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Resilience Is Not Enough: Toward a More Meaningful Rangeland Adaptation Science

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ABSTRACT

Rangeland ecosystems, and their managers, face the growing urgency of climate change impacts. Researchers are therefore seeking integrative social-ecological frameworks that can enhance adaptation by managers to these climate change dynamics through tighter linkages among multiple scientific disciplines and manager contexts. Social-ecological framings, including resilience and vulnerability, are popular in such efforts, but their potential to inform meaningful rangeland adaptation science is limited by traditional disciplinary silos. Here, we provide reflective lessons learned from a multidisciplinary Rangelands, Ranching, and Resilience (R3) project on U.S. western rangelands that addressed 1) biophysical science projections of forage production under future climate scenarios, 2) ranchers' views of resilience using social science methods, and 3) outreach efforts coordinated through extension professionals. Despite the project's initial intentions, human dimensions and ecological researchers largely worked in parallel subteams during the project, rather than weaving their expertise together with managers. The R3 project was multidisciplinary, but it provides a case study on lessons learned to suggest how social and ecological researchers can move towards approaches that transcend individual disciplines. Transdisciplinary science and management in rangelands requires more than just conceptual social-ecological frameworks. Additional methodological concepts need to include: 1) relationship building; 2) shared meaning making; and 3) a commitment to continual conversations and learning, or staying with the trouble, following Haraway (2016). If the goal is to address meaningful rangeland adaptation science rather than just produce academic products, researchers, outreach professionals, and rangeland-based communities should address a series of critical troubling questions. In the process of addressing these, deeper engagement among and

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beyond disciplines will occur as relationship building, shared meaning, and continual conversations and learning facilitate staying with the trouble.

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Introduction

As the effects of climate change unfold across rangelands, research and outreach organizations are increasingly initiating collaborative projects aimed at improving the adaptive capacity of these systems. Researchers and decision-makers are recognizing that the risks climate change and increasing variability pose to rangeland ecosystems and livelihoods are too complex for a single discipline to address in isolation. Furthermore, research organizations and funders are calling for more interdisciplinary research where social and ecological fields collaborate, through the use of *transdisciplinary* methodologies that push past disciplinary traditions and directly engage with societal partners and multiple types of knowledge (Ganguli and O'Rourke, 2022). When social scientists, biophysical researchers, and outreach professionals team up to address climate change challenges, their first step is often to select a common theoretical framework to guide the development of their research agenda and outreach activities. Social-ecological systems (SES) concepts, broadly inclusive of the concepts of resilience and vulnerability, have become a popular theoretical meeting place for adaptation research teams (Berkes et al., 1998; Havstad et al., 2007; Dudney et al., 2018). Despite the promise of these frameworks to bring social and ecological sciences together with resource management expertise, disciplinary and conceptual barriers continue to stall science's ability to inform climate adaptation on rangelands (Brunson, 2012; Fernández-Giménez et al., 2019; Moser et al., 2019). After decades of conceptual development and application in rangelands, it is timely to consider what capacity SES frameworks have to transcend the limitations of siloed social and ecological approaches, and to bring in new ideas that motivate meaningful, impactful rangeland adaptation research and outreach.

In this paper, our goal is to conceptualize a more meaningful rangeland adaptation science by first identifying and then addressing limitations of the current SES frameworks. We reflect on the experience of a multiyear, cross-institutional project that focused on understanding the resilience and vulnerability of rangeland cattle production systems in the Western US, the U.S. Department of Agriculture (USDA)-funded Rangelands, Ranching, and Resilience (or R3) project. The R3 project had aspirations for societal as well as scientific impact, and the team initially set out to build bridges across the multiple disciplines. R3 scientists also aspired to engage with the knowledge and context of local managers through both social science and outreach efforts. In retrospect, the R3 team generated insights about the systems we studied, successfully published scientific findings (Dinan et al., 2021; Felton et al., 2022; Greene et al., 2022; Walsh et al., 2022), and fostered important cross-disciplinary conversations over the life of the project. We also held outreach efforts to translate findings to managers and gather feedback (Dinan et al., 2021; Walsh et al., 2022). However, the SES conceptual frameworks employed were insufficient to allow the R3 team to achieve the high bar of transdisciplinary knowledge integration[1] (Angelstam et al., 2013; Knapp et al., 2019; Roche, 2021). We use this case to explore the challenges and opportunities for improving outcomes for teams that include human dimensions, ecology, and rangeland ecology and management disciplines.

The case study leads us to argue that SES framings may actually reinforce disciplinarity. This occurs because SES frameworks lack the explicit methodological capacity to overcome the underlying human/nature dualism persistent in Western scientific traditions separating social and ecological disciplines. Without the capacity to transcend this dualism, scholars rely on distinct disciplinary lenses, operate apart from the social worlds of societal partners and, ultimately, remain separated from rangeland ecosystems themselves. Put another way, when SES framings lack an explicit intention to weave multiple knowledges together (Tengö et al., 2014; 2017), their application in rangeland adaptation projects such as R3 may result not in adaptive capacity development, but in the more traditional "parallel play" common in multidisciplinary studies. In these scenarios, socially- or ecologically- framed research results largely fail to affect one another or to converse with manager communities. Therefore, additional theory of method, or *methodological power*, is needed to transcend social/ecological dualisms and disciplinary traditions. To gather that methodological power, we offer concepts from science-and-technology (STS) scholarship that de-emphasize the human/nature binary and suggest the importance of 1) relationship building; 2) shared meaning; and 3) commitment to continual conversation and learning, or *staying with the trouble* (Haraway, 2016). We draw inspiration from Haraway's argument that co-creating a better world requires us to develop methods to more responsively and collaboratively "compost" or mix new ideas and approaches to deal with climate, ecological and social crises. While there are limitations framing our analysis around one of many STS scholars, Haraway's scholarship is a useful tool to motivate dialogue and theoretical development.

We first review SES concepts as they were interpreted by human dimensions (focused on resilience) and ecological scholars (focused on vulnerability) in the R3 project. Then, we describe and examine the R3 project to illustrate the challenges of SES approaches to climate adaptation science. We discuss insights revealed from this analysis, including how an emphasis on relationship building and shared meaning can help research teams transcend disciplines and connect with societal applications. To construct this argument we provide a conceptual diagram that outlines disciplinary lenses employed by resilience and SES scholars (Fig. 1) and a table highlighting their application in the R3 project (Table 1). A revised framework with additional transdisciplinary methodological concepts (Fig. 2) is followed by a set of reflective "troubling questions" research teams can use to move towards a more engaged collaboration (Table 2). This analysis is complemented by two vignettes of existing projects that demonstrate effective partnerships with managers and communities at actionable local scales (Box 1 and 2). The paper concludes with a vision for a more meaningful rangeland adaptation science that can inform future collaborative projects.

