift?

3. What is the feel of our network's culture? Does the culture of our network, both in running the network and in doing the research and other work, cultivate trust, understanding and respect? Are we satisfied with our engagement and communication across our members/partners and stakeholders?

4. Whom are we really serving? Was this network established by scientists to reinforce their vision of the world and how science should be done, or are stakeholders and end-users setting the research agenda?

5. What expectations have been set, and by whom? Have we set (and modeled) clear expectations for interactions and engagement among network members, partners, affiliates, and other participants?

6. Who really calls the shots? Funders? Stakeholders? Network members? Think about this with an open mind; it is not necessarily what you wrote in the proposal. Do you have a "pipeline" of individuals well-equipped to lead your network in an inclusive yet decisive way?

7. How are you going to measure your success? How will you know you have achieved your goals and objectives? How much will you invest in monitoring and evaluation?

8. What is your funding plan? How might funding structures change during different stages in network evolution? Do you have a clear network endpoint? How will funding needs, and sources, change with time?

9. In what areas are you willing to change? How can we determine whether our network should adapt, reinvent itself, or phase out certain elements? When should network leaders be strict and when flexible?

10. What is the balance between center and nodes? Are we satisfied with the balance of power/ responsibility/ agency/ coordination contributed by the network's central body vs. its members?

CONCLUSION

EKNs provide important infrastructure that can help to address complex environmental challenges, but these networks themselves are complex and require significant time and effort to manage. It is important to structure a network in a way that is well-suited to the primary issue it is trying to address. EKNs can enable a diverse community of scientists to address hard questions that cannot be answered otherwise, create a vibrant culture of science, and collaboratively provide useful information and knowledge to society. EKNs are necessarily dynamic and evolve over time, and this process can create a community of practice and forum that enables diverse researchers to speak with one voice, whether delivering a message to environmental managers, the general public, or funders. A generation of EKN leaders have already learned by doing, and we hope the next generation of EKN leaders can benefit from and build on our experience.

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Data Availability:

The metadata that support the findings of this study are openly available in the ResNet Data Portal at https://data.nsercresnet.ca/ by searching the title of this publication and the data can be made available upon request. Ethical approval for this research study was not required, as all data were collected from article co-authors.

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Appendix 1: Participant survey taken prior to symposium

1. What were your motivations for joining / forming the environmental research network (henceforth "your network") with which you are affiliated?

2. What are the goals and objectives of your network?

3. How long has your network been in existence?

4. How well did your network meet its goals in its first 1-3 years?

5. How well do you think your network is achieving its goals and objectives today?

6. For the goals your network has been struggling to achieve, what do you think are the reasons?

7. What were your assumptions upon joining your network about how the network would function and the kinds of data and research it would produce?

8. How does the network help advance your personal objectives as a scientist?

9. What were the surprises and challenges you encountered once the network was initiated?

10. What were some lessons you took away from the first 3-5 years of working in your network that helped you to accomplish your scientific goals (or modify them)?

11. What advice would you give to a brand-new national network doing distributed, interdisciplinary, place-based research?

Appendix 2:
Unabridged table of participating environmental knowledge networks, their aims, characteristics, and key outputs.

Network Name	Key aims of the network	Network origin story	Membership expectations	Funding Structure	Key outputs / outcomes
Alternet, Europe-founded; now international	Fostering the science-policy interface on biodiversity and ecosystem services in Europe	The network was formed in 2004 through funding from the European Union under the Framework Programme 6 as a EU Network of Excellence. When the project ended in 2009, Alternet continued with 22 of the original partners. A Council and Management Board facilitate the activities of Alternet, which has grown to 33 partners from 19 countries.	The members participate in holding annual summer schools, biennial conferences, science-policy webinars and joint activities to promote research cooperation such as multi-site research (funded by Alternet) and a research call exchange (building consortia to bid for external funding). Since 2022, Alternet has supported the Eklipse initiative, which helps governments and others to make better-informed decisions related to biodiversity, mainly by synthesizing knowledge from scientists and other knowledge holders.	Alternet is funded through membership fees, which vary according to the size of the partner institution. Substantial in-kind support is also provided by the partners, particularly in the running of the summer schools. Since 2022, the summer schools have been co-sponsered by Biodiversa+, the the European Biodiversity Partnership.	Alternet's outputs include 15 summer schools and five conferences, activities that are open to non-partners and which have, in the case of the summer schools, attracted participants from across the world. In its early years, Alternet developed the pan-European Long-Term Ecosystem Research (LTER) Network. Since 2022, Alternet has participated as a funded partner in EU projects.

