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Contextualizing climate science: applying social learning systems theory to knowledge production, climate services, and use-inspired research

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Abstract
Scientists need to acknowledge the inherent social contexts that drive the scientific process if they want their research to improve complex societal problems such as vulnerability to climate change. Social interactions and relationships are essential elements for conducting use-inspired research, creating usable knowledge, and providing climate services. The Climate Assessment for the Southwest (CLIMAS) program was founded on theories of use-inspired research and co-producing knowledge with non-academic partners. A recent program evaluation illuminated gaps in these underlying program models and led to the inclusion of social learning systems theory and communities of practice. Using grounded examples, we demonstrate the CLIMAS program's ongoing role in fostering, maintaining, and expanding a climate resilience social learning system in the U.S. Southwest. Broader implications from the evaluation focus on the importance of establishing and maintaining relationships, increasing institutional and individual flexibility in response to change, and improving the practice of transdisciplinarity. These findings inform new program evaluation metrics and data collection techniques. This paper contributes to current theory and practice of use-inspired science and climate services by identifying and demonstrating how social interactions inform climate knowledge production. The reconceptualization of the CLIMAS program as part of a growing regional social learning system serves as an example for similar types of programs. We encourage climate services and use-inspired research programs to explore applications of this framework to their own operations.

Keywords Social learning systems · Communities of practice · Climate services · Use-inspired research · Evaluation

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1 Introduction

Seasonal and annual climate variability, extreme weather events, and long-term climate change present complex challenges to society. As climate problems have grown more acute—including increased risk of floods, droughts, sea level rise, and wildfires—subsets of the climate research community are focused on ways to make their research more responsive to societal needs. These efforts show that addressing complex problems requires re-thinking conventional modes of knowledge development. The standard linear model of science assumes that scientists will develop a wellspring of knowledge to advance social goals, while remaining isolated from specific applications of their work (Guston 2000). In contrast, value-laden problems like climate change call out the need for socially engaged research processes to generate "use-inspired" (Stokes 1997) knowledge that is useful-for and usable-by society to confront these so-called wicked problems (Head 2008).

Several scholars have outlined overlapping theories, approaches, and processes for conducting useful research and providing effective climate information services (e.g., McNie 2013; Kirchhoff et al. 2013; Wall et al. 2017). Broadly defined, climate services are climate data and information products designed to support decision-making and planning (Hewitt et al. 2012). Climate science is rapidly advancing, but as Miles et al. (2006) note, its use in planning and decision-making has not kept pace—an observation that continues to be relevant today. Likewise, Lemos et al. (2012) refer to a "persistant gap between knowledge production and use" (p. 789). Brasseur and Gallardo (2016) identify several critiques of climate services practice: stakeholder diversity remains unrecognized; products often do not meet user needs; and uncertainty in climate data presents particular challenges for their use. To be more effective, climate services and use-inspired climate research need to be better defined, monitored, and evaluated (Vaughn and Dessai 2014; Lourenço et al. 2016).

In 2012, the Climate Assessment for the Southwest (CLIMAS[1])—a regional climate research and services program—initiated a long-term monitoring strategy to better understand the program's impact on climate adaptation and resilience. This evaluation has led to the following: (1) an evolution of CLIMAS's underlying program theory to include social learning systems theory; (2) articulation of the specific roles CLIMAS plays in a social learning system for regional climate resilience; and (3) improved monitoring practices to better assess the CLIMAS program's value and impact.

In this paper, we first review the theoretical principles of use-inspired research upon which the CLIMAS program was founded. Drawing on our program evaluation and literature about social learning systems and communities of practice, we offer a revised conceptual model of CLIMAS's program theory. We illustrate this new framework by translating its theoretical principles into practice. Using five examples, we show how the CLIMAS program actively participates in a social learning system for regional climate resilience. We indicate how our evaluation findings and application of social learning systems theory can inform other use-inspired research and climate service programs through increased emphasis on relationship-building, institutional and individual flexibility, and transdisciplinary practices. Finally, we reinforce the need to establish routine monitoring and program evaluation to advance social learning systems theory and create effective communities of practice.

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1.1 Use-inspired research and knowledge production

Scholars from several fields have pushed beyond the idea that research meant to confront complex climate-related problems should simply be informed or inspired by potential use. A mature literature describes multiple pathways for achieving usable science (e.g., Dilling and Lemos 2011), actionable science (e.g., Beier et al. 2017), or usable knowledge (e.g., Clark et al. 2016). These pathways originate in the field of science and technology studies wherein researchers conceptualize interactions between science and society (e.g., Jasanoff et al. 1995; Biagioli 1999).

In the 1990s, several theories addressed the evolution of science in response to rising social and environmental issues. Funtowicz and Ravetz (1993) formulated the concept of post-normal science, which was issue-driven and aimed to impact decisions and policy. Post-normal science required new methodologies, the legitimization of multiple forms of expertise, and stood in contrast to basic research, defined by Funtowicz and Ravetz as curiosity-inspired. Gibbons et al. (1994) identified a new form of knowledge production (mode 2) that emerged from traditional scientific practice (mode 1). They described mode 1 research as conducted for the pursuit of knowledge itself and housed within traditional academic disciplines. Mode 2 was driven by societal context and characterized by transdisciplinarity and multiple sites of knowledge production. Like post-normal science, mode 2 included a diversity of people and types of research in knowledge production (Nowotny et al. 2001). Other scholars further developed these models into interactive research frameworks for social and environmental sciences (e.g., Caswell and Shove 2000; Woolgar 2000). These ideas matured in tandem with rising societal and environmental problems of the era—a time period that coincided with the development of federally funded research programs designed to inform climate policy and decision-making.