Overview of SES Concepts

We see SES theory as an overarching approach, with the ideas of resilience and vulnerability emerging as associated frameworks that enable scholars to draw from the traditions and assumptions of SES (Berkes et al., 1998; Lei et al., 2014; Marshall et al., 2014;

[1] Transdisciplinarity is distinct from interdisciplinary research in that it seeks to bring together knowledge and expertise from not only distinct academic disciplines, but from other expert knowledge systems outside of academia. Following Knapp et al., 2019, we conceptualize transdisciplinarity as knowledge development that "connects diverse knowledge holders with one another and the realm of practice, shares power within the process, and arrives at different outcomes including action and problem management" (2).

Table 1
Two studies of the same rangeland ecoregions in the western U.S., one using a social and the other using an ecological lens, provide distinct views of system dynamics under the over-arching social-ecological theoretical framings of resilience and vulnerability.

Disciplinary lens	Driving question	Temporal scale–Where?	Spatial scale– When?	What and how?	Applications by whom?
Human dimensions team	"How do ranchers view resilience?"	Rancher career (20+ y), Retrospective	Ranch and community scale responses to regional, national, global change	Resilience of ranching operations and communities across Western U.S.	Social scientists, rangeland managers, rural communities, government agencies and outreach professionals
Ecology team	"Forage sensitivity to climate change"	Decadal scales, Prospective	Regional outcomes of global change	Change in primary production in five U.S. ecoregions	Ecologists, land managers, government agencies and outreach professionals

Table 2
While the R3 project was *multidisciplinary*, it can serve as a case study to suggest how social and ecological researchers can move towards *transdisciplinary* approaches that transcend disciplines. These "troubling questions," help researchers, outreach professionals, and rangeland-based communities move toward the sort of dialogue and relationships necessary to address rangeland resilience.

Temporal scale- when?	Spatial scale- where?	Methods- how?	Implications- for whom?
How do we reconcile social knowledge of manager-relevant time-scales with long-term predictions of change? How can we think and act together for long-term resilience? How can rancher knowledge, which is retrospective, relate to scientific (predictive) scales of analysis to enhance adaptation? How can communities where climate change skepticism is common effectively plan for decadal-scale change and adaptation?	How will decisions made at ranch and community levels deal with regional and global change? How can researchers and practitioners mobilize beyond-ranch-level strategies?	What does it look like to conduct inclusive valuation of each lens and the interactions among different systems and scales? What is limiting this analysis and meaningful action? How do we develop a pluralistic and collective vision for a viable new future?	Who will deal with the consequences of change? Who has the capacity and agency to address change at multiple scales? What new roles and partnerships are needed to address resilience?

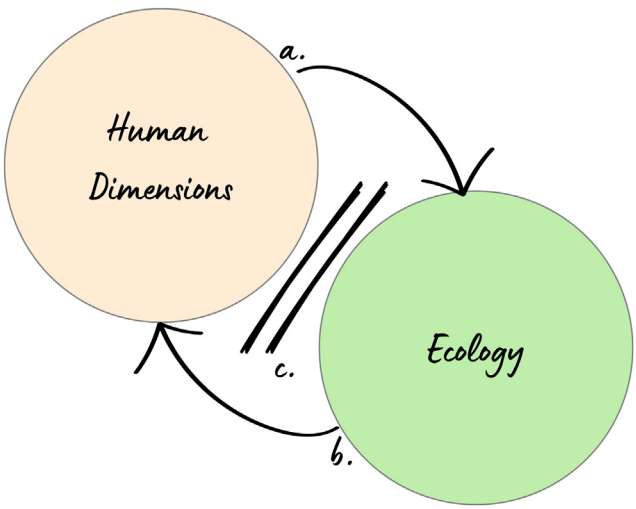

Figure 1. A conceptual representation of the relationship between disciplinary lenses in the R3 project. Human dimensions scholarship aims to contextualize the social experience of resilience with appreciation for social-ecological relationships **A**, while ecological research aims to quantify and predict vulnerability of socially important system processes as a function of exposure, sensitivity, and adaptive capacity. **B**, Social-ecological framings can help distinct disciplinary recognize one another, but a social/ecological divide of the disciplines persists C, without the additional application of transdisciplinary methodologies.

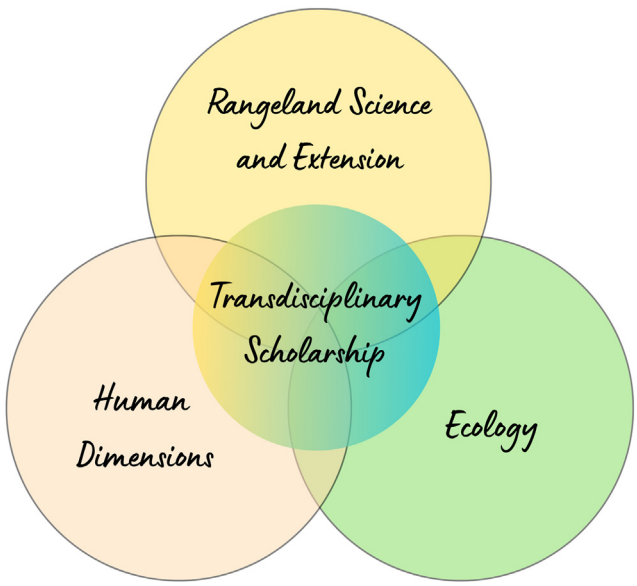

Figure 2. Methodologies to bridge disciplinary lenses in rangeland adaptation sciences by linking human dimensions, ecological, and rangeland science disciplines through transdisciplinary scholarship. This is fostered by relationship building, shared meaning, and a commitment to continued dialogue (Haraway, 2016).

Moser et al., 2019). The existing scholarship reflects a range of goals and methodologies, and each disciplinary lens has a distinct conceptualization of SES systems and of the contribution science makes to adaptation outcomes (Fig. 1).

