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Actionable Knowledge for Environmental Decision Making: Broadening the Usability of Climate Science

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Abstract

Despite the rapid evolution and growing complexity in models of science-society interaction, the rate and breath of use of scientific knowledge in environmental decision making, especially related to climate variability and change, remain below expectations. This suggests a persistent gap between production and use that, to date, efforts to rethink and restructure science production have not been able to surmount. We review different models of science-policy interfaces to understand how they have influenced the organization of knowledge production and application. We then explore how new approaches to the creation of knowledge have emerged, involving both growing integration across disciplines and greater interaction with users. Finally, we review climate information use in the United States and United Kingdom to explore how the structure of knowledge production and the characteristics of users and their decision environments expose the challenges of broadening usable climate science.

Contents

1. INTRODUCTION

What is society's relationship to science? And how does this relationship shape the science that is produced? How does science move from production to use in decision making? These are among the answers scholars have increasingly sought to explore for both normative and practical reasons. For the past 50 years, there has been a rapid evolution of science-society interaction thinking, ranging from the 1940s linear model (characterized by a strong disciplinary-based, basic research focus) to more complex models of science production that embrace interdisciplinary approaches and involve users in helping to solve societal problems (see, for example, References 1 and 2). One outcome of this effort is the emergence of a robust empirical literature focusing on exploring different ways of producing/delivering scientific information that can more effectively support decision making. These include institutionalizing more participatory approaches through boundary organizations, knowledge systems, and scientific assessments (see, for example, References 3–5).

Boundary organization: an organization that facilitates the interaction between science producers and users and stabilizes the science-policy interface

Knowledge system: a system that encompasses programs and institutional arrangements that effectively harness science and technology to improve decision making

Scientific assessment: an action that organizes, evaluates, and integrates expert knowledge to inform policy or decision making

Although these new models and structures for knowledge production have, in general, increased information use in environmental decision making, for climate information, in particular, the pace of use has not been commensurate with the expected need (6, 7). This suggests a persistent gap between production and use that, to date, efforts to rethink and restructure science production have not been able to surmount. That is not to say that no progress has been made. In climate-related decision making, empirical evidence suggests that scientific information uptake can be improved for specific decision makers in specific contexts (see, for example, References 8–10). But the urgency and widespread reach of projected climate change impacts demand more than incremental improvement. Moreover, as the problem becomes more salient for decision makers across the world (with more intense storms, rising seas, etc.), the demand for usable climate information may quickly outstrip our ability to produce it using the approaches we currently employ (11). Hence, there is an urgent need to reconsider how we approach the challenge of creating usable climate information from what has been predominately a focus on individual users or small groups of users to approaches that meet the needs of a diversity of decision makers.

This review aims to contribute to this practical and scholarly discussion by surveying the rapid evolution of the field and highlighting the practical lessons that can both support the creation of new science/policy interfaces and inform the institutionalization of successful models. We particularly focus on processes and mechanisms to increase usability when there is some level of willingness or support for the use of scientific information. Throughout the review, we strive to identify where the intellectual community in this area has made strides and where it still needs to narrow knowledge gaps. In addition, we aim to provide a road map for those interested in forms of knowledge production as both participants (that is, as producers and users of science) and as objects of study.

Drawing on our review and synthesis of a wide range of research on science-policy models and empirical research on factors, processes, and structures that influence science usability, we propose that to move beyond the current paradigm requires understanding knowledge users not just at the individual but also at the aggregate level exploring the opportunities and challenges of scaling information production while maintaining and/or increasing usability.

We start this review by examining different models of science-policy interfaces and how they have influenced the organization of knowledge production and application. We then explore how these models have been challenged both from academia and society as well as how new approaches to the creation of knowledge have emerged, including those that involve potential users in the process and those that involve different levels of interaction between producers and users. In the third part of this review, we examine what influences scientific knowledge application, focusing predominantly on empirical studies of climate information uptake across a range of uses. Finally, we review two cases of knowledge production and use—one in the United States and one in the United Kingdom—to explore the primary challenges to usability identified in the review and their implications for the opportunities and challenges of scaling information production while maintaining and/or increasing usability.

2. SCIENCE-POLICY MODELS

2.1. Science, the Endless Frontier

In *Science the Endless Frontier*, Vannevar Bush (1) argued that science benefits for societal progress ensue innately from the unencumbered linear flow of information from both basic (research that contributes to the general knowledge and understanding of nature and its laws) and applied research (undertaken for some identified individual, group, or societal need) to decision making. The report also advocated for the separation of science from society to maintain objectivity and credibility and to ensure that science is not tainted by values and politics. This highly influential report not only provided the basis for the reorganization of the scientific enterprises in the United States in the mid-twentieth century but also established many of the tenets for science production still in existence today (12). One of these tenets—that societal benefits accrue precisely because of the separation of science from society—has been increasingly under fire for the past 30 years.

Science-policy model: a conceptual means to simplify and explain the interactions and boundaries of science production and society or policy decision making

Part of the reason for challenging this model—heretofore referred to as Mode 1—is that, despite the steady and continuous progress in the production of science, there is widespread concern that not enough of the public decisions that should benefit from the science produced actually do (13, 14). Specifically regarding climate science, while trying to explain why that is, a number of researchers have speculated about a "disconnect" between the science produced ostensibly to inform decision making and actual policy processes (14–19). More generally, one explanation is that Mode 1 science makes "a number of unsubstantiated assumptions about the resources, capabilities and motivations of research users" (20, p. 12), including that the science produced is expected and presumed to be useful to solve problems (15). For example, empirical research has shown that a whole range of contextual and intrinsic factors affect the use of information in decision making, including informal and formal institutional barriers, what the decision and policy goals are, the information's spatial and temporal scale resolution, the level of skill required to utilize the information, and the level of trust between information producers and users, among others (17–24). A second explanation for this disconnect is that Mode 1 science is overly focused on disciplinary knowledge originating from university settings and has ignored both other sources of knowledge and other disciplinary perspectives (25).

Another challenge to the Mode 1 construct is that there is no such thing as science produced separately from society. Influential scholars, such as Latour (26) and Jasanoff (27), have convincingly argued, and empirically shown, that the separation between science, policy, and society is artificial; in reality, knowledge is neither unfettered nor neutral, and science and policy are coproduced in the day-to-day interaction between scientists and their social environment. Rather than objective and value free, knowledge influences and is influenced by social practices, identities, discourses, and institutions (25). Taken together, scholars in this tradition argue that the interface between science and society is a hybrid, mutually constructed arena in which social relations between producers and users of science shape facts about the natural world being studied (27, 28). More recently, the idea of coproduced science and decision making has become associated with the purposeful creation of institutions and organizations (e.g., boundary organizations) that facilitate the interaction between science producers and users (17, 29).