In traditional models of U.S. government-funded science, conceptual boundaries between research and application help ensure that science is not captive to political interests (Guston 2000). Over time, scholars and practitioners have described permeable boundaries as a more apt metaphor when considering problem-oriented research (Cash et al. 2003; Agrawala et al. 2001). The concept of boundary organizations (Guston 2001) emerged as a structural means for better connecting science and society. For climate services and research organizations, Agrawala et al. (2001) described these connections as an "end-to-end system running from climate researchers to consumers of climate information, and back again" (p. 459).

Other constructivist ideas about science and society informed the development and ongoing evolution of climate service and research programs. Knowledge co-production (Lemos and Morehouse 2005; Meadow et al. 2015)—or processes that involve researchers and nonacademic partners working towards shared goals of producing robust, novel, and useful knowledge for real-world applications—remains an important touchstone. Similarly, repeated and sustained interaction between scientists and non-academic partners is important to maintaining healthy relationships that allow use-inspired science to occur (Lemos and Morehouse 2005; Gibbons et al. 1994). Transdisciplinarity has emerged more recently in the U.S. as a framework for connecting research to societal challenges (Jahn et al. 2012; Mauser et al. 2013; Weichselgartner and Truffer 2015). Transdisciplinarity attempts "to link two processes of knowledge production: 1. a societal process, in which actors try to understand and tackle a particular societal issue, and 2. a scientific process, in which scientists design and conduct research on the societal issue" (Pohl et al. 2017, p. 44). These theories help contextualize the evolution of science for societal applications and have shaped the development of the CLIMAS program's theory and practice for creating usable knowledge.

1.2 Historical context of the CLIMAS program

In the mid-1990s, the U.S. National Oceanic Atmospheric Administration's Regional Integrated Sciences and Assessments (RISA) program was established with a mission to improve the nation's capacity to adapt to climate variability and change. RISA supports climate research that encourages inter- and transdisciplinarity; is regionally focused; encompasses climate variability and long-term climate trends; and emphasizes institutional learning and innovation (Meadow 2017). A fundamental tenet of the program recognizes that for societies to adapt to climate variability and long-term change, researchers must gather "knowledge about behavior, policy, institutions, and decision contexts because these aspects often affect the ability of society to respond to and incorporate climate knowledge" (Simpson et al. 2016, p. 3).

CLIMAS was established in 1998 as the second RISA-funded research team. The initial proposal—written by social and physical scientists at the University of Arizona—articulated a regional assessment program focused on "collection, interpretation, valuation, and communication of information of relevance to decision-makers, resource managers, and other interested individuals" in the U.S. Southwest (Bales et al. 1997, p. 3). CLIMAS has continuously evolved in terms of research questions, team composition, and approaches to conducting a sustained regional climate assessment. However, it has remained connected to two core principles about developing use-inspired knowledge established at the program's outset: (1) "sustained interaction with stakeholders" and (2) "modifying science agendas in response to stakeholder needs" (Bales et al. 2004, p. 1728). Since the program's inception, several CLIMAS researchers have articulated various methods, approaches, and concepts used in use-inspired, co-produced, and transdisciplinary work and reflected upon the effectiveness of these principles in practice (see Liverman and Merideth 2002; Lemos and Morehouse 2005; Guido et al. 2013; Meadow et al. 2015; Ferguson et al. 2016).

2 Program monitoring and evaluation

Investigating how these theoretical concepts work in practice is a worthwhile endeavor. Substantiating how use-inspired research, climate assessments, and climate services translate into demonstrable progress towards addressing climate-related challenges is becoming increasingly relevant (Corell et al. 2014). Scholars have described or tested evaluation frameworks and methodologies to measure progress towards climate change adaptation (e.g., Preston et al. 2009; Moser and Boykoff 2013); use-inspired climate research programs (e.g., McNie 2008; Ferguson et al. 2016); knowledge co-production (e.g., Fazey et al. 2014; Wall et al. 2017); and climate services (e.g., McNie 2013; Vaughn and Dessai 2014).

In 2012, CLIMAS implemented evaluation as a core component of the program, using a theory-based evaluation framework (Funnell and Rogers 2011). This approach entails defining a "theory of change" that connects a program's actions to desired outcomes. Action-logic models are often the mechanism used to establish theories of change. Between 2012 and 2017, we identified 23 projects to include in the evaluation. Selection criteria included projects that engaged nonacademic partners and allowed for annual monitoring and data collection. Aided by our CLIMAS co-investigators, we designed evaluation research plans for each project using a series of action-logic models to articulate how program activities and outputs could lead to measurable outcomes (Ferguson et al. 2016). This process included defining contexts, research inputs, expected outputs, short-to-medium term outcomes, and broader impacts. Data measuring progress towards outputs and outcomes were collected via periodic semi-structured interviews with CLIMAS investigators in 2012 (15 interviews), 2014 (12 interviews), and 2017 (11 interviews), and annually through project reports between 2012 and 2017. In addition, two projects used online pre- and post-surveys (distributed between 2013 and 2017) and a follow-up survey (2018) in to collect data from 51 students who participated in annual CLIMAS training programs in conducting use-inspired science.

3 Evolving the CLIMAS program model by incorporating a social learning systems framework

The CLIMAS program evaluation revealed that our underlying theory about how the program functioned needed updating. The impact of the CLIMAS program could not be demonstrated using evaluation methods that characterized the program as a boundary organization, a one-time intervention, or a singular source of climate data. In the context of a regional climate program, improved technology for collecting, visualizing, and sharing information; observable impacts attributed to climate change and variability; and escalated public and private concern have contributed to an expanding network of people and institutions connected by climate-related problems. Network growth and iterative social interactions have led to increased knowledge usability and multiple sites of academic and non-academic knowledge production (Dilling and Lemos 2011). By creating new network connections, institutional boundaries become perforated and the need for a singular organization to pass information back and forth from end-to-end between science and society is no longer necessary. In this evolved context, organizations dedicated to increasing density of communication (Gibbons et al. 1994), expanding research participation to peer communities (Funtowicz and Ravetz 1993), and fostering iterativity and interaction (Dilling and Lemos 2011) are crucial. To harness diversity in multi-sited knowledge production, CLIMAS researchers have embraced methods that move towards social learning[2] (Wenger 2000) and building knowledge systems (Van Kerkhoff and Szlezák 2006; Cornell et al. 2013) that support regional climate resilience.