Network Name	Key aims of the network	Network origin story	Membership expectations	Funding Structure	Key outputs / outcomes
eLTER RI (Integrated European Long-Term Ecosystem, Critical Zone, and Socio-Ecological Research Infrastructure), Europe	To provide evidence-based knowledge and ecosystem observation data across the European continent for addressing complex sustainability challenges (e.g., climate change, biodiversity loss, soil degradation, pollution, and unsustainable resource use) over spatial scales from the local to the global, and over the long-term; To catalyze scientific discovery and insights through a state-of-the-art research infrastructure, collaborative working culture, and transdisciplinary expertise.	In 2001, a European Environment Agency (EEA) report critiqued the fragmentation of ecosystem research in Europe and called for stronger links between ecosystem research and monitoring. LTER - Europe, or “eLTER”, evolved out of a European-funded Network of Excellence, Alternet (see row 1 of this table). It is comprised of 26 formal national LTER networks in Europe. In 2018, eLTER was added to the European Strategy Forum for Research Infrastructures (ESFRI), and has since been engaged in an intensive process of cross-country harmonization of activities and institutionalization of its research and data observation infrastructures. Thus, What started bottom-up in a highly distributed manner, has evolved into a complex system of related communities, projects, services and research sites.	Prior to 2018, eLTER was largely decentralized, organized around national networks of LTER sites and socio-ecological research platforms. Each national network paid dues to a central organizing office. Since becoming part of the ESFRI roadmap, a much higher degree of coordination of research activities, service provision, and harmonized observational data collection is expected. Further, as eLTER RI is planning on becoming a recognized European Research Infrastructure Consortium (ERIC), national networks, along with their governmental sponsors, will be responsible for paying dues to support eLTER ERIC.	Prior to 2018, national networks paid a membership fee to eLTER, and individual sites and platforms were funded locally, each according to local context. As part of its acceptance to the ESFRI roadmap in 2018, eLTER is currently developing a long-term business model and funding structure.	A large and diverse set of ecosystem observational sites and socio-ecological research platforms performing both local research and comparative research across ecosystem gradients. eLTER is increasingly engaged with stakeholder communities at the local to continental scale, co-producing knowledge and collaboratively proposing and addressing questions relevant to ecosystem integrity and socio-ecological sustainability.

Network Name	Key aims of the network	Network origin story	Membership expectations	Funding Structure	Key outputs / outcomes
ESCom (Ecosystem Services Community), Scotland	(a) align Scottish ecosystem services research, to maximise benefits, identify synergies, and avoid duplication; (b) work with policy and practice to gain better understanding of user needs, provide relevant research, and achieve impact; and (c) organise and promote events to support knowledge exchange through a dedicated website.	Substantial Scottish Government and EU research funding for ecosystem services research (with some overlapping objectives) prompted researchers from four institutes and one university to identify synergies and opportunities for collaboration. They agreed to establish a community for ecosystem services research, decision-making and natural resource management in Scotland.	Communities of practice like ESCom have fuzzy boundaries and different levels of participation, with a self-selected membership based on expertise or interest for a topic (Wenger et al. 2002). As such, it is difficult to determine a formal membership. The best indication of participation is probably attendance at ESCom activities, where we can distinguish between the active core group of approximately 35 individuals who are ESCom Central members, those who have organised events and/or those who frequently attend events (35 individuals have attended 5 or more events in 4½ years). A larger group can be considered to be active members, regularly attending events and occasionally contributing to ESCom by presenting work or contributing blogs or news items (66 individuals attended between 3 and 5 events). Finally, there is a substantial peripheral group of over 500 individuals who have participated in just one or two events and, perhaps, engaged with ESCom as on social media.	Primarily supported by researchers with relevant project funding, and some in-kind and minor financial support from partners. Crucially, the administrative coordination was paid by a research grant and when this funding ended, ESCom struggled to keep its momentum.	Social learning through sustained networking and collaboration between science, policy and practice; a series of events that haveattracted over 1000 participants, amounting to over 4500 person-hours; tangible content including content includes over 20 blogs, 30 news stories, 5 newsletters and over 85 online resources in the form of presentations, briefing notes, workshop reports and videos.