Postnormal science: an approach for high-risk situations when science is uncertain and constituents need their own forms of knowing to evaluate risks

2.2. Mode 2, Postnormal, and Hybrid Science-Policy Models

In response to the failure of Mode 1 science to fulfill its social contract, new models have emerged that better characterize the evolving relationship between science, scientists, the public, and policy. Proponents of these new models argue for two major changes in the way that science for societal benefit is produced. First, the complexity of contemporary problems requires more than one disciplinary view to solve them. Moreover, science should go beyond providing neutral, credible, and legitimate support for decision making to incorporate other kinds of knowledge and different ways of "knowing" (30, 31). Second, science produced for the solution of problems needs to be more flexible, and the process of production needs to be more iterative and interactive. Together, these changes help ensure that the science produced this way is more likely to help solve pressing problems and meet its public value functions (i.e., knowledge for its own sake, knowledge for economic value, information useful for decision makers, participation in agenda setting by stakeholders, and communication of findings to the public) (14, 32).

Hence, new models of science production for societal benefit have become more complex both in terms of how scientific information is organized and coproduced and in terms of how it is communicated, disseminated, and used (or not). In the production function, this increased complexity has increasingly challenged not only the motivation of scientists (e.g., basic versus applied science) but also the ways they interact with the potential users of the knowledge they create and with society in general (32–35). The need for knowledge that benefits society has also put growing pressure on the scientific enterprise to produce usable science or science that decision makers seamlessly perceive as fitting their needs and decision environments (11, 16, 17, 36).

The Mode 2 model, proposed by Gibbons and his colleagues (2, 25), organizes science production at increasing levels of interaction and integration across disciplines (from multidisciplinary to transdisciplinary) and across the science-society divide. In contrast to Mode 1, this new approach produces science that is heterogeneous, reflexive, and more socially accountable. In this model, multidisciplinary refers to understanding a problem from the viewpoint of different disciplines, whereas interdisciplinary combines perspectives, methods, and ideas to foster innovation in ideas, solutions, and decision tools. Transdisciplinary research, in turn, goes beyond the mere bringing together of teams of specialists from different disciplines to guiding scientific inquiry through a specifiable consensus regarding appropriate cognitive and social practices (25). Although interdisciplinary work has been widely supported by the scientific community as an ideal and as a practice (7, 37, 38), transdisciplinary is more contested, both in terms of institutional resources required as well as of the role of scientists themselves in working beyond scientific boundaries (38). In addition, integrating across organizations can be more challenging than across disciplines, despite the overall scholarly and practical benefits of integrative science (31).

Beyond Mode 2, postnormal science is both a framework (35) and a practical approach

(39) for problem situations in which the stakes are high and science is uncertain. In this case, scientific knowledge alone is not enough to solve societal problems, and constituents need their own forms of knowing to better evaluate the risk of their situation (35). For both Mode 2 and postnormal science, interaction between producers and users of science across the science-society interface means the specific involvement of stakeholders. Here, stakeholder interaction involves more than simple communication from science to society. It entails substantive multidirectional interactions and involvement of constituents in the research process, which may include problem definition and formulation of research questions, data collection, selecting methods for and conducting actual research, analyzing findings, and developing usable information (2, 17, 40). **Figure 1** illustrates the evolution in the complexity in both knowledge production on the one hand (from Mode 1 through postnormal science) and user participation on the other.

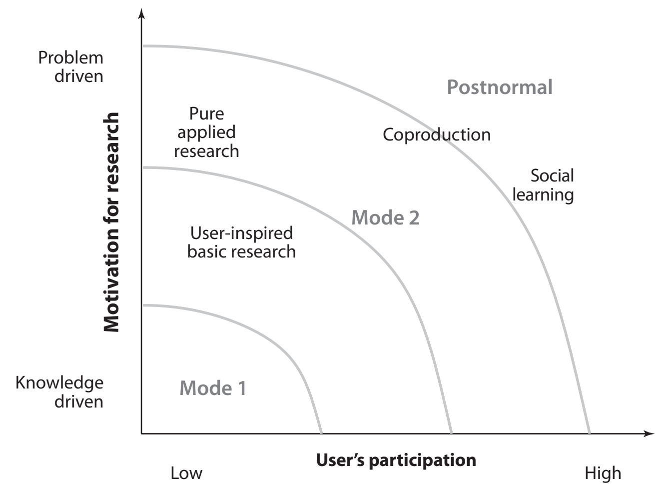

Figure 1

Evolution in the complexity of knowledge production and user participation. On the vertical access, the complexity of knowledge production increases from low (where production is predominately focused on increasing our fundamental knowledge) to high complexity (where production aims to help solve societal problems). On the horizontal axis, the complexity of user participation changes from low to high as users become increasingly active agents in the knowledge creation process.

Arguments for participatory modes of knowledge production and use range from issues of democratization, citizenship, civics, and accountability to calls for a new way of producing science that meets the need of decision makers seeking to solve ever increasingly complex environmental problems. In this new mode of knowledge production, society speaks back to science, affecting the "scientific activities both in its forms of organization, division of labor and day-to-day practices, and deep down in its epistemological core" (2, p. 161). Different forms of participatory science production include boundary organizations and science shops, participatory technology assessment, citizen science, knowledge networks, integrated assessments, public ecology, and science-policy dialogues (5, 9, 29, 30, 41–48).

At its most participatory, science at the interface is carried out in nonhierarchical, heterogeneously organized forms, involving close interactions with many actors throughout the process of knowledge creation. Knowledge produced in this way is expected to be more relevant and usable for solving problems and supporting management (e.g., improving the fit between what users want and what science can offer); more likely to be "bought in" by stakeholders and be more legitimate in their eyes; and more likely to build trust and improve communication (9, 30, 41, 42, 46, 49–52). In addition to producing more usable information, participatory processes also amplify the role of science in society (scienticizing decision making) and the role of society in science (politicizing science) (53, 54).