A social learning system connects diverse ways of knowing to collectively evolve practice and thought (e.g., Wenger 1998; Pahl-Wostl and Hare 2004). These systems identify and respond to complex problems through social engagement and knowledge sharing. Learning occurs through shared interactions within communities of practice, which “are the basic building blocks of a social learning system because they are the social ‘containers’ of the competences that make up such a system” (Wenger 2000, p. 229). Communities of practice organize around emergent problems, interests, identities, and skills (Wenger 1998; Pahl-Wostl and Hare 2004). Membership is flexible, spanning across boundaries such as geographic location, academic discipline, or economic sector. Social learning occurs through iterative engagement within and across communities of practice. People share knowledge, expertise, and information needs, while learning from others’ expertise and about their needs.

[2] Wenger’s conceptualization of social learning systems and communities of practice emerges from information science and anthropology, but has been applied in several fields, including health, education, and business management.

These ideas have shaped the latest iteration of CLIMAS program theory, which is repeated interactions between physical, natural, and social scientists and non-academic partners contribute to a flourishing social learning system comprised of researchers and practitioners who collaborate to address climate-related issues important to the U.S. Southwest. These interactions lead to three primary outcomes: (1) new use-inspired knowledge, (2) increased likelihood that this knowledge is useful and usable for decision-making, and (3) enhanced capacity to develop usable climate knowledge and to utilize that knowledge. We refer to this conceptual model as a climate resilience social learning system for the Southwest (Fig. 1).

This social learning system is embedded in an extended network of individuals, groups, and organizations that aim to build regional climate resilience. Within the system, communities of practice cohere around climate-related challenges. Participation manifests in several ways, including funding projects, collaborating on research, and contributing or receiving climate information. Membership is dynamic and activity waxes and wanes depending on stakeholder interests and needs. The social learning system provides a solid base that retains enough flexibility to respond to urgent information needs, emergent research priorities, novel funding opportunities, and policy decision frameworks. It works to connect diverse ways of knowing and producing knowledge within the network, to incorporate multiple viewpoints, enable new partnerships, and create space for transformation.

The climate resilience social learning system for the Southwest is not bounded. Social learning systems are simultaneously communities of practice themselves and nested “constellations of interrelated communities of practice” (Wenger 2000, p. 229). Shared

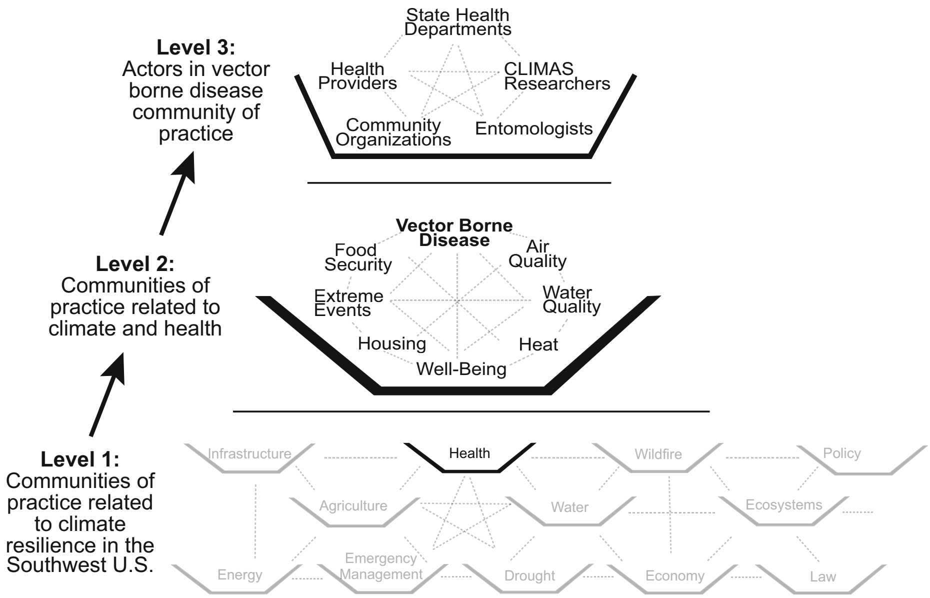

Fig. 1 Conceptual model of a climate resilient social learning system in the Southwest U.S. Social learning occurs based on relationships and interactions within and across different communities of practice; level 1 illustrates a sample network of communities of practice working to address regional climate resilience issues; level 2 focuses on the health and climate community of practice, revealing eight more communities of practice, each addressing a specific human health issue; level 3 identifies groups of actors who work within a regional vector borne disease community of practice.

practices, resources, tools, routines, language, interests, and histories create boundaries for each community of practice. These boundaries are negotiable and "rather fluid" (Wenger 2000, p. 232). Learning occurs through interactions within a community of practice (e.g., a deep dive into a particular way of thinking), and across these boundaries (e.g., as people are challenged to recognize new points of view, new approaches, and new problems).

A social learning system cannot be run by any particular organization—the CLIMAS program is one organization among many in the regional climate resilience social learning system. However, CLIMAS performs several functions within the system, carried out by the program's researchers, including: fostering interaction within and across communities of practice; encouraging network growth; providing academic expertise and scientific information; and facilitating use-inspired research. CLIMAS also supports the system's evolution by maintaining, analyzing, evaluating, and conceptualizing it as a whole. The rest of this paper further illustrates these functions by drawing on examples from the program evaluation and tying them to social learning systems theory.