Network Name	Key aims of the network	Network origin story	Membership expectations	Funding Structure	Key outputs / outcomes
LTAR (Long Term Agroecosystem Research network), U.S.	Create a vibrant and inclusive agricultural economy supported by evolving scientific knowledge that enables farmers and ranchers to achieve production, environmental, and societal goals sustainably.	LTAR was initially established by the Agricultural Research Service (ARS) of the United States Department of Agriculture (USDA) to build the knowledge required for sustainable intensification of agriculture, increasing yields from the current agricultural land base while minimizing or reversing agriculture's adverse environmental impacts.	There are 18 LTAR sites across the US that cover diverse production systems. Scientists, partners, collaborators and stakeholders can join the diverse working groups to address current and emerging issues in agriculture and natural resources.	LTAR is predominately supported by USDA. Co-funding comes from grants, cost-share, and in-kind contributions.	Develop and implement climate-smart solutions and innovations for sustainable and resilient agroecosystems, and ensure thriving and diverse rural and agricultural economies.

Network Name	Key aims of the network	Network origin story	Membership expectations	Funding Structure	Key outputs / outcomes
LTER (Long Term Ecological Research Network). U.S.	LTER envisions a society in which exemplary science contributes to the advancement of the health, productivity, and welfare of the global environment that, in turn, advances the health, prosperity, welfare, and security of our nation. Thus, the LTER network mission is to provide the scientific community, policy makers, and society with the knowledge and predictive understanding necessary to conserve, protect, and manage the nation's ecosystems, their biodiversity, and the services they provide.	The LTER Network was founded in 1980 by the U.S. National Science Foundation with the recognition that long-term research could help decipher the principles and processes of ecological science, which frequently involves long-lived species, legacy influences, and rare events.	Research within the LTER Network is place-based, and addresses site-specific ecological and social-ecological questions that demand long-term study. However, the research programs at all sites are organized around a common group of "core areas". Sites share data and participate in a range of network meeting and synthesis activities.	Sites are individually funded and reviewed by the U.S. National Science Foundation in six year increments.	a) Understanding: To understand a diverse array of ecosystems at multiple spatial and temporal scales. b) Synthesis: To create general knowledge through long-term, interdisciplinary research, synthesis of information, and development of theory. c) Outreach: To reach out to the broader scientific community, natural resource managers, policymakers, and the general public. d) Education: To promote training, teaching, and learning about long-term ecological research and the Earth's ecosystems. e) Information: Creating well-designed and well-documented databases. Legacies: To create a legacy of well-designed and documented long-term observations, experiments, and archives of samples and specimens.