As information moves across disciplines and between producers and stakeholders in highly iterative modes of knowledge creation and use, the process of interaction itself reshapes the perceptions, behaviors, and agendas of the participants (11, 17, 24, 55). Indeed, science and its application give rise to a new politics of expertise in which scientists rather than "speaking truth to power" become part of a much broader, messier social experiment (26). On the one hand, the creation of participatory knowledge production and governance processes in itself does not guarantee knowledge democracy, especially when the use of scientific knowledge becomes a source of authority of some groups over others and an instrument of inequity in the distribution of power across participant groups (30, 56–58). For example, in Brazil, the use of reservoir charge and discharge scenarios within river basin committees may provide members with technical expertise and an advantage over other members when making decisions about water allocations (59). Part of the problem is the black box of technical knowledge, that is, the obfuscation of the assumptions, values, and methods embedded in the knowledge by those who create and/or employ it in the context of decision making (30, 57). For example, in Denmark, a government organized citizen-experts dialogue conference, focusing on expertise around environmental economics as a policy tool, exposed dissent not just between experts and nonexperts but also between the experts themselves when disagreements over assumptions and methods emerged (30). Moreover, in practice, it is also the case that postnormal science alone cannot counteract the role of politics in shaping critical issues within participatory/deliberative processes, such as agenda building, or the definition of who participates and who does not (for specific critiques of postnormal science see References 60 and 61; for a review of deliberative democracy and knowledge, see Reference 58). And, although there is wide speculation about the impact of politics, political ideology, and the politicization of science (see, for example, References 62–64) on science usability (see, for example, Reference 65), there is much less empirical research systematically assessing their implications in specific decision-making environments.

On the other hand, scholars have argued that participatory forms of knowledge production and use can avoid the inequity often introduced using scientific expertise by being inclusive and transparent and by integrating different kinds of knowledge (e.g., scientific, lay, and indigenous knowledge) (60, 66). Moreover, in the context of interaction, producers and users of scientific information can resolve conflicts and build consensus, which, in turn, may help them overcome barriers for information use, including issues of trust, communication, legitimacy, information accessibility, and lack of fit (30, 58, 59). The experience of interaction in a common social context is at the core of social learning—defined as learning from others through observation and modeling (67). Through social learning, producers and users of different kinds of knowledge learn from each other (44), positively shaping common perceptions of problems and solutions, which, in turn, may support collective action and effective management (55). However, implementing social learning as a methodology has its own set of challenges, including reconciling the diversity of values, worldviews, and epistemologies between all participants, and a high level of human resources required to carry it out in practice (55).

2.3. Boundary Organizations, Knowledge Systems, and Assessments

2.3.1. Boundary organizations. In the context of science-decision-making interactions, the role of boundary organizations is twofold. First, they stabilize the knowledge production function by providing a protective layer against the undue influence of extraneous factors such as politics. Much of the early research on boundary organizations focused on their stabilizing function. Second, boundary organizations provide a bridge for and broker knowledge between the production side (universities, research institutes) and the use side (stakeholders, decision makers).

In the first role, boundary organizations achieve stabilization by internalizing and collaboratively negotiating the contingent character of the science-policy boundary by using boundary objects and standardized packages (54, 68, 69). Boundary objects (for example, a climate scenario) are distinguished from data through their use; boundary objects facilitate stabilization between two social worlds (for example, climate modeling and climate policy) both by fostering a sufficiently shared understanding to gain legitimacy in each world and by enabling negotiation to resolve mismatches in overlapping areas (68). For example, Hulme & Dessai (23) showed how from 1991 to 2002, and particularly since the emergence of the UK Climate Impacts Programme (UKCIP) in 1997, the United Kingdom's national climate change scenarios transformed from being primarily data for impact scientists to becoming increasingly more like boundary objects. Indeed, because they are coproduced by the worlds of science and policy, they gain authority in both. Boundary objects are most helpful when they are produced in a transparent fashion and when they are used to reshape and redefine meaning reflexively and iteratively (70). As stabilizers, boundary organizations provide a means for producers and users of knowledge to work together to form a common point of reference and shared understanding while maintaining their separate identities (54, 71). This is tricky work as "opposing pressures and accountability for the actors in the two social worlds. . .challenge efforts to stabilize the boundary" (72, p. 222). The Office of Technology Assessment and the Health Effects Institute are exemplars of this sort of stabilizing function, helping to maintain stability when negotiating science production and use amid fractious party politics, in the case of the Office of Technology Assessment, and an adversarial regulatory environment, in the case of the Health Effects Institute (27, 54).

In their second role, as a bridge for and/or broker of knowledge, boundary organizations have at least three characteristics: (*a*) They create a legitimizing space and sometimes incentivize the production and use of boundary objects and standardized packages; (*b*) they involve information producers, users, and mediators; and (*c*) they reside between the producer and user worlds with "lines of responsibility and accountability to each" (54, p. 93), allowing both sides to pursue their own goals (5). In this sense, boundary organizations are institutional structures that contribute to the coproduction of science and policy, first, by facilitating the collaboration between scientists and nonscientists (30); and, second, by creating a combined scientific and social order (5). Rather than acting merely as a conduit or a funnel, boundary organizations are a "forum where multiple perspectives participate and multiple knowledge systems converge" (73, p. 261). For example, in the United Kingdom, the UKCIP has been widely recognized as a successful boundary organization working at the interface between scientific research, policy making, and adaptation practice (39, 74, 75).

UKCIP: UK Climate Impacts Programme

Further understanding of boundary organizations' role as a bridge for and broker of information has come about as scholars carried out in-depth empirical studies to examine both the interactions across epistemological and ontological boundaries, as well as the characteristics of organizations, producers, and users that lead to increased usability (41). For example, Kirchhoff et al. (76) found that in both the US and Brazil interactions in the context of a boundary organization improved the use of climate information by water managers. Similar improvements to climate information usability associated with interactions between producers and users have been observed across a variety of applications from sustainable land management (50) to disaster reduction (77) and urban sustainability (78). In the context of boundary organizations, it is not just interaction between producers and users that matters. Building capacity for information uptake, integrating multiple forms of knowledge, and managing the inequities in power between producers and users also improve usability (79).

2.3.2. Knowledge systems. In earlier usage, knowledge systems referred to indigenous ways of knowing about the world that encompassed nature, culture, environment, and their interrelationships (see, for example, Reference 80) and farmers' knowledge of agricultural practices (see, for example, Reference 81). In their seminal paper, Cash et al. (3) reframed knowledge systems to encompass programs and institutional arrangements that effectively harness science and technology to improve decision making for sustainable development. They argued that for knowledge systems to be effective, they must actively manage the boundary between expertise and decision

RISA: Regional Integrated Sciences and Assessment

making, enforce accountability of actors on both sides of the boundary, and jointly produce outputs (e.g., models, reports). For scientific information to be usable, decision makers must perceive it to be credible, salient, and legitimate (3). To be judged by these criteria, scientific knowledge needs to show distinctive characteristics decision makers recognize (82). For instance, information is likely to be deemed credible if the science is accurate, valid, high quality, supported by some form of peer review, and funded from one or more recognizable or established institutions. To ensure the information is legitimate, it must have been produced and disseminated in a transparent, open, and observable way that is free from political persuasion or bias. To be salient, information must be context sensitive and specific to the demands of a decision maker across ecological, spatial, temporal, and administrative scales (3, 18, 23, 83–85).