Social-ecological systems theories. SESs occur at multiple scales but are typically defined as integrated human and natural resource systems in which subsystems are identifiable but inextricably linked (Díaz et al., 2006). SES research has roots in complexity theory and natural resource management economics and governance (Berkes et al., 1998; Ostrom, 2009). Elinor Ostrom's work, for example, challenged the assumption that communities cannot manage their resources and outlined design principles for the sustainable governance of common pool resources (1990).

There are several reasons SES concepts like resilience are appealing for rangeland scholars (Brunson, 2012). The theoretical

premise that natural resource contexts are complex systems where social and ecological sub-systems cannot be disentangled aligns well with rangeland contexts, which are largely defined by human-nature relationships (Ellis and Swift, 1988; Havstad et al., 2007; Huntsinger and Oviedo, 2014). SES concepts create theoretically rich and relatively flexible spaces where scientists from different disciplines can hypothesize relationships between sub-system dynamics at multiple scales (Bagchi et al., 2011). Finally, SES framings offer relatively tractable concepts like vulnerability and resilience that serve as boundary objects[2] by which scientists can collaborate and communicate with policy makers, administrative agencies, and communities (Bentley Brymer et al., 2016).

Resilience. Resilience is a broad theoretical framework for characterizing SES change (Moser et al., 2019), though it is defined in various ways across social and ecological disciplines (Brunson, 2012). As defined in the ecological literature, resilience is the amount of disturbance or change a system can withstand and still return to its pre-disturbance state and function (Holling, 1973; Gunderson, 2000). Resilience explains how SES systems function in cycles of change, including complexity and uncertainty, and incorporates multiple drivers of change that operate across numerous spatial and temporal scales (Gunderson, 2000; Angeler and Allen, 2016). Resilience is also concerned with nonequilibrium system dynamics and the potential that systems could cross thresholds among states (SES or ecological states) (Westoby et al., 1989). Systems may be more or less vulnerable to undesirable state shifts, though the issue of "who decides" what state is desirable remains a critical question. To achieve resilience, the theory suggests that adaptive management—or adjustment of management actions based on scientific goal setting and monitoring information—can be more effective to enhance desired system outcomes than rigid, pre-determined approaches (Holling, 1973; Allen and Gunderson, 2011). Increasingly, it is recognized that this adaptive management will be more effective if it includes all kinds of knowledge and the goals of diverse stakeholders, including local land users. SES scholarship has also contributed to the recognition of traditional and local ecological knowledge and conceptualized methods to co-produce research with human communities (Tengö et al., 2014). Importantly, this work emphasizes a respectful process of weaving multiple knowledge rather than merging them (Tengö et al., 2017).

SES concepts in the rangeland sciences. Rangeland scientists have used SES and resilience concepts to increase understanding of land management systems and to conceptualize plant community change (Westoby et al., 1989; Briske et al., 2008; Bagchi et al., 2011). The discipline made contributions to non-equilibrium ecology (Ellis and Swift, 1988; Fernandez-Gimenez and Allen-Diaz, 1999) and to the proliferation of state-and-transition models within the ecological site concept (Briske et al., 2008) and globally (Wonkka et al., 2019). Additionally, the rangeland literature has contributed to methods for adaptive management and publicly engaged research (Galvin et al., 2016; Brugger et al., 2018; Reid et al., 2021). Resilience concepts continue to enhance ecological research at multiple scales (Chambers et al., 2017), though Brunson (2012) noted that resilience may not be as promising a framework for SES science as many might think, partly because of differences in how social and ecological scientists conceptualize resilience, and proposed a multiscalar framework to guide decisions about management alternatives. This brings into question the ability of boundary objects such as resilience to genuinely coordinate tractable collaborative or transdisciplinary thinking.

[2] "Boundary objects are able to coordinate different groups without a consensus about their aims and interests. If they are both open to interpretation and valuable for various scientific disciplines or social groups, boundary objects can be highly useful as a communication tool in order to bridge scientific disciplines and the gap between science and policy" (Brand and Jax, 2007, 10).

SES concepts in the human dimensions of environmental change. SES and resilience concepts have also been used in the social sciences, which have focused on the adaptive capacity and response actions of various actors in natural resource systems like rangelands (Cote and Nightingale, 2012; Brown, 2014; Green et al., 2021). Recent work has classified resilience capacities, including adaptive, absorptive and transformational capacities, in farming communities to help identify key leverage points for resilience (Malherbe et al., 2024). Qualitative research can document the research needs and perspectives of managers, producers, and conservation actors on rangelands, and can raise the voices or perspectives of communities, orient researchers to the contexts and needs of managers, and can potentially enable more effective research and outreach in multi-disciplinary studies.

But do theories that explain the dynamics we observe in rangeland ecology translate directly to human communities? The social sciences have critiqued the assumption that ecological framings apply easily to social realms (Moser et al., 2019; Greene et al., 2022). Resilient ecosystems may not necessarily produce resilient human communities, and framings of system change in terms of "complex adaptive systems" may be more appropriate in ecological settings than in social ones, and social scientists have argued that resilience is unappealing to the critical social sciences (Olsson et al., 2015). These fields evaluate how social and SES outcomes are developed and maintained by social structures of power and do not consider these outcomes to be emergent properties of complex systems as suggested by Holling's (1973) original definition (Olsson et al., 2015; Moser et al., 2019). As Figure 1 indicates, social scientists on the R3 project emphasized the impact of social processes on social conditions within a particular environmental or ecological context.

Vulnerability frameworks. Vulnerability has distinct theoretical roots from resilience, serving as a framework for approaching climate adaptation (Pachauri, 2014) and in natural hazards research (Cannon, 1994). However, vulnerability is often employed in SES applications (Eakin and Luers, 2006; Fernández-Giménez et al., 2012; Brown, 2014), and brings attention to the factors and processes within a system that make it likely to experience harm due to a specific threat (often a climate-related threat) (Marshall et al., 2014; Berrouet et al., 2018; Timberlake and Schultz, 2019). Some of these factors may be social contributors to vulnerability, such as a community's access to financial or political capital (Tucker et al., 2015; Ronco et al., 2023) while others may be physical or ecological, such as a the sensitivity of an area's vegetation to drought or exposure to extreme winter storms (Timberlake and Schultz, 2019). While multiple system drivers and thresholds may be quantifiable, vulnerability is perhaps most powerful as a conceptual tool for communicating climate risks to decision-makers.