Network Name	Key aims of the network	Network origin story	Membership expectations	Funding Structure	Key outputs / outcomes
NEON (National Ecological Observatory Network), U.S.	(a) Continental-scale environmental data and archival samples. (b) Infrastructure for ecological research studies. (c) Educational tools to work with large data.	The Earth and its ecological processes are changing at unprecedented rates due to human activity; the effects of these changes are uncertain. To address this uncertainty, the science, education, computing, and engineering communities provided input to NEON's design, with the shared goal of creating a long-term ecological observatory that collects and provides a diverse suite of comparable and consistent ecological data at multiple spatial and temporal scales.	NEON collects and processes data from field sites located across the continental U.S., Puerto Rico, and Hawaii over a 30-year timeframe.	NEON is funded by the U.S. National Science Foundation (NSF) and operated by one contractor (Batelle).	A diverse suite of comparable and consistent, publicly available ecological data at multiple spatial and temporal scales.
NSERC ResNet, Canada	Support Canada's capacity to monitor, model, and manage its working landscapes and seascapes (and all the ecosystem services they provide) for the long-term shared health, prosperity and resilience for all Canadians through community-engaged research.	EMB wanted to build a network of scientists focused on multi-scale ecosystem service monitoring and modeling to improve environmental governance in working landscapes.	Individuals work as part of a team based either at one of six case-study landscapes or in one of three conceptual working groups or themes.	Primarily funded in the last year of NSERC's Strategic Network program that focuses on scientific networks in partnership with industry, government, and NGOs. Most of the funding comes from NSERC; co-funding (cash or in-kind) comes from partners including other government entitites and the universities themselves.	A framework for monitoring ecosystem services at multiple scales in Canadian working landscapes.

Network Name	Key aims of the network	Network origin story	Membership expectations	Funding Structure	Key outputs / outcomes
NutNet (Nutrient Network) U.S. funded; international in scope	a) To experimentally test specific hypotheses about elemental nutrient supply and herbivory arising from ecological theory; b) To build on single site theory tests and meta-analyses by generating data using identical methods at every site and experiments replicated under many conditions to understand generalities and biotic & abiotic contingencies in responses; and c) To develop a new, distributed experimental approach to testing ecological theory.	NutNet was conceived by a few early career scientists with the goal of overcoming the limitations of meta-analysis for testing ecological theory.	All participating sites must follow the same experimental protocol and use templates available on the NutNet website for data submission. Data must be submitted within six months of collection and is centrally curated for all sites in the network.	Individual NutNet sites are funded by investigators at each site using a wide range of funding sources. Initially, the network meetings and a postdoc were funded by a U.S. National Science Foundation Research Coordination Network grant. Funding for the postdoc was provided for a few years by a University of Minnesota institute. Funding has, more recently, been part of a US NSF grant to support the Cedar Creek LTER site.	The NutNet long-term experimental data and globally-extensive infrastructure are two major outcomes. Together, these have led to more than 120 scientific publications.
Red SocioEcoS, Mexico	Red SocioEcoS aims to convene different research groups dealing with social-ecological and sustainability issues in Mexico. Since there is a wide array of institutions and research groups focusing on social-ecological research in Mexico, Red SocioEcoS was designed to convene research groups and identify common interests to create a platform for knowledge exchange, collaboration, transdiciplinarity research, outreach, and funding opportunities.	Red SociEcoS was created in 2014 as a "network of networks". The original idea was to identify and gather research groups in Mexico with common social-ecological interests and a focus on sustainability research. The proposal was supported by the National Council for Science and Technology, and it provided the means for a first thematic gathering of nearly 80 representatives of the different networks involved in social-ecological and sustainability research, outreach, and teaching.	Members are expected to participate in one of the organizational nodes to design and implement common tasks and thematic activities for the broader membership. Researchers and students in the network are entitled to be included in the Geographic Information System that includes the research sites registered in the network as well as the research topics for each academic member, as well as their geographical location. Members receive a periodic newsletter with funding opportunities, conferences, and other academic activities of interest.	The network is mainly funded by the National Council for Science and Technology. Complementary funding has been provided by individual projects to support specific network activities (mostly related to conference attendance).	Outputs include four national conferences, participation in most sustainability-related conferences, and direct organization of three international conferences. Four different research proposals were funded by external entities, helping to form a community of practice that constitutes a vibrant opportunity for outreach with local and regional authorities, local communities, and academic bodies in Mexico and beyond.