Empirical observations suggest salience, credibility, and legitimacy are often tightly coupled; improvement of one measure can result in a reduction in another (3). Hence, achieving these three criteria simultaneously maybe tricky as trade-offs between them may negatively influence the overall perception of information usability. Moreover, stakeholders may have different perceptions of what makes credible, legitimate, and salient information (3, 16). To reduce these trade-offs, Cash et al. (3) argue that knowledge systems need to have active, iterative, inclusive, and open communication and translation that promotes mutual understanding between participants. When all else fails, conflict across the three criteria may require active mediation to prevent the system from collapsing. Here, boundary organizations can help maintain the integrity of the system because they can enhance communication, translation, and mediation; make boundary spanning activities routine; and help stabilize knowledge systems in a changing sociopolitical context (86).

The knowledge system criteria can be a valuable heuristic to assess stakeholders' perspectives of what constitutes usable science because it considers the entire process (from inception to dissemination) of the science in question. Indeed, credibility can be used to assess stakeholders' perceptions of the quality of science underpinning the disseminated information; legitimacy can assess stakeholders' perceptions of the level of transparency and bias of the individuals and institutions involved in its development; and saliency directly assesses stakeholders' perceptions of its relevancy to their needs and requirements. Proving its versatility, the knowledge systems framework has been applied to a diversity of research foci that range from understanding how the Global Fund to Fight AIDS, Tuberculosis, and Malaria contributes to support the global response to these diseases (87) to the investigation of how such systems support climate forecast use by farmers and water managers in Australia, water managers in Hawaii, natural resource managers in the Columbia River basin and a range of users in the United Kingdom (82, 86, 88–90).

2.3.3. Integrated scientific assessments.

Assessments organize, evaluate, and integrate expert knowledge to inform policy or decision making (4). They also interpret and reconcile information produced from disparate scientific domains making the information more useful for policy deliberations and for addressing an identified problem (91). For example, global environmental assessments have been undertaken to inform responses to pressing global environmental concerns, including climate change, biodiversity loss, and stratospheric ozone depletion (92–94). However, despite their designed intent (to be usable for policy or decision making), in practice, their influence on national and international responses to environmental threats has been limited, with ozone depletion and acid rain being notable exceptions (95, 96). In the United States, regional-scale assessments, like the Regional Integrated Sciences and Assessments (RISAs), have been relatively more successful in providing usable information for policy makers. This is partly because they reduce barriers to and leverage drivers of information use (24, 97) and because, in many cases, they successfully reconcile the production of information with users' demand (18, 19, 29) through sustained and frequent interaction between scientists and stakeholders (97).

At the global level of environmental regimes, research applying the knowledge systems approach to evaluate scientific assessments finds that assessments perceived to be salient, credible, and legitimate are more successful (4, 9). In this case, success encompasses both the usability of the product and the process of information production. For example, Clark & Dickson (98) found that more effective assessments achieve a balance of saliency, credibility, and legitimacy, where saliency refers to the perceived relevance and credibility refers to the perceived authoritativeness of the process to the scientific community. Lastly, legitimacy captures the perceived fairness and openness of the assessment process to the mostly policy or political community, which might reasonably use the assessment product (98).

Others have questioned the sufficiency of perceived salience, credibility, and legitimacy to determine assessments' effectiveness, that is, their influence on the policy-making process—particularly for those conducted at other than international scales (e.g., national, regional). For example, a number of researchers have found the US National Acid Precipitation Assessment Program to be irrelevant to the policy-making process despite efforts to maintain credibility, saliency, and legitimacy (99–101). Similarly, in spite of efforts to ensure the credibility (e.g., peer reviewed), legitimacy, and saliency (e.g., stakeholder participation) of the product and process of the first United States National Assessment of the Potential Impacts of Climate Change, limitations of the assessment process itself (e.g., budget constraints) and political meddling effectively contributed to lessen its impact (L. Carter, personal interview; also see References 102 and 103).

At the regional scale, empirical research suggests that effective assessments are ongoing, interactive, and iterative (17), and also match the scale of assessment with the relevant scale of decision making or management (104), and employ buffering and linking strategies (100). To be effective at producing usable information, regional assessments need to straddle the line between understanding complex problems and producing information that meets decision makers' perception of their needs (17). Hence, the early and continued involvement of stakeholders in the process of knowledge production is likely to positively influence the actual use of information in decision making (105, 106). Likewise, matching the scale of an assessment of a particular phenomenon of interest (e.g., climate change impacts) to the scale of a potential response (e.g., water management adaptation policies) improves the assessment effectiveness (104). Finally, when assessments protect scientific work from bias and politicization (buffering) while maintaining ties to the potential assessment information users, who might rely on the outputs to inform policy decisions (linking), they are more effective (100).

3. WHAT INFLUENCES INDIVIDUALS' USE OF SCIENTIFIC INFORMATION

3.1. Users' Perception of Risk

Attitudes toward risks vary across people, cultures, time, and experience; these attitudes have a profound impact on the character and type of information sought and used (or not) in decision making. For example, O'Connor et al. (107) found that risk perceptions were the strongest determinants of weather and climate forecast use among two eastern American states. Water managers who expect to face problems from weather events in the next decade are more likely to use forecasts than are water managers who expect few problems; their expectations of future problems are closely linked with past experience. Feeling at risk thus leads to a greater use of climate information. In her study of water managers in the US Pacific Northwest and Southwest, Kirchhoff (24) points out that water managers' risk perceptions were strongly correlated with information seeking and collaborative behaviors through which water managers gather and employ climate information as a strategy to manage risk and inform decision making. These behaviors (seeking information and developing multiple collaborative relationships) help managers assemble a portfolio of information to manage both the uncertainty related to their specific decision context and the uncertainty embedded in the information that is ultimately used in decision making (24) (for a discussion of uncertainty in water decision making, also see Reference 65). Finally, various decision environments influence risk perception differently as well. In Australia, Power et al. (108) discovered that water resource managers perceived the risk from public outcry over not using climate information in planning as more worrisome than the risk associated with using it.

Human cognition and experience also play a role in risk perceptions. Specifically, the ways in which people process information analytically (slowly, with attention and awareness of rules such as logic and probabilities) or experientially (fast and relating to emotion and experiences and learning from them) affect their perception of risk and influence their use of information (109). Marx & Weber (110, 111) found that approaches that encourage users to employ a combination of these processes positively influence forecast use. In terms of experience, worry stemming from personal experiences can influence risk perceptions and response. For example, individuals who are alarmed about a potential hazard or risk are more likely to take action informed by climate information, whereas those who are not alarmed do not take precautions (112). Visualization can also improve the likelihood of taking action. For example, Weber (112) found that interventions (e.g., visualizations) that help move future events closer in time and space raise individuals' visceral concern, which, in turn, may lead to increased responsiveness.