4 Social learning systems in practice: examples from the CLIMAS program

A social learning system framework illustrates pathways towards more useful research and climate services. Pahl-Wostl et al. (2007) note that "Bridging institutions play a major role in strengthening the generation of social capital and creating new opportunities and multilevel cooperation and learning. The question arises of how these characteristics are developed and sustained" (p. 6). Clear demonstrations of the structural mechanisms that encourage the social interactions that inform knowledge production are needed (Kirchhoff et al. 2013). The primary purpose of the CLIMAS program is generating scientific knowledge. Here we describe five additional core functions that CLIMAS performs within the social learning system: communicating, convening, consulting, collaborating, and training.

4.1 Communicate

Communicating information to members of the regional social learning system is an essential component of CLIMAS. Every project in our evaluation (23/23) disseminates information such as research results, regional climate conditions, or seasonal outlooks. CLIMAS investigators aim to improve general climate knowledge, increase comprehension of specific climate issues, and inform decisions, planning, or policies. Communication and outreach often represent the initial social interactions people have with CLIMAS and typify how the majority of people connect with the program (Ferguson et al. 2016).

Communication approaches include presentations and authoring technical reports, white papers, and peer-reviewed journal articles. Although journal articles are highly valued within academia, CLIMAS investigators produced 25% more technical reports and white papers than journal articles in the projects assessed. Scientific knowledge production is important, but a priority for CLIMAS investigators is providing information to people who will use it in practice—people for whom academic journals are not often accessible. CLIMAS communication approaches aim to reach broader portions of the social learning system using online communication platforms such as email list-servs, recurring newsletters, podcasts, blogs, websites, interactive data tools, news media, and social media.

Four CLIMAS projects focus on climate communication. Their central purpose is to distribute useful and usable information at intervals that mirror seasonal-to-interannual climate patterns. One such product is the Southwest Climate Outlook (SWCO), a monthly newsletter focused on recent and future regional climate conditions. With approximately 1600 subscribers, SWCO has helped establish the CLIMAS brand across the Southwest (Guido et al. 2013; Ferguson et al. 2016). SWCO stems from a project relatively early in CLIMAS history. Beginning with persistent drought conditions in the Southwest in 2002 and an interest in understanding and fulfilling regional needs for climate information, CLIMAS researchers collaborated with potential readers to design a monthly newsletter. The newsletter contained information on recent conditions, climate forecasts, and explanatory articles about the climate of the region. Since then, SWCO has evolved in format and content by responding to reader feedback, advancements in technology, and increased online access. It has expanded into other forms of outreach including a monthly podcast, a series of online information hubs and a blog on the CLIMAS website, and a bilingual monthly outlook for the Rio Grande/Rio Bravo river basins.

Wenger identifies the need for artifacts (such as tools, models, and documents) and the importance of common language and knowledge to help maintain social learning systems (2000). Our evaluation does not comprehensively measure the impact of SWCO and other CLIMAS communication efforts, but it provides evidence regarding how these communication products work to engage others, incite action, and reach new audiences within the regional social learning system for climate resilience.

\Google and social media analytics show constant interest in SWCO, the blog, podcasts, and website content based on unique views, with spikes of interest leading up to annual climate events. Viewership intensifies in May, June, and July with the onset of seasonal extreme heat, the annual monsoon, and regional wildfires. Spikes also occur during occasional events such as the 2015–2016 El Niño. Regional journalists use CLIMAS communication tools to inform their work. Michael Crimmins, CLIMAS investigator and co-host of the Southwest Climate Podcast, has received an increasing amount of media requests, especially since the 2015–2016 El Niño. He says, "Weather has become the number one click-bait, so local newspapers have really stepped up their weather reporting. Some [reporters] listen to the podcast and then follow up based on some of the stuff we've talked about to help drive their writing and frame their interview questions" (personal communication, M. Crimmins, April 2017).

Key climate messages from these tools are redistributed by other members of the social learning system through their own social media or in presentations. For example, one user states, "I have used CLIMAS products since … 2006. I have always found the *Southwest Climate Outlook* to be extremely informative, and a useful tool to communicate climate issues in the Southwest with our stakeholders. I've used the graphics in frequent presentations. I recently started listening to the podcast and have enjoyed that as well. CLIMAS is a great resource for distilling global and national products to services that impact the Southwest."

CLIMAS communication products also inform decision-making about regional climate and impacts. For instance, members of the New Mexico Office of the State Engineer and the Interstate Stream Commission use SWCO's diagrams of regional reservoir levels in presentations to the New Mexico State Legislature. They requested adding the Ute Reservoir along the Canadian River to the diagram because it was important to their policy discussions. SWCO also sparks engagement within the climate resilience social learning system. A phone call about inaccurate depictions of drought in the Four Corners region sparked a new CLIMAS research project, for example.

These outreach and communication tools serve as a form of engagement within the climate resilient social learning system. They maintain, align, and improve people's knowledge of regional climate by providing information on a regular and expected basis and builds CLIMAS's reputation for providing pertinent, timely, and reliable information.

4.2 Convene

CLIMAS connects people and organizations whose interests relate to climate. By creating opportunities and spaces for people and organizations to connect (online and in-person), convening activities facilitate social learning by "enabling a rich fabric of connectivity among people" (Wenger 2000, p. 232). Regular convening activities assist communities in developing a sense of joint initiative, accountability, and trust, as well as shared resources such as tools, languages, and projects. Approximately half of the projects included in this assessment (14/23) have a specific convening function such as network building or hosting events. CLIMAS acts as a connector between organizations and individuals, with the intent of maintaining a relationship or partnership beyond the life of a workshop or project.