In many applied cases, vulnerability is conceptualized to be positively impacted by both exposure and sensitivity, and negatively impacted by adaptive capacity (Marshall et al., 2014; Halofsky and Peterson, 2018). As a hypothesis for rangeland adaptation science, this suggests that reductions in sensitivity or exposure for socially-relevant ecological variables, such as forage production, can help create actionable frameworks for reduced vulnerability and enhanced resilience. Climate and ecological sciences can help quantify or predict the magnitude of these relationships to provide society with a forecast of future risks and trends (Fig. 1), but leave it to other disciplines to theorize social or political mechanisms that drive or might serve society in adapting to these dynamics.

Bridging or reinforcing the "Great Divide"? One of the great opportunities of SES approaches is to overcome what is now recognized as a limiting human/nature dualism embedded in Western scientific traditions, not only via engagement with human dimensions and ecological disciplines but also in partnership with man-

agers and local knowledge (Collins et al., 2011). The need to do so is increasingly apparent (Lewis and Maslin, 2015, Diaz et al., 2018). Indigenous sciences have long called for attention to human-nature relations (Salmón, 2000; Whyte, 2020; Tynan, 2021). Posthumanists and science and technology (STS) scholars have also discussed the importance of overcoming the modernist Great Divides(s) [3] between society and nature (Latour, 1993). Now-mainstream concepts like the Anthropocene and human-natural systems framings further challenge us to identify and employ more robust frameworks for understanding interrelated ecological and economic processes and to address their long-term consequences for earth systems (Folke et al., 2021; Lewis and Maslin, 2015; Waters et al., 2016). Bridging the divide in our scientific frameworks is then a key first step for adaptation sciences capable of responding to these "troubling and turbid times" shaped by climate change, biodiversity loss, and other realities of the Anthropocene (Haraway, 2016).

Rangeland adaptation science focuses on systems defined as SES, and so offer a great starting place to bridge the human/nature divide. For example, human dimensions scholars on US rangelands provide an intimate view of how ranchers navigate social and ecological resilience. This effort can contextualize the project, document local knowledge, and illuminate opportunities for ecological research to be most informative to managers (Fig. 1A). One way ecology can inform social systems is by providing predictions about climate impacts to a socially important ecological variable, such as forage production. These predictions warn society of what may be to come in terms of system sensitivity and vulnerability to climate change (Fig. 1B). However, distinct disciplinary lenses create challenges for incorporating social or ecological findings into the world view of one another (as explored in the analysis section below and Table 1). Without additional methodological motivation to engage in transdisciplinary conversations, these distinct lenses can reinforce separate social and ecological framings. This can leave researchers on either side of a project wondering why the other cannot hear their findings and leave end users without useful applications (Fig. 1C).

Adding Additional Theory of Method

To help find a path out of this persistent disciplinary divide, we pull ideas from STS scholar Donna Haraway. We selected ideas from her volume *Staying with the Trouble* (2016) because this text theorizes relationships and methods that transcend the human/nature divide. Her work also frequently involves examples that may be accessible to rangeland scholars. Here, Haraway offers a generative response to SES problems that involves building relationships and committing to a co-produced viable future. This approach de-emphasizes human-nature divides and the primacy of the individual, and instead considers how and where we can "compost" or foster responsive relationships for a sustainable future, even in times of socio-environmental crisis. We employ concepts inspired by her work to help lend methodological power to rangeland SES research (Fig. 2). These are:

(1) *Relationship building.* Haraway's scholarship stresses the critical importance of relationships. In *Staying with the Trouble*, she envisions a co-beneficial future for people and ecosystems through the process of creating and nurturing new bonds and responsibilities among one another and with other species (what she calls "kinmaking"). These relationships are enabled through a sense of responsibility towards one another, which Haraway frames as "response-ability." This includes accountability towards teammates and their respective SES subsystems of study. Relationship building is a well-described methodological concept in the transdisciplinary literature (Ferguson et al., 2022).

(2) *A shared sense of meaning.* Shared meaning is common background knowledge that guides team members in organizing and developing their interpretations of events and systems (Bjørn and Ngwenyama, 2009). A broader discussion of meaning includes the importance of a sense of awe (see: Shiota et al., 2007) as a motivator or catalyst for scientific discovery (Gottlieb et al., 2018). Haraway suggests that "*The task is to become capable, with each other in all of our bumptious kinds, of response…Our task is to make trouble, to stir up potent response to devastating events, as well as to settle troubled waters and rebuild quiet places*" (2016, pg 1). Shared transdisciplinary meaning, therefore, is distinct from an individual's interest, passion, or care about environmental change issues and topics, and may be pluralistic in that it assumes the existence of multiple ways of knowing and being (Rigolot, 2020).

(3) *Staying with the trouble.* Here we borrow the title phrase from Haraway's book to emphasize the importance of committing to the challenging work of conversation and learning over the long term. Haraway writes about the value of continued dialogue and learning, to staying with the trouble, as she argues that "*a common livable world must be composted bit by bit*" (2016, pg 40). No single project, team, or institution can fully address the extensive and complex implications of climate-related challenges on rangelands, which are ongoing and shaped by emergent dynamics across scales. This is why the maturity of collaborative partnerships is an important determinant of success (Ferguson et al., 2022). This concept brings perspective to the processes and time scales that enable transdisciplinary approaches, and so reminds researchers that prolonged engagement and effort can promote learning and innovation.

With these concepts, we seek to enhance the abilities of rangeland resilience scholars and practitioner communities to co-develop increased knowledge and adaptive capacity through shared meaning as well as stronger relationships. Below, we describe the case of the R3 project and examine the specific conceptual contributions of the project to SES understanding.

Project Case Study Description: The R3 Project

The R3 project was initiated in 2018 in response to growing concern that rangeland systems are increasingly vulnerable to undesirable, transformational change (Joyce et al., 2013). The project sought to leverage multiple disciplines to better understand these system dynamics and develop adaptation strategies for managers. The project proposal broadly employed resilience and vulnerability concepts, recognizing the need to better understand linkages among social and ecological aspects of rangelands. R3 involved ecologists, social scientists, rangeland researchers, extension professionals, and climate adaptation experts from multiple institutions, and focused on range beef cattle production systems and rangeland ecosystems in five regions of the U.S. West (Dinan et al., 2021). The project was framed under principles that recognized regional specificity of climate change impacts on rangelands across the western US; the coupling of social and natural system components; the role of uncertainty in social and natural environments; and the necessity of including the experience and knowledge of local actors to better understand adaptive capacity at the local scale through iterative research and extension activities throughout the project.