3.2. Interactions, Information Fit, and Decision Environments

Within the broad scope of science-policy models, boundary organizations, knowledge systems, and assessments and their success (or failure) in producing usable information, a large body of literature has focused on understanding the factors that influence scientific information use in diverse areas of environmental decision making at both the producer-user interface and in the wider institutional context. In their review of this literature, Lemos et al. (11) argued that usability is affected mainly by three interconnected factors: the level and quality of interaction between producers and users of climate information; the fit, how users perceive climate information meets their needs; and the interplay, how new knowledge interacts with other types of knowledge decision makers currently use.

At the producer-user interface, robust empirical evidence from well-developed literature focusing on the use of seasonal climate forecasts by different decision makers suggests that, first, two-way communication that improves mutual understanding and, second, long-term relationships that build trust between producers and users play a significant role in increasing scientific information uptake (8, 113–119). In turn, trust building and accountability influence users' perceptions of information salience, credibility, and legitimacy in particular decision contexts (24, 120). In addition, establishing convening, translating, mediating, and collaborative processes that link producers and users increases the salience, legitimacy, and credibility of information leading to improved usability (9). For example, in the US Pacific Islands and US Southwest, ongoing collaboration between scientists and decision makers facilitated the production of information tailored to users' needs and context in the Pacific Islands case (9) and built the capacity of users to incorporate forecasts in decision making in the US Southwest case (121). Similarly, interactions and the long-term relationships they support can critically accelerate dissemination of new knowledge through the many networks to which users belong (119). Finally, usability is enhanced with interactions that help potential users understand, process, and ultimately use information in decision making.

Drawing on what is familiar to potential users and using holistic scenarios, especially those created using information visualization processes, improve salience and facilitate more comprehensive understanding (122). These kinds of visualization techniques have been used as an aid to local decision making across a range of applications from climate change impacts and responses (122, 123) to sustainable forest management (124) and landscape change (i.e., tourism, agriculture, and forestry) (125).

What many of these in-depth studies have found is that interaction can help mitigate many of the barriers to information use, including users' perceptions that scientific information is too uncertain to use or that it lacks the perceived level of accuracy and reliability needed to be used in decision making. Interaction can help change users' minds by facilitating in-depth discussions, including the potential trade-offs, the effects on decision making, and the risks in using information (24, 108, 126, 127). For instance, producer-user interactions over the course of a workshop helped users gain a more in-depth understanding of how stream flows are reconstructed from tree rings and how this information can be used to extend what is known about the range of natural variability for individual streams to aid in long-term drought planning (10). Similarly, explaining decision-making tools in more depth positively influences users' willingness to deploy them (72). Users also benefit from producers' explanations of choices, trade-offs, and limitations of different kinds of knowledge/information. For example, in a decision simulation experiment carried out by researchers in Arizona, disclosing data sources and assumptions underlying a water simulation model helped policy makers evaluate the salience and credibility of the model, ultimately influencing its perceived usability (72). Interaction can also help users to better integrate information in their decision making. In their study of coastal managers in California, Tribbia & Moser (128) found they need more than just information when planning for climate change; they also need support in integrating and facilitating science knowledge into practical management. Finally, interaction may work to decrease mismatches between different kinds of knowledge and values, such as explicit (e.g., facts and figures) and tacit knowledge (e.g., experience and context) (112, 129). Indeed, interaction fosters learning, which, in turn, may reduce conflicts between knowledge types by helping to transform one type of knowledge (e.g., explicit knowledge) into another (e.g., experiential or tacit knowledge).

Case studies in the United States and around the world have shown that institutions and organizational culture affect the usability of information (65, 114, 118, 130–137). For example, research found that organizations with more flexible decision-making frameworks (69) and those that insulate technocratic decision makers (138) are more likely to use information. Having sufficient human or technical capacity in-house or having access to relevant external expertise makes climate forecast use (134, 139) and climate projection use (82) more likely. Furthermore, a decision-making culture that views the use of climate information as a strategy to mitigate risk (10, 24, 140) rather than as a risky practice in itself (141) is more likely to promote integration of climate information in decision making. Finally, organizations that value research and provide incentives that promote incorporation of information into decision making also improve knowledge use (24, 115).

Although the number and breath of empirical research efforts focusing on understanding the factors that influence the science-policy interface in environmental decision making have increased dramatically during the past 20 years, there has been relatively less effort to employ experimental approaches that have successfully evaluated knowledge uptake in other fields of enquiry, such as medicine and education (142, 143). Indeed, the design and implementation of naturalistic and laboratory-based social experiments could critically enhance our understanding of how different kinds of interventions and treatments (e.g., visualization, customization, communication) and controlled decision environments can effectively improve

REGIONAL INTEGRATED SCIENCES AND ASSESSMENTS

Fueled by a user-oriented mission stymied by low rates of information uptake, the National Oceanic and Atmospheric Administration established the RISA Program in the late 1990s to support innovative, interdisciplinary, use-inspired research to inform policy and decision making and to build the capacity to prepare for and adapt to climate variability and change (29). Presently, there are 11 RISAs in the United States, covering all or part of 39 U.S. states. RISAs engage in boundary work—communication, mediation, and translation—to diminish barriers to information use (9, 43) and support ongoing interactions between RISA scientists and their stakeholders to improve the usability of information (17). Boundary work and interactions help shape decision-relevant research programs, produce relevant information, and aid in forming and maintaining a dedicated user network to improve information uptake (146).

our understanding of the factors enhancing or constraining knowledge use (144, 145).

4. BROADENING USABLE CLIMATE SCIENCE

In our review, we have synthesized a wide range of research on science-policy models and empirical research on factors (institutional and organizational issues, risk attitudes, perceptions, and others), processes (e.g., interaction, visualization), and structures (e.g., boundary organizations, knowledge systems) that influence information use. What this empirical research shows regarding climate science is that many of the strategies for increasing climate information usability focus primarily on improving interactions between producers and users of information and obtaining a better fit of information to the specific user contexts (8, 9, 86, 88, 114). This makes sense given that most empirical examples of successful adoption have been driven by highly interactive and well-established relationships between producers and users of climate information brokered by mechanisms created specifically for that purpose (10, 17, 18, 24, 43, 119, 140).

The US RISA program (see the sidebar Regional Integrated Sciences and Assessments) is an example of a successful, highly interactive approach whereby information uptake is motivated by users' perceptions of climate risks and is predicated both on users seeking climate information and having a decision context that supports its use (24). The influence of users' behavior and decision contexts on use is an important consideration for usability because RISAs operate in the United States where climate information use is not yet regulated or mandated by the federal government. Yet, the usability of RISA-produced climate information is not just a function of users' behavior and their decision contexts.