One example comes from a project involving agricultural producers in southeast Arizona who wanted better tailored climate forecasts for their region. Their crops are sensitive to weather and climate extremes like freezes, hail storms, wind, floods, and drought. Forecasts can help growers prepare for these events, but the information is not always readily available or accurate enough. In 2014, the Tucson Weather Forecast Office of the National Weather Service (NWS) approached CLIMAS researchers and University of Arizona Cooperative Extension specialists to help build a stronger partnership with this agricultural community. These agencies convened a working group to assess information needs, provide training opportunities, and develop decision-support tools. Outputs included an email list-serv (which jumped to 100 subscribers in the first year and is now at 150) and new forecast visualizations for frost and freeze events.

The email list-serv maintained and facilitated by CLIMAS remains a linchpin of this working group, enabling direct discussions between NWS, growers, and resource managers about regional weather and climate briefings. Interactions are regular but fluctuate seasonally with regional climate events including spring frosts, fall heat waves, winter precipitation, and the summer monsoon. In-person and online feedback has improved forecasts and advanced notifications for freeze events are now timelier. The simple technology of the email list-serv has encouraged new relationships to develop.

Evaluation of this project shows how CLIMAS investigators helped build a community of practice around the need for accurate agricultural forecasts. A federal policy enacted in 1991 prevented NWS employees from providing tailored forecast services to specific sectors or individuals. A CLIMAS investigator notes that many regional agricultural producers said that this policy hurt their relationships with the NWS—they felt abandoned by their local offices (J. Weiss, personal communication, March 2018). When this policy changed in 2006, the NWS mission shifted towards increased engagement with sector representatives. The local NWS offices wanted to reestablish trust and communication with growers in southeast Arizona and asked to leverage CLIMAS's relationships and reputation with this community. Without this connection, NWS representatives would have had to build these relationships from scratch and would have had to find a different means of communication.

CLIMAS researchers participated in the working group primarily as a means to catalyze further partnerships, discussions, and interactions. By facilitating engagement, they helped to rebuild trust, a key component of a functional social learning system (Wenger 2000, p. 229). Agricultural growers now have a better working relationship with local NWS representatives, who listen to agricultural needs and provide resources to help them deal with regularly occurring climate issues.

4.3 Consult

Almost all evaluated projects (21/23) incorporate consulting by providing tailored, expert advice for targeted audiences. Organization representatives identify information needs and seek expertise from CLIMAS investigators, who collect data and deliver findings, often as written reports or presentations. Investigators make their research skills and ties to academia available to others within a community of practice, who may not have the same time, data access, specific knowledge, or funding.

The length, breadth, and depth of consultations vary and interactions may extend to larger research collaborations beyond original requests. Consultation needs are generated through formal assessment activities including surveys, interviews, or facilitated group discussions, and informally through personal conversations. While the information produced is designed for a specific purpose, lessons from these exchanges are often transferable to people and organizations facing similar issues.

In 2014, CLIMAS investigators convened a workshop on public health and climate, which included representatives from the Arizona Department of Health Services (ADHS). ADHS was partnering with other researchers on extreme heat risk and exposure but expressed their need to know about other climate change impacts to health. CLIMAS researchers offered to assess potential health risks and to model projections of vector-borne diseases and Valley Fever in Arizona. For example, projections showed how increased seasonal temperatures would impact mosquito populations that transmit West Nile Virus, but that these impacts would vary differentially by altitude (Roach et al. 2017).

ADHS representatives outlined their information needs, informed research questions, and verified emerging results from the health risk assessment and vector projections. CLIMAS researchers published their findings in academic journals (Brown et al. 2017; Lega et al. 2017) and co-authored public reports with ADHS representatives (Brown et al. 2016; Roach et al. 2017). ADHS representatives disseminated research findings within their organization and included them in statewide adaptation plans to address future health risks.

Within public health there are several established communities of practice. “I am in the engagement, vector-borne diseases and methods communities of practice—I don’t even know how many of these there are,” explains one CLIMAS researcher. “They are made up of your peers who are doing similar work in different places. Being an academic in this space is rare. Being an academic is a service in this case, in support of the work others are doing” (H. Brown, personal communication, April 2017). Consulting builds trust and confidence between members of a social learning system through an iterative practice of building shared knowledge for a particular purpose. In this case, members of a community of practice focused on human health invited CLIMAS investigators to help meet specific information needs. By following through on these research and information requests, CLIMAS investigators showed that they brought an added value to an already established community of practice.

4.4 Collaborate

Over half of the projects evaluated (16/23) are research collaborations between CLIMAS researchers and representatives from other organizations, agencies, and communities in the regional social learning system. Collaborations occur when “communities of practice deepen their mutual commitment” and include “exploring the knowledge domain, finding gaps in community practice, and defining projects to close these gaps” (Wenger 2000, p 232). Collaborative projects are designed to generate mutually useful and usable research. Iterative and sustained collaboration between CLIMAS researchers and project partners provides opportunities for communication, feedback, and discussion. Collaborative research aims to produce information that impacts decision support, planning, policymaking, education, or awareness.

The lifespan of a collaborative project includes many stages from beginning-to-end. In these 16 projects, CLIMAS researchers were involved in all stages, while non-CLIMAS collaborators were involved in beginning stages (e.g., project brainstorming and developing research priorities) and/or later stages (e.g., co-authoring reports and papers and disseminating findings). Collaborators were typically less engaged during the research itself, such as research design, data collection and analysis, testing results, or evaluation. Project collaborations develop over time and often originate from previous interactions, including communication, convening, or consulting activities. Together, project collaborators learn about one another, build trust, determine the most useful products or research, and set realistic project outcomes.