[3] Bruno Latour describes two great divides. The first separates humans from nature (the first great divide) and, critically, distinguish certain humans from other humans based on a proximity to Nature (the second great divide) (Latour, 1993).

The R3 ecologist team. An ecological team centered their analysis around vulnerability and sensitivity. They assessed the climate sensitivity of U.S. western rangelands in terms of forage production (the herbaceous component of annual net primary productivity). The model of Felton et al. (2022) follows a tradition of modeling rangeland aboveground net primary production as a function of precipitation using field-based measures of production (Sala et al., 1988; Lauenroth and Sala, 1992; Huxman, 2004) as well as remotely-sensed measures (Maurer et al., 2020). We predicted changes in forage production by mid (2060) and late-century (2100) based on the model of Felton et al. (2022) for the five US ecoregions, including California annual grasslands, cold desert, hot desert, northern mixed prairie, and shortgrass steppe. We fit statistical models that explained historical (1986–2015) satellite-derived estimates of forage production as a function of growing season precipitation and temperature. Only pixels dominated by rangeland vegetation were used. After fitting the statistical models, we then fed in projections from 11 different climate models for two greenhouse gas emission scenarios (representative concentration pathways, RCP 4.5 and 8.5) to project changes in forage production.

Projections using these models showed little change in forage production in California annual grasslands, cold deserts and the northern mixed prairie, but dramatic decreases in the hot deserts of the Southwest and the shortgrass steppe. These qualitative patterns were similar for both the RCP 4.5 and 8.5 emission scenarios (Felton et al., 2022, Supplementary Information). Projections for the mid-century period using the same models (Fig. S1) show decreases in forage production of 10% or more in most counties in the Southwest, while many counties are projected to experience declines of 50% or greater.

The ecologist team discussed the contribution of these findings to a broader literature on climate impacts ecosystems. The key result of Felton et al. (2022) is that different assumptions about the rate at which ecosystems respond to climate change lead to great uncertainty in long-term projections of forage production. An important feature of the model was the decomposition of climate covariates into spatial and temporal components. Previous work has shown that forage production is more sensitive to spatial variation in mean annual precipitation than it is to temporal variation in annual precipitation (Lauenroth and Sala, 1992; Huxman, 2004; Sala et al., 2012). This difference reflects the fact that two locations that differ in climate will also differ in plant species composition and soil structure, among other attributes. In contrast, while 2 y at one location may feature very different weather, the plant species composition and soils will remain fairly constant, constraining the capacity of the ecosystem to respond to variation in weather.

The R3 human dimensions team. A second team was comprised of interdisciplinary social and physical scientists with backgrounds in climate adaptation, rangelands, and geography. This team sought an emic, or insider's view, of how ranchers perceived rangeland and ranching resilience. They worked with local community conveners (primarily Extension professionals) to conduct focus groups with ranchers in nine communities. Findings published in Greene et al., (2022) reveal how ranchers felt they had more capacity and tools to deal with ecological and climate change-related dynamics than with three other forms of change: sociological (rural community change), economic (changes in the cattle market), and political (land use change).

Ranchers had few strategies to address transformational changes in their rural communities, such as intensifying pressure for rangeland use from recreation, development, consolidated agriculture, and amenity users. Overall, these results revealed mismatches between the ranchers' perceived ability to adapt (what social scientists refer to as their *agency*) by employing ranch and some community-scale strategies, and the scales of the challenges they face such as global cattle markets, agricultural policy, and land use trends.

The R3 outreach team. A third team, the outreach team, gathered feedback on our work from ranchers and managers in the region via expertise within the USDA Southwest and Northern Plains Climate Hubs. The outreach team developed an interactive website of their findings and conducted follow-up online calls with each community (Walsh et al., 2022). USDA Climate Hub outreach professionals coordinated a workshop with managers and ranchers in 2020, during which social and ecological scientists presented their findings and solicited feedback from attendees (Dinan et al., 2021; Walsh et al., 2022).

Analysis

The contributions and limitations of disciplinary lenses

While not inclusive of all resilience concepts and modes of analysis (there are many), the R3 project illustrates the promise and limitations of SES frameworks to inform meaningful rangeland adaptation science. A stated goal in the R3 project proposal was to "*develop a framework to assess the sensitivity of rangeland production systems to climate variability and identify strategies to improve the adaptive capacity of these systems*." But making the link between scientific findings and actionable strategies for managers is difficult. R3 scholars conceptualized relationships between SES sub-systems, but ultimately failed to braid their individual contributions into a generative synthetic effort (Fig. 1). Below we expand on the summary provided in Table 1 related to the limitations and opportunities of each approach. We recognize that delivering effective rangeland resilience research is difficult under the best of circumstances, and so we emphasize the theoretical and methodological contexts of the work over the challenges of team dynamics (see: Hall et al., 2018; Bamzai-Dodson et al., 2021; Beck et al., 2021; Karrasch et al., 2022).

Challenges and opportunities from the R3 ecological analysis

There are several key challenges associated with enhancing the usability of climate change science and forage models for managers. These challenges result from a framing of SES systems that weakly conceptualize social dynamics and do not engage with transdisciplinary methods to converse with manager contexts, but also from the challenges of climate science. For example, recent scholarship has shown a link between climate change skepticism and low adoption of adaptation practices in agricultural communities in the US (Prokopy et al., 2015; Yung et al., 2015). Communication framings that emphasize win-win solutions and tractable adaptations to drought, extreme events, and weather variability may draw more producers toward climate science information (Rivera-Ferre et al., 2016; Telg et al., 2020, Dinan et al., 2021). Even when producers are interested in climate change science, mid- and late-century projections of annual forage production are difficult to operationalize within ranch planning horizons (Smith et al., 2021). Many ranchers work with multi-generational operations and have long-term goals for sustainability, but their active adaptive ranch planning centers at seasonal, annual, or mid-term (10+ y) scales that relate to a manager's active decision-making career (Wilmer and Fernández-Giménez, 2015). The R3 research team learned that ranchers were more interested in seasonal time scales that matched their decision-making calendars (Dinan et al., 2021), while the ecological team saw an opportunity to examine a higher level research question that addressed regional, longer-term predictions in forage sensitivity to climate change. The team also grappled with the fact that researchers may not be able to offer predictive climate science at these time scales.