As boundary organizations, RISAs increase usability by contextualizing the information, translating information into more usable forms, and assessing user needs. For example, by "placing climate-change variability into the geographic, political, and economic contexts of the regions," the RISAs helped users consider climate in place-based decision making (146, p. 18). In addition, by identifying shared problems among multiple users, RISAs tailored their research agendas to produce information that meet the needs of both individual users and groups of users (43, 146). In this way, the RISAs are adaptive "learning organizations" able shift in response to user information demands and input rather than getting stuck producing information that is not needed (146). By focusing on producing information users want and in a format they can access easily, RISAs increase information usability (146, 147).

Although the RISAs are effective at increasing usability among individuals and groups of users, the RISA model faces a number of constraints. First, the intensity of interaction (to respond to user information needs; to contextualize, translate, and customize information; and to build trust and capacity for information use) is costly. For example, the process of information coproduction by both producers and users can be slow, often resulting in long lead times for usable information (24). Additional costs (or trade-offs) are the limited number and types of potential users RISAs are able to effectively serve (11, 24). Research suggests that highly interactive research models, like the RISAs, tend to reach predominantly high-capacity users located near the RISAs, raising questions about broader accessibility of climate information for users with less capacity and those located further away from the RISAs (24). Persistent challenges for RISA-like models have been how to broaden the reach and accessibility of information produced through highly interactive models of information production in a cost-efficient manner. As the need for climate information to inform policy increases (6, 11, 16, 65), knowledge gained from the RISA program will be necessary to create new approaches that are capable of dramatically increasing the scale of actionable climate knowledge production.

An alternative approach is the production of climate information at the national scale to serve many users and to maintain national consistency (23, 82). In the United Kingdom (see the sidebar Long-Term Climate Information Uptake in the UK), centralizing production of climate information increases the accessibility of the information for all users. Moreover, mainstreaming climate change into policy and regulation and creating successful boundary organizations, such as the UKCIP, have enhanced the uptake of long-term climate information. For example, almost all reporting authorities (companies with functions of a public nature, such as water and energy utilities) used the 2009 UK Climate Projections (UKCP09) (82).

Even though information is broadly accessible and use of the information is enhanced through mandates for certain industries and sectors, effective use is limited for a variety of reasons, including the complexity of the climate information (e.g., probabilistic climate change projections) and a lack of specificity of the scenarios to users' particular decision contexts (82). This highlights an important tension between increasing the salience of climate information for users while maintaining national consistency. Another challenge faced by the UK approach is the reliance on a single source of climate information, national climate scenarios (e.g., UKCP09), which if incorrect could create widespread vulnerability (148). By contrast, in the US RISA case, where use is voluntary and climate information production is decentralized, users seek to assemble a portfolio of information to manage both the uncertainty related to their specific decision context and the uncertainty embedded in the information (13). **Figure 2** illustrates the trade-offs in usability in the US and UK examples.

As **Figure 2** shows, neither the UK approach nor the US RISA approach, in their present incarnations, completely solves the science usability gap. In the United States, RISAs improve climate information usability for a subset of high-capacity, connected users leaving large segments of society effectively underserved. In the United Kingdom, despite a mandate, which in principle should support risk assessment, to improve information accessibility, broadly drive uptake, and reduce societal vulnerabilities in one fell swoop, usability is limited

LONG-TERM CLIMATE INFORMATION UPTAKE IN THE UK

The first two sets of UK national climate scenarios released in 1991 and 1996 were largely aimed at the impact research community (23). With the emergence of a boundary organization, the UKCIP in 1997, subsequent scenarios, released in 1998 and 2002, saw an increasing uptake from numerous organizations (149), which was also propelled by the beginning of mainstreaming of climate change into regulation and planning. The latest set of climate scenarios, released in 2009, is known as the UK Climate Projections 2009 (UKCP09), published by the Department of Environment, Food and Rural Affairs (150). In 2008, the government adopted the Climate Change Act 2008, which has led to a significant increase in climate information uptake through (*a*) the Climate Change Risk Assessment (CCRA) and (*b*) the Adaptation Reporting Power. The first CCRA came out in 2012, making use of existing climate information to assess hundreds of impacts across 11 key sectors (151). The Adaptation Reporting Power enables the Secretary of State to direct reporting authorities to prepare reports on how they are assessing and acting on the risks and opportunities from a changing climate (152).

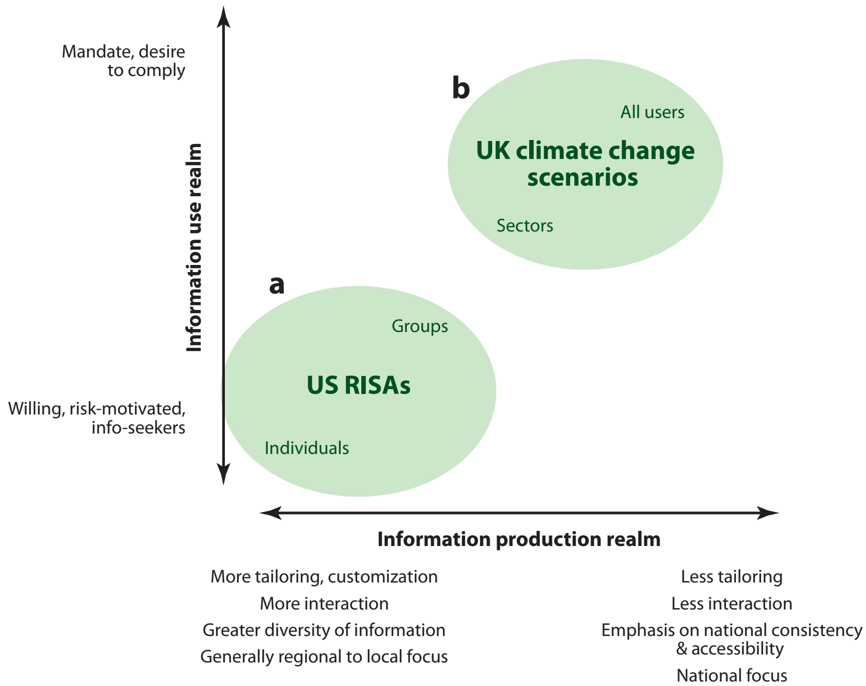

Figure 2

Usability space in the United Kingdom versus the US Regional Integrated Sciences and Assessments (RISAs). The vertical axis depicts the information use realm where users range from being primarily self-motivated to use information (e.g., risk motivated, information seeking) to users who are motivated through the regulatory environment (e.g., desire to comply with existing or future regulations). The horizontal axis shows the range of information production. On the left, production is characterized by high levels of tailoring, interaction, and support for use; there is diversity of information; and there is a regional to local focus. On the right, information production is characterized by much lower levels of tailoring and interaction; the emphasis is on national consistency; and the focus is the national level. The two green ovals represent the usability space achieved through the US RISAs (in oval *a*) and the UK climate change scenarios (in oval *b*).

by the complexity of the information, which requires high scientific competence/training and familiarity in dealing with climate information.