In 2011, Federal Emergency Management Agency Region 9 (FEMA-R9) relied on weather forecasts to prepare for emergencies but recognized that climate forecasts could help them identify potential disaster risk (Meadow et al. 2016). Representatives communicated with the Western Region Headquarters of the National Weather Service (WR-NWS) who contacted CLIMAS, sparking collaboration between these three organizations to develop a climate information tool for disaster preparedness. Through an assessment of information use and distribution within FEMA-R9 operations, the Watch Standers Office became the target audience for this climate service—they consolidate several sources of information about potential disasters and coordinate emergency response. Watch Standers outlined a product that synthesized climate trends and forecasts but did not know what specific information would be most useful. “It took a lot of discussion to figure out what kinds of decisions they wanted to make with this product, and why the 30-day forecast period was so important. There was a lot of back and forth” (A. Meadow, personal communication 2014). Together, CLIMAS, FEMA-R9, and WR-NWS developed a hydro-climate information dashboard with historical data, current conditions, future outlooks, and potential risks.

While the project established relationships across the three institutions, enhanced the usability of climate information, and improved climate awareness, the usefulness of the product remains unclear. As Watch Standers began to incorporate climate information, it appeared the dashboard did not match their needs. A better product would show analogies between current climate conditions and climate conditions that led to past emergency situations. “Unfortunately by then, it was too late. We were running on fumes of money and a wholesale revamp wasn’t possible” (A. Meadow, personal communication 2017). This project aimed to design a climate service by balancing the needs, capacity, and expertise of each organization. However, more time, interaction, and product development were necessary. This example underscores the need for long-term, sustainable institutional relationships and flexible approaches to manage unexpected barriers. Nevertheless, results from this project have informed new collaborations with regional emergency managers.

4.5 Train

As a university-based program, CLIMAS seeks to build capacity to conduct use-inspired research. The program helps train current and future generations of researchers to apply interdisciplinary and transdisciplinary theory in practice. For graduate students, CLIMAS provides classroom and experiential opportunities including the following: a seminar presenting theory and case studies that connect science and decision-making; research assistantships on CLIMAS funded projects; and fellowships for students to conduct their own use-inspired research. Between 2012 and 2017, CLIMAS researchers taught 63 seminar students, hired 46 research assistants, and funded 16 fellows.

Many academic programs focus their training on preparing graduate students for academic careers, even though the job market for those who hold PhDs has diversified beyond the faculty track. Approximately 40% of current U.S. PhD graduates ever hold tenure track positions, but student training has remained relatively unchanged over the last several decades (National Academies of Sciences, Engineering, and Medicine (NASEM) 2017). These findings are reflected in our survey results that indicate most CLIMAS seminar students (90.5%) and fellows (93.8%) are not solely seeking academic positions after graduation, but are also interested in positions at non-profit, government, or other non-academic organizations. CLIMAS training efforts stem from the following principle—if students want to make their research useful and usable outside of university settings, they must build disciplinary competence but also develop the skills to work with multiple kinds of experts and practitioners. Training focused on use-inspired climate research and services helps maintain and secure the longevity of the social learning system.

Disciplinary training is a necessary component of graduate and faculty development, however creating useful knowledge for social applications requires additional interdisciplinary training (e.g., training physical scientists in ethnography, discourse analysis, or survey administration); technical training (e.g., facilitating meetings or communicating to general audiences); and transdisciplinary training (e.g., assisting organizations on their research projects or seeking expertise from non-academics). These efforts consume time and compete with other expectations for graduate students and tenure-track faculty. Even after collaborations have been established, a partner's needs may not fit a university researcher's timelines, funding, or disciplinary interests. CLIMAS prioritizes interdisciplinary and transdisciplinary research and training opportunities that are not often present within traditional disciplinary boundaries.

The Climate & Society Fellowship was created in 2013 for graduate students to conduct use-inspired research and to develop science communication skills. Funded projects address research needs expressed by non-academic partners. For example, a project to quantify climatic drivers of forest growth grew from a partnership between a graduate student who studied paleoclimate and the Navajo Nation Forestry Department (NFD). The NFD wanted to know how regional climate and projected tree-growth would affect forests in the Chuska Mountains so they could develop a 10-year management plan. The graduate fellow and NFD representatives collaborated on research questions and design, data collection, and production of a tree-ring and climate records database. One finding revealed that observed extreme drought conditions experienced over the past 1000 years represent expected average drought conditions by 2050 (Guiterman 2015). This project laid the groundwork for ongoing research collaborations and has resulted in additional funding from the U.S. Environmental Protection Agency, the Bureau of Indian Affairs, and the Navajo Nation.

In a recent follow-up survey, the majority of past research fellows indicated that lessons they learned about conducting use-inspired science, engaging stakeholders, communicating science, and collaboration have influenced their current career and research trajectories. Past fellows have collectively received approximately $500,000 in grants to extend their work beyond their original 1-year projects.

5 Implications of adopting a social learning systems framework

The CLIMAS program evaluation led us to re-frame our conceptual model for conducting use-inspired research and providing climate services. Instead of assessing the program as a singular institution, we have come to view the program as inseparable from the larger knowledge system. While CLIMAS cultivates, maintains, and benefits from a social learning system, it does not drive the system. Several organizations, individuals, and communities of practice within the system symbiotically influence and motivate one another; therefore, the outcomes and outputs are not tied solely to the efforts of CLIMAS but to the efforts of several people and institutions involved. The following discussion explores broader implications of the social learning system model to inform similar programs that conduct use-inspired research and produce climate services.