The regional spatial scale of climate and production projections is also an important consideration. Managers have some decision-making power over various "postage stamps" of land, perhaps a ranch or even a National Forest allotment, but cross-boundary resource planning remains a challenge in the U.S. West, as various regulatory schemes and farm policies shape land and water use. Seeing vulnerability at the National Forest, ecosystem, or regional scale, as R3 presented, is an opportunity for managers to plan for SES transformations beyond the ranch gate (see: Davies et al., 2011; Remington et al., 2021). Such planning would involve collaboration across boundaries in multiple senses of the word (social, political, economic, and ecological) (Brunson et al., 2016). Data that is relatable to context-specific scales, such as those employed in the ecological site concept, may be more tractable for specific land management planning processes and program implementation.

Challenges and opportunities from the R3 social science analysis

One goal of social scholarship is to bring theoretical tools to bear on complex social issues and to enhance our ability to see our own realities within broader contexts. Greene et al. (2022) point out that large social structures and processes, and not just ranch decision-making or social psychology, are barriers to ranch resilience. Ranchers who attended virtual feedback sessions and viewed the interactive website commented that the human dimensions findings reflected their experience and could help explain ranchers' perspectives to the broader public, consumers, and public land users.

However, it is challenging for producers to turn these social science findings into actions because they point to large scale drivers of change beyond the ranchers' immediate scale of influence. What adaptive strategies do rancher operators possess to deal with issues such as exurban development or volatility in the international cattle market? And, when or how would they enact those strategies while their daily lives are consumed with timely business and livestock management decisions related directly to their ranching operations?

Furthermore, the R3 human dimensions team chose to address a retrospective view of resilience, and focused on operational or social adaptations at the ranch and community scale. We also focused on Anglo American ranching communities, which is a common but limiting approach in range social sciences (Bruno et al., 2020). The team did not capture rancher actions related to community and political activity. Embedded in the focus group data are a rich body of local political ecological knowledge, which is critical to understanding rangeland resilience and is likely entangled with local ecological knowledge, but which we did not emphasize (Robbins, 2006; von Essen, 2017). How ranching social landscapes are characterized by local organizing and policy engagement such as rancher participation in public lands management debates and policy making, farm policy, and conservation issues, through a spectrum of strategies from the highly collaborative to the violent, merits more consideration (Childers, 2015; Bestelmeyer et al., 2019; Ingalls et al., 2019).

Troubling questions to help transcend disciplines

Each conceptual lens used by the R3 teams captured a distinct temporal, spatial, and social scale, via different research questions, and offered insights for application by different actors (Table 1). However, these lenses do not inherently relate to one another, and as such, leave managers with gaps in terms of the implications for action (see Table 2).

To foster greater relevance for end users, we propose a series of troubling questions in the spirit of Haraway's volume *Staying with the Trouble* (Table 2) such that we developed questions that would help us operationalize inter- and transdisciplinary dialogue that could advance mutual understanding and respect for future projects. These questions bring nuance to the R3 teams' approaches, and to the contribution of social and ecological approaches outlined in Table 1. They prompt complex dialogue about issues of scalar mismatch between manager decision-making contexts and long-term predictions of change. They prompt us to consider how ranchers and community members can respond to, adapt to, or prepare for regional and global change (Bradford et al., 2018; Smith et al., 2021). They can also point researchers towards previously "underappreciated aspects of difficult problems" (Brunson, 2012, pg. 636).

Discussion

From troubling questions to new insights

The case study leads us to argue that that SES conceptual framings can actually reinforce disciplinary perspectives if they are not employed with intentional consideration of transdisciplinary methodologies. However, that a broader transdisciplinary conversation did not emerge from the R3 project is not a failure. This effort constituted a necessary first step towards a deeper conceptualization of the complexities of rangeland climate adaptation problems that can serve as an informative case example for the field and for future projects, as there remains great potential to produce meaningful adaptation science at the intersection of rangelands, ranching, and resilience through transdisciplinary approaches. A number of opportunities exist for future research efforts to more fully braid multiple disciplines and scales of rangeland knowledge into actionable strategies for adaptation.

By applying critical *troubling questions* to our experience in the R3 project and to the issue of rangeland adaptation science, we draw a number of insights. These include: 1) new opportunities to understand SES relationships; 2) the value of rangeland science and Extension to complement ecological and social disciplines and build relationships; and 3) the possibilities of *staying with the trouble* on rangelands. Together, these insights deepen and complicate resilience and vulnerability lenses used by the project team with additional attention to scale, relationships, and the potential of transdisciplinary synthesis.

Unpacking SES dynamics. Transdisciplinary thinking can produce new insights about how social and ecological systems interact. For example, if we zoom in to local scales of R3's research findings, we can begin to see how local ecological and social knowledge shapes land management outcomes through ranch succession, vegetation management, and livestock production patterns. This provides a window of opportunity to develop new science-management partnerships that address climate adaptation for specific places and communities. Alternatively, if we zoom out, to consider very large and long historical (old) scales of SES relationships, we can better contextualize rangeland resilience historically relative to the current discussion of rangeland use across North America (Dunbar-Ortiz, 2014; Sayre, 2008; 2018) and longer scales considered as the Anthropocene or Capitolocene, which make visible common historical and political economic drivers of the ecological and social dynamics observed by the R3 team (Moore, 2017, 2018). A wider, longer view at the *lounge duree*[4] helps us see up out of the pasture, ranch, or career-length scales to better identify the systems in which we are working and to identify leverage points for action based in policy and organizing. As rangeland sciences increasingly plea for consideration of scale to ad-

[4] This term, first used by Fernand Braudel, refers to a school of history that emphasizes relatively long-term historical structures and social time frames (Armitage and Guldi, 2015).

dress the most pressing issues of invasive species and habitat loss (McMillan et al., 2023), concepts like "restoring pattern and process" (Fuhlendorf and Engle, 2001), "defend the core" (Chambers et al., 2017; Maestas et al., 2022) and "think like a grassland" become increasingly important. In this vein, the social sciences offer tools to address at longer time and larger spatial scales to inform adaptation and to better understand the connection between economic conditions and ecological conditions on rangelands. Both the hyper local and the macro scales of analysis bring to light creative insights and transdisciplinary opportunities to plan and achieve more generative, life-sustaining systems (Whyte, 2020).