5. CONCLUSION

There are an ever growing number of complex environmental problems that increasingly need science to support decision making. Despite the growing availability of scientific information, there is a persistent gap between knowledge production and its use to inform decision making. Scholars have explored different ways to narrow this gap through better understanding society's relationship to science, including both how it shapes the science that is produced and how that science is used (or not) to support decisions. These efforts have produced a rapid evolution of science-society models, ranging from the 1940s linear model to more complex models of science production that embrace interdisciplinary approaches and involve stakeholders to help solve societal problems. In spite of these efforts to rethink and restructure science production, current approaches have not been able to surmount the usability gap. This review advances this practical and scholarly inquiry by surveying a wide range of research on science-policy models and empirical research on the factors, processes, and structures that influence science usability, highlighting the lessons that can both support the creation of new science/policy interfaces and inform the institutionalization of successful models. We also compare two different climate information production approaches one in the United States, the RISA program, and one in the United Kingdom, the national climate change scenarios/projections. What this comparison shows is that neither approach solves the science for society challenge. In the United States, RISAs improve climate information usability for a limited group of high-capacity, connected users potentially at the expense of other high-priority needs. And in the United Kingdom, despite a mandate, which should dramatically increase uptake, usability is hampered by the complexity of the information. Furthermore, the overreliance on a single source of climate information introduces the risk of maladaptation should this information be incorrect.

The larger literature review and the cross-country comparison revealed a number of challenges and areas where additional work is needed to enhance information production and uptake. Although interaction has been shown to consistently increase usability, there remains a need to overcome the constraints and disincentives that limit both the ability of scientists to engage with user communities and broker knowledge and that limit users' ability to engage with scientists. A particular challenge is overcoming the entrenched institutional roadblocks that can circumvent information uptake despite the establishment of successful information provisioning efforts between scientists and groups of users. Institutional change can be more difficult and much slower to occur, but finding ways to make even small gains in these areas (integrative, holistic strategies for interaction) can result in vast improvements in uptake when groups of users are targeted. Another critical need is to think beyond individual producer-user interactions, which are time-consuming and costly for both parties, to understand what is common and/or unique about the information users and their decision environments that would inform the aggregation of users into groups. Creating groups of users with similar information needs and decision contexts could aid producers in two important ways: (*a*) Increasing the efficiency of each interaction would help producers serve a broader range of users, and (*b*) guiding the range of potential strategies producers may choose to employ to those potentially more compatible with the target audience (once the characteristics of that target audience are known). Finally, rather than incremental improvements to existing ways we produce information, we may need systemic changes rendering new approaches capable of more effectively responding to higher levels of demand and a broader user base. Understanding how to improve usability for broad groups of users and scales of decision making is a reasonable first step.

SUMMARY POINTS

1. There has been a rapid evolution of increasingly complex science-policy models to help understand science-society interaction and to aid in understanding how to provide information to solve societal problems.
2. Despite this advancement and attention to problem solving, there is a persistent gap between production and use of scientific knowledge.
3. Much of the work to bridge the gap has focused on interactions between producers and individual users and their decision contexts.
4. We propose that to achieve more widespread uptake in information requires a shift in the way in which we approach information provisioning.

5. To advance more broad dissemination and use of information, we suggest there is a need to better understand users in the aggregate to increase the efficiency of interactions and to inform the strategies producers use to reach groups of potential users.

FUTURE ISSUES

1. Beyond understanding users in the aggregate, there is a need to overcome institutional constraints that limit information uptake in spite of the best efforts at information provisioning.
2. There is a need to explore how interactions between producers and users that have increased usability in the past can be more integrative, representing more of the users' decision contexts (e.g., institutions, regulators, etc.).
3. More in-depth ethnographic studies across a range of users are necessary to understand how science informs decision making and whether decision-making outcomes improve.
4. Deployment of experimental and quasi-experimental approaches is needed to understand how different interventions shape scientific knowledge uptake by environmental decision makers.
5. More empirical studies to explore the range of ongoing naturalistic experiments in climate information provisioning across the world could also critically contribute to the design of more effective science-policy interfaces.

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Narrowing the climate information usability gap

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Climate-change-related risks pose serious threats to the management of a wide range of social, economic and ecological systems. Managing these risks requires knowledge-intensive adaptive management and policy-making actively informed by scientific knowledge, especially climate science[1]. However, potentially useful climate information often goes unused[1,2]. This suggests a gap between what scientists understand as useful information and what users recognize as usable in their decision-making. We propose a dynamic conceptual model to address this gap and highlight strategies to move information from useful to usable to reduce climate-related risks.

Worldwide, the complexity of environmental problems and their increasing negative effects on social and ecological systems have heightened the stakes for research that both increases understanding and informs potential solutions. Climate change is perhaps the most important of these problems, with potentially unprecedented damaging impacts on a wide range of systems and sectors[3]. In this context, even if a lack of climate information has not necessarily precluded decision-making in this area (see, for example, refs 4,5), scholars from different fields have suggested the need for urgent policy responses and adaptive management grounded by science[1]. However, despite both the considerable amount of climate change research made available in the past thirty years[6] and evidence that decision-makers at the local and resource management level (for example, agriculture, water, disaster response and urban planning) are actively seeking to increase their climate information uptake[7,8], there is a persistent gap between knowledge production and use[1,2].

In this Review, we argue that to narrow this gap we need to delve deeper into understanding the processes and mechanisms that move information from what producers of climate information ('producers' henceforth) hope is useful, to what users of climate information ('users' henceforth) know can be applied in their decision-making. In his now classic study, Stokes[9] defined both use-inspired basic research (in which consideration of both use and advancing fundamental understanding are high) and applied research (in which consideration of use is high and advancing fundamental understanding low) as useful because they tend to users' needs. In our conceptualization, we revisit Stokes to argue, theoretically and practically, for a distinction between useful and usable information that reflects the different ways that producers and users perceive scientific information. Indeed, producers may make the assumption that knowledge is useful when they engage in research they think users need (in Stokes's sense), but because they do not completely understand or know potential users' decision-making processes and contexts, the knowledge produced remains 'on the shelf'. Users, in turn, may not know or may have unrealistic expectations of how knowledge fits their decision-making and choose to ignore it, despite its usefulness. We recognize that producers and users are far from homogeneous in the way that they produce and use climate information, and suggest that it is precisely these different perceptions and understandings of useful and usable[5] that create the usability gap reflected in the low level of climate information use in the real world. Indeed, although all forms of user-inspired knowledge are in principle useful, they are not always usable, unless users and producers take specific steps to make them so[10].