5.1 Increasing flexibility

Climate service and research organizations should aim to become more flexible regarding their desired goals and outcomes. CLIMAS projects in this evaluation were designed to develop useful research and products using explicit co-produced and transdisciplinary processes; however, several researchers noted that they did not achieve all their project goals. As one researcher states "You can have the most perfect process and it still doesn't work out" (A. Meadow, personal communication, April 2017). Falling short of project objectives does not always equate to failure or signify that products or research outcomes are not useful or usable. A social learning system is dynamic—it is constantly shifting as new knowledge is developed, artifacts are produced, and social relationships deepen (Wenger 2010). Researchers must negotiate changes such as expected length of time to reach a goal, personnel changes within partner institutions, or sudden revisions to project funding and governmental policies. Political, social, economic, and environmental factors can unsettle the best laid plans. Project goals, products, or processes must be dynamic to accommodate these evolving contexts.

Increasing flexibility can be implemented at both organizational levels (McNie et al. 2016) as well as personal levels (Lemos and Morehouse 2005). McNie et al. (2016) argue that becoming more responsive to "users' needs, developing problems, and emerging research windows of opportunities requires higher degrees of organizational flexibility." Use-inspired research and climate service programs should provide the time, space, and economic resources to allow researchers to change course as necessary, in response to shifting user needs, unexpected challenges, and windows of opportunity. Individual researchers should be encouraged to reflect upon and learn from unmet project goals to improve future research processes and objectives. Within the context of climate resilience and adaptation, projects, people, and institutions must themselves be flexible, resilient, and adaptable to change.

5.2 Establishing and maintaining relationships

Social learning systems emphasize the importance of relationships. Gibbons et al. (1994) argue that knowledge production "is above all embodied in people and the ways they are interacting in socially organized forms" (p. 17). Organizations in the field of use-inspired research and services must develop and maintain relationships that are grounded in trust and accountability. This evaluation shows how the CLIMAS program establishes, maintains, and improves relationships with individuals and climate-related organizations in the Southwest. These relationships form the foundation of an effective use-inspired research or climate services practice.

Relationships can be individual as well as institutional. Folke et al. (2005) indicate that one role of organizations is to store collective memory and mobilize these experiences to address new challenges, future uncertainties, and changes. CLIMAS and similar organizations accumulate collective experiences through their research, relationships, and institutional credibility. As shown in Section 5.2 with agricultural producers and the NWS, other institutions leverage the CLIMAS program's reputation as well as individual relationships to enhance present and future projects and tool development.

Through relationship building and sustained collaboration with communities of practice, climate service providers learn about information needs while integrating themselves as members of those communities. This process increases adaptive capacity (Pahl-Wostl et al. 2007) and encourages climate service providers to seek out diverse expertise and technical capacities (World Meteorological Organization (WMO) 2018). Building trusted relationships also has several institutional barriers, is time consuming, and does not guarantee success. As demonstrated above, CLIMAS, FEMA-R9 and WR-NWS were unable to create the ideal climate information product within timing and funding constraints. However, their interactions formed a new community of practice combining emergency management and climate information, which has informed new projects. Relationship building is a main component in building successful communities of practice. These connections are integral to developing a shared set of instruments—languages, practices, tools, websites, and products (Wenger 2000)—that make a partnership more effective (Hewitt et al. 2017).

5.3 Practicing transdisciplinarity

A social learning system reflects a distributed, transdisciplinary network, and situates climate research and service organizations within multiple practices, knowledges, and forms of expertise. If scientists want their research to inform problems with societal implications, it is important that research processes incorporate multiple types of expertise and knowledge. This nonlinear process requires building personal and institutional relationships over time, establishing trust and credibility, developing avenues for ongoing communication, and integrating these interactions into research and practice.

The concept of transdisciplinarity predates CLIMAS (e.g., Funtowicz and Ravetz 1993; Gibbons et al. 1994); however, practical methods to accomplish it were not well developed during the program's initial formation. Stakeholder engagement was expressed as multidisciplinary and interdisciplinary interactions among the research team, which was somewhat novel for climate research at that time (Bales et al. 2004). The embedded social learning system model pushes CLIMAS program theory and practice towards transdisciplinarity by incorporating and valuing diverse forms of expertise and participation beyond academic knowledge.

A transdisciplinary approach calls out the power relations within knowledge production that "assume some forms of climate knowledge are more relevant than others" (Serrao-Neumann and Coudrain 2018, p. 4) and create hierarchies of value, use, and trust. Pahl-Wostl et al. (2007) argue, "An obvious consequence of the establishment of [collaborative] platforms is a change in power relationships" (p. 14). Within a well-functioning social learning system, academic knowledge and expertise should not hold higher positions of power or value. While formal disciplinary knowledge, training, and expertise are valuable, their decentralization serves to prioritize and promote other types of expertise and ways of knowing. The social learning system framework displaces earlier descriptions of organizations like CLIMAS as a pivotal mediator on a boundary between science and society. These models have proved useful to identify specific roles CLIMAS can play within a system (e.g., Feldman and Ingram 2009; Kirchhoff et al. 2013), but do not adequately capture the program's function and purpose.

Climate resilience viewed through a social learning system framework clarifies how use-inspired research and services programs can encourage transdisciplinary research practices. One way is to connect diverse sites of knowledge production by supporting researchers who collaborate within and across communities of practice. Within these networks, academic and climate researchers play an important role, among the many roles that others also play (see Section 5.3 regarding the public health community of practice). While CLIMAS projects do not always practice transdisciplinarity, the social learning system model guides programmatic operation and research decisions towards it. Furthermore, it is likely that transdisciplinarity does not represent the final form in an evolution of conducting use-inspired research—like interdisciplinary practices, transdisciplinary approaches will eventually evolve into new ones. However, the decentralization that occurs through the social learning system model depicts one evolutionary step towards practicing transdisciplinarity.