The potential of rangeland science and Extension. Our reflection also highlights the value of rangeland science and Extension to advance resilience scholarship, particularly because of the field's capacity for contextual awareness, relationship building and knowledge weaving. As such, the sum of a collaboration among the fields of range science, ecology, and the social sciences can be greater than its parts. The promising characteristics of the rangeland sciences, and rangeland-based collaboratives to generate new forms of adaptation and well-being are well described in the literature and academic discourse (Havstad et al., 2007; Huntsinger and Oviedo, 2014; Provenza et al., 2021; Sayre et al., 2017). This tradition likely stems from the acute need for multi-dimensional thinking and context-specific solutions in rangelands, where human relationships with ecosystems (e.g. via grazing-based livelihoods) are a foundational part of the system (Galvin et al., 2016). Other ecosystems are viewed to have much less human-caused influence (e.g. wilderness or preserved forest areas in the U.S.) or more human influence (e.g. intensive livestock or crop agriculture and developed areas). Rangeland science, like forestry and natural resource management fields, operates in an in-between space to bridge ecological and human dimensions with an emphasis on management and practice. It is an integrative field that nurtures working land thinking with potential to transcend wilderness/built environment or human/nature dichotomies, and knowledge creation methods such as co-production that recognize how cutting edge science, local knowledge, and inter-species stewardship in our food production systems can "hold the world together" (Thad Box, 2005; Starrs, 2018; Provenza et al., 2021; Ganguli and O'Rourke, 2022).

Additionally, rangeland science is an applied field. In the U.S., this includes strong connections to Extension and outreach expertise through the Land Grant University system, and state and regional educational and extension institutions that help promote management-science partnerships.[5] Despite these promising characteristics, meeting the full potential of rangeland science to bolster real adaptation remains an elusive goal (Roche, 2021), particularly because of the complexity of the work required to leverage range science for change making.

A more meaningful rangeland adaptation science would build relationships. It would co-develop accessible strategies and responses with managers based on a complete theory of change—agreed upon by all who are involved—and contextual awareness such that it fosters trust, consent, accountability, and reciprocity (Brugger et al., 2018; Whyte, 2020). This is where rangeland science and Extension could make a critical contribution to resilience scholarship: by fostering high-quality, effective partnerships with managers and communities at *actionable local scales.* Around the U.S., ranching communities have already been at the helm of collaborative processes seeking to better navigate bureaucratic and ecological challenges for a variety of social and ecological goals (resilience). Collaborations such as the Malpai Borderlands group (Sayre and Knight, 2010) or participatory research projects (e.g. the "CARM" project in Colorado, Augustine et al., 2020) use various approaches to engage ranchers, land managers, conservation organizations, educators, and students around conservation and land management science. We elaborate on this point with brief case-study examples from rangeland science in the U.S., work at the Panhandle Research and Extension Center in Nebraska and in the Tonto National Forest conducted with university staff, community members, and land managers, recognizing that our theoretical analysis does not address the resources needed to achieve this type of work (Boxes 1 and 2). Climate adaptation approaches could learn from or engage more directly with these wildlife conservation and livelihoods-focused groups to link up with living knowledge of SES dynamics and effective tools for adaptation, whether those are prolonged engagement with federal land management planning, youth education activities, participatory research, or some combination of actions. This work could support what Bradford et al. (2018) propose as an "anticipatory science and management" approach that brings shorter-term climate projections of seasonal forage conditions (up to a few years out) to bear for adaption through the support of institutions that can help overcome social, legal, and organizational barriers (e.g. Brugger et al., 2018). By engaging with local networks and community organizations, and partnership with rangeland professionals, disciplinary scientists may be able to make new kin across rangeland peoples and ecosystems with whom to *stay with the trouble* and support adaptive capacity and therefore, resilience.

Box 1. Building place-based management-science partnerships to support long-term resilience: The case of University of Nebraska-Lincoln's (UNL) Research, Extension and Education Centers.

Generational transition of farms and ranches is important to the viability of rural communities and a foundation for establishing a long-term legacy within land-based agricultural operations. However, environmental (drought, blizzards, etc.), economic (markets, costs, etc.), and other events often challenge the opportunity, resolve, or interest of new generations to take over the farm or ranch. In western Nebraska, the UNL Panhandle Research, Extension, and Education Center (PREEC) has been in operation since 1910 and has worked with stakeholders to support agriculture in the Nebraska Panhandle and the broader High Plains area of the western Great Plains. This center, one of three managed within the University of Nebraska system, has a mission to, "Develop solutions that enhance the lives of Nebraskans through improved management of landscapes, production systems, and resources across our state". Over the last century, working relationships with extension university faculty housed at the center and stakeholders at multiple scales of operation have provided trusted connections and resources to co-produce science and provide options to difficult management challenges and decisions. Faculty at the centers develop programs based on the direct needs of stakeholders to address applied research questions, test and develop agriculture products, and explore and increase understanding and management of complex business, production, and biological systems. This often includes conducting scalable research and extension outreach events directly on cooperating farms and ranches. By developing relevant learning resources, backed by applied research and in cooperation with the local knowledge of stakeholders, the PREEC seeks to bring the university resources to the local producer within a co-learning environment that enhances the management and sustainability within the agriculture community.

[5] Although these have been shaped by the power dynamics of history to the benefit of certain groups over others (Sayre, 2018).

Box 2. Linking science to adaptation action: The case of drought planning on the Tonto National Forest.

Drought de-stocking decisions are critical to ranch and rangeland viability on public lands in Arizona, but occurs at broad social and spatial scales that can make preparation challenging. The diverse and rugged rangelands of the Tonto National Forest are grazed by ~70 ranchers, each with unique operations and histories. These lands are managed under a complex set of environmental and use laws and policies by a multi-scalar bureaucratic structure. Researchers at the University of Arizona developed a project aimed at improving drought preparation and management flexibility by codeveloping a plan with scientists, public employees, and ranchers at the Forest scale (Brugger et al., 2018). They integrated theory from the health sciences and natural resource management, and methods that engaged ranchers and managers with social-ecological modeling and scenario planning over a 4-y period (Hawkes et al., 2018). This involved helping managers anticipate the probabilities of drought severities and imagining the impacts of those droughts to ranch operations and forest management goals. Then, the team developed plans for when those droughts occurred and began the necessary federal approvals needed to realize those plans. Their meticulous and thorough approach to co-development anticipated nonlinear learning and complexity in the social and public administration realms. This brought different viewpoints, innovative climate science and decision tools, and local knowledge together repeatedly and systematically in a process guided by an explicit, context-informed theory of action. This process ensured not only that research results were locally relevant, but that they were integrated into real-world action.