5.4 Designing new evaluation practices

To be continually innovative and successful, use-inspired research and climate service organizations must reflect upon the work they produce as well as the processes used to produce that work (McNie 2013; Vaughn and Dessai 2014). Several conceptual frameworks now exist to guide organizations in applying monitoring and evaluation practices (e.g., Vogel et al. 2007; McNie 2008; Wall et al. 2017), but no one-size-fits-all model exists. In our case, the social learning system concept helped us organize CLIMAS program activities—beyond its primary function of producing new knowledge—into five categories: communicating, convening, consulting, collaborating, and training. These categories have revised our understanding of the program's objectives and impact, revealed gaps in our previous evaluation design, and identified areas for improvement. By uncovering the underlying processes of the CLIMAS program, we hope to better understand and articulate the usefulness and impact of the program's research and services. Our 2012–2017 program evaluation has inspired new metrics and data collection techniques for the 2018–2022 program evaluation.

While monitoring progress towards outputs, outcomes, and impacts remain important components of our evaluation, we are now prioritizing tracking individual and institutional relationships, specifically on how they are built, maintained, strengthened, or lost over time. As one CLIMAS investigator points out, "We have relationships with people. They call us, and we call them when something arises. While it's squishy and low level, it does make a difference. [An interaction] with us may have turned into something that other people did and now they are better off—but it actually started with us. How do we put better values on these social components?" (M. Crimmins, personal communication, April 2017). To monitor how relationships develop through the practices of communication, convening, consulting, collaboration and training, we recently developed a database to document the variety of interactions between CLIMAS investigators, information users, and project collaborators. By tracking this information over time, we aim to better understand how these commonplace, but sustained, interactions provide pathways to better climate service products and more useful research. Through this process, we intend to better articulate the value of these underlying social components.

Because we strive to do transdisciplinary work, our evaluation metrics should better mirror the practices of transdisciplinarity. Our 2012–2017 evaluation revolved around data collection from CLIMAS investigators. The current evaluation focuses more on non-academic partners and tracking the roles they play within projects. Partners and climate information users will be directly involved in the evaluation process through annual interviews. We aim to include metrics that demonstrate progress towards their own individual and/or institutional goals. Involving partners in the evaluation process will help establish adaptable project outputs and outcomes. In addition, we aim to better explain if and how a transdisciplinary approach leads to more effective outcomes.

Finally, we are incorporating flexibility into our evaluation design by documenting responses to unexpected changes, barriers, or other outside factors that impact relationships and project outcomes. Several scholars have identified flexibility as a key attribute for organizations and individuals involved in climate adaptation and resilience (e.g., Nelson et al. 2007; Adger et al. 2011; Amaru and Chhetri 2013); however, more empirical evidence is needed to demonstrate how a flexible approach leads to more useful climate research and services. To monitor flexibility, our evaluation-related interviews now include in-depth questions regarding the political, economic, social, historical, and environmental contexts surrounding particular projects. Questions interrogate how responses to sudden or external changes in a project lead to improved relationships, outputs, and outcomes.

In a similar respect, the ways we monitor project outcomes should be less rigid and more flexible themselves, to acknowledge information use at varying timescales and diverse decision-making practices. Climate information use does not always occur in a linear fashion; it is rare that an information product is made and immediately used to make a decision, for example. As a CLIMAS researcher notes, "You often have to look at much more nebulous, conceptual uses of information … It may take longer to layer these conceptual uses, but over time people start to understand the information better. They trust it more because they are hearing the same kinds of information from a bunch of sources. Next time they have to make a decision, they might use that information … but we don't know how long that takes" (A. Meadow, personal communication, April 2017). To better understand these more circuitous and layered uses of climate information, our evaluation process will extend beyond the "end" of a project. We will continue to interview CLIMAS researchers and partners after project funding runs out to record information use or project outcomes. Similarly, our interviews will include questions about the historical context of how project start and why it was needed.

6 Conclusion

In this paper, we use a social learning systems model to demonstrate a programmatic evolution of theory and practice for use-inspired research and climate services. Developing the appropriate knowledge to address complex issues such as climate change requires approaches that situate science within the social context of these problems. Social learning systems theory provides one way to understand the process of contextualizing science. This model decentralizes traditional sites of knowledge production and empowers communities of practice to determine how knowledge is produced, communicated, and valued. Communities of practice provide a foundation for establishing relationships and creating opportunities for learning and innovation across different forms of expertise. Actors within communities of practice must actively maintain these relationships and opportunities, which requires practice and skill, especially when maneuvering through institutional, political, and economic barriers.

A climate resilience social learning system in the Southwest provides a solid theoretical transdisciplinary framework for conducting use-inspired research and creating usable knowledge. While the CLIMAS program has roots in engaged, use-inspired research, we find the social learning systems framework supplies a missing theoretical component in understanding how the program operates. Social learning systems theory has been used to analyze projects based in adaptive and community-based resource management (e.g., Pahl-Wostl et al. 2007; Fernandez-Gimenez et al. 2008; Berkes 2009) and climate change adaptation (e.g., Pelling et al. 2008; Collins and Ison 2009; Wilder et al. 2010), but has not been explicitly incorporated into guiding theories and frameworks for use-inspired research and climate services programs. Understanding the CLIMAS program as one piece of a larger social learning system comprised of multiple communities of practice reveals the importance of developing and fostering different types of social interactions for knowledge production. Our findings are not prescriptive or formulaic—not all climate service and use-inspired research programs should operate under the social learning systems framework. However, we encourage programs that aim to produce useful and usable knowledge to explore how social learning systems theory could apply to their programmatic objectives.

Social learning systems theory is well described in academic literature but more evidence of social learning systems in practice is needed. Routine and deliberate monitoring and evaluation will improve use-inspired research and climate services, while also informing theories of knowledge production. By documenting incremental steps, such programs can make adjustments that strengthen a social learning system over time. Systemic change, or lack of it, will be noticeable by collecting this data over several years. Through practice, reflection, and documentation, we can understand how social learning systems evolve, are maintained, and work towards climate resilience.

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