Finding shared meaning and *staying with the trouble.* The third insight brought forth from the *troubling questions* is just how challenging the road ahead will be for rangeland resilience scholars and for rangelands systems. As Roche (2021, pg 158) said in her plenary address at the Society for Range Management meeting in 2020, "*Finding transformative solutions to the grand challenges facing rangeland systems calls for changing the culture of our institutions and disciplines, which is no small task. If we—as scientists, educators, students, land managers, producers, and conservationists—want to have impact beyond the experimental unit (e.g., beyond the pasture) and build broad-scale solutions, then we need to work beyond institutional, land ownership, and political boundaries.*"

Here is where we can rise to the task of advancing actionable adaptation science by building shared meaning in our work together. While boundary objects like resilience can help motivate these processes, they are not enough to steward them fully towards solution-oriented transdisciplinary outcomes. This involves a commitment to discussion and to one another and our societal partners, for example through the questions outlined in Table 2. These questions allow teams to identify contributions and gaps in disciplinary approaches and to frame new, synthetic directions for research and manager engagement. This could open new avenues of care and dialogue, and to research that operates around a shared responsibility to rangeland systems, even when disciplinary silos, team dynamics, and the scale of the problem become overwhelming (Ferguson et al., 2022). As outlined from the short example cases in Boxes 1 and 2, ranching community leaders, and Extension professionals can be quite good at relationship building (kinmaking) (McDowell, 2001; Wilmer and Fernández-Giménez, 2016; Hawkes et al., 2018), and could possibly mentor researchers in these skills to bring people and rangelands together. Our reflection on the R3 project experience underscores this need. Even the most skilled team of researchers may struggle to harness the power of transdisciplinary approaches without a common intellectual and philosophical motivation, without *meaning.* Had we engaged in this way in R3, we might have co-developed a shared vision for the project with manager or rancher communities early in the project, noting both scholarly and applied goals from the onset. These additional methodological ideas help us move beyond examining a system's ability to "bounce back" and remain in the same state, into an imaginative, generative mindset. Here, we can create a *better* state, though it will be hard, constant work.

Using transdisciplinary approaches inside disciplinary institutions. It is predictable that SES framings may reinforce disciplinary approaches when they are applied in institutional contexts that reward disciplinary scholarship. It is important to note that many structural, administrative, and funding limitations, including the short-term time frame of many grant programs and the incentive structure of academic institutions, create real barriers to effective, long-term collaborative rangeland research (Roche, 2021). The transdisciplinary science literature offers a large body of work proposing best practices for publicly engaged research, coproduced team science, and the braiding of multiple knowledge that can inform more synthetic and generative collaborative projects to help work around or through these issues (Hall et al., 2018; Karrasch et al., 2022). Our goal here was not to address these dynamics explored elsewhere (Galvin et al., 2016), but to offer new insights into the SES conceptual framings. The transdisciplinary tradition suggests that knowledge is not a zero sum game. If transdisciplinary efforts are seen to be in competition with disciplinary research resources or team members do not have access to these well-vetted transdisciplinary methodologies they may face exceptional challenges to effective collaboration.

Finally, this framework offers a starting place for dialogue and team building that may be particularly helpful for multidisciplinary teams initiating new work on rangelands. It is not a complete conceptual model of rangeland transformation, but a starting-place for collaborative engagement and knowledge weaving. This discussion does not replace SES conceptual framings, or offer teams complete guidance to deal with issues of power, conflict, and structural inequalities that characterize many natural resource management challenges. May (2022) provides an extensive adaptive systems governance framework to understand social structures and to identify leverage points to enhance equitable outcomes.

Implications

Today, livestock producers face barriers to flexible management strategies, land access, and mobility as social demands for rangeland use compete with grazing uses (Swette and Lambin, 2021). Rapidly shifting rural community dynamics and economies, broader trends in land use change, and globalized commodity markets and supply chains continue to squeeze rangeland uses and users (Joyce et al., 2013; Briske et al., 2015; Specht, 2019; Klemm et al, 2020). Public lands grazing administration and National Environmental Protection Act (NEPA) policy compliance processes already require public land agencies to integrate multiple disciplines and types of data. If scientists are to take on these issues by supporting the managers who are already transcending disciplinary boundaries to make decisions on rangelands, we will be challenged to do more than stand under a shared resilience umbrella. We will need to engage in effective transdisciplinary science together with manager communities. Building a team or institutional structure to enable that engagement with multiple knowledges takes time and commitment. Conceptualizing a more actionable SES framework with explicit methodological recognition of relationship building, shared meaning, and commitment to one another can help find

common ground where meaningful adaptation scholarship can address the most complex problems.

As this type of research becomes more popular, potential partners—such as land managers and ranching communities—may be increasingly selective about their choice of research partnerships, seeking out those with grounded understanding of real knowledge needs. Partners will be wary of efforts that claim to be collaborative or transdisciplinary but which have no real benefit to their communities, as is unfortunately common (David-Chavez and Gavin, 2018). In this environment, researchers can improve their collaborative capacity by bolstering skills in transdisciplinary science, engaging with the vast methodological literature in this realm, or by putting effort into long-term collaborative partnerships with academics and community partners capable of staying with the trouble beyond the typical (3–5 y) grant cycle (Ferguson et al., 2022; Karrasch et al., 2022). Scholarly resources for this form of professional and scientific development abound (Eigenbrode et al., 2007; Tengö et al., 2021). Explicit processes can be built for teams to develop a shared sense of meaning throughout the research project life cycle. This will require a refocused energy toward building effective teams and institutions and away from individualistic modes of research program design. *Staying with the trouble* (Haraway, 2016) helps us see that breaking down disciplinary silos is more than seeing others' perspectives or learning new methods. It is about first building our collaborations on a SES framework for scholarship and action centered on transdisciplinary meaning and shared responsibility– a relationship–to one another and to the systems upon which we depend.

Declaration of Competing Interest

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

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