Many scholars have tackled the usability gap from different and overlapping perspectives[11–17]. Some have focused on the push and pull factors of science production and decision-making, and others have examined institutions and processes at different scales that foster or constrain scientific information use (for example, politics, national organization of research and development, public engagement, stakeholder participation and deliberation). Scholars have shown that the level of interaction — or co-production of science and decision-making — between information producers and information users critically affects the rate of climate information use[8,11,18–19]. A series of studies has focused on how different factors (organizational, cultural, institutional, political, cognitive, behavioural and so on) characterizing knowledge, and those who use it, influence climate information uptake in specific contexts[8,20–25]. In their influential article, Cash *et al.* argue that information is usable only if perceived by users as salient, credible and legitimate[26]. Others have shown how organizations and different forms of information communication and dissemination (for example, boundary organizations and knowledge systems) influence how science fails or succeeds in supporting decision-making[15,26,27]. For example, in advocating for a new form of climate adaptation science that influences decision-making, Meinke *et al.* emphasize the role of highly participatory, context-specific dialogues aided by modelling approaches that bring together producers and users of knowledge across disciplines, and define climate impact as one of many stressors shaping users' decisions[28]. Finally, research has also focused on the role of uncertainty in decision-making and on the negative effect of the highly politicized context of climate policy-making on the use and public value of climate science[29,30].

Although we recognize the strength of this rich literature in elucidating different aspects of the usability gap and build on its constructs to inform our own model, we contend that so far there has been relatively little effort to explain how perceptions, willingness and ability to use information change through time, and how a particular piece of information goes from being useful to usable. In our model, we focus on the factors and actions that change users, producers and the character of information to increase use. We argue that usability depends on three interconnected factors: users' perception of information fit; how new knowledge interplays with other kinds of knowledge that are currently used by users; and the level and quality of interaction between producers and users. We propose different strategies to narrow the usability gap, including varying levels of interaction, value-adding, customization, and retailing and wholesaling of existing knowledge to meet users' needs.

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Table 1 | Summary of opportunities and barriers that affect usability derived from the literature.

	Barriers identified in the literature		Opportunities identified in the literature	
Fit	Not accurate and reliable Not credible Not salient	Not timely Not useful; not usable Excessive uncertainty	Accurate and reliable Credible Salient	Timely Useful; usable
Interplay	Professional background Previous negative experience Value routine, established practices, local knowledge Low or no perceived risk Difficulty incorporating information	Insufficient technical capacity (for example lack of models) Culture of risk aversion Insufficient human or financial capacity Legal or similar Lack of discretion	Previous positive experience Threat of public outcry; public pressure Perception of climate vulnerability Sufficient human or technical capacity More flexible decision framework	Technocratic insulation Water scarcity In-house expertise Triggering event/crisis (drought, El Niño and so on) Organizational incentives Value research; information seeking
Interaction	Not legitimate One-way communication	Infrequent interaction End-user relationship	Legitimate Two-way communication Iterative	Trust Long-term relationship Co-production

Adapted from ref. 8 © Univ. of Michigan.

The promise of climate information

Much of what we know empirically about the use of climate information comes from the literature focusing on the application of seasonal climate forecasts (SCF) around the world. Although SCF deal with shorter temporal scales (climate variability), they have often been used as an analogue to understand information uptake and response to climate-driven effects, including climate change[5,31]. In this Review, we rely heavily on the well-developed literature examining the opportunities and constraints of SCF application (Table 1) to inform our model. We use the term climate information to refer both to SCF knowledge and to other kinds of climate-related information such as paleoclimate reconstructions and climate change projections, although empirical evaluation of their use is relatively scarce (but see ref. 8).

Regarding perception of fit and how it affects the application of climate information in decision-making, empirical research finds that different factors influence knowledge uptake and dissemination. First, users are more likely to deploy climate information products that they perceive to be accurate[32,33], credible[26], salient[11,25,26,33–35] and timely[11,33,34,36,37]. Usability is bolstered when users perceive climate information as useful to their decision-making needs[11,19,32,33,35,38,39]. Not surprisingly, decision-makers are less likely to use inaccurate, ill-timed information as well as that which they perceive to be lacking relevance or credibility[22,25,32,34,40–42].

Regarding interplay, problems emerge when current uses of different kinds of knowledge make the introduction of new ones difficult[22,23,39,43]. For example, Rayner *et al.* found that many US water resource managers resisted using new knowledge because of the perceived risk posed by deviating from more established knowledge use practices[43]. These managers feared that using climate information might expose them to undue criticism in case of negative outcomes. In the US southwest, Rice *et al.* found that customized climate information integrated into water system models went unused because users relied on more established routines and knowledge such as those embedded in environmental impact statements[22].

Institutions and organizational culture play critical roles in making interplay better or worse in different sectors[21,40,44–53]. For example, research found that organizations with more flexible decision-making frameworks are more likely to use information[54]. Having sufficient human or technical capacity in-house or access to external relevant expertise makes climate forecast use more likely[23,39,41], as does previous positive experience with innovation[41,55,56]. In contrast, for wealthy and poor nations alike, the lack of institutional capacity to respond to, for example, improved scientific predictions of stream flow and seasonal weather patterns, constrains information use[25,43,45,57]. Furthermore, a decision-making culture that views the use of climate information as a strategy to mitigate risk[8,19,22] rather than as a risky practice in itself[58] is more likely to promote integration of climate information in decision-making. External influences such as public pressure, the perception of vulnerability[41,59,60] or actual water scarcity[22] can help overcome resistance to using novel information. For instance, because of intense water-supply challenges, water resource managers in Australia perceived themselves to be at greater risk from not using available climate information than from using it[38]. They believed that many in their constituency would find it unacceptable "if a known risk to supply was ignored in earlier planning"(ref. 38). Finally, knowledge-seeking behaviour among potential users, valuing research, and organizational incentives also shape knowledge use[7,8]. Table 1 summarizes the opportunities and barriers that affect usability as a function of fit, interplay and interaction that are well documented in the literature (see also recently published reviews focusing on different areas of climate information application[10,17,46,48,61]).

Interaction and usability dynamics. How users obtain, receive and participate in the production of climate information affects decision-makers' willingness to use that information. Moreover, moving from production to use requires bridging gaps created by cognitive, emotional and behavioural influences that shape both public and private decisions. Empirical evidence from in-depth case studies shows that two-way communication and establishing an ongoing relationship are important to usability in many ways. First, they build trust between producers and users of information[8,11,33,41,43,49,59,62]. In turn, trust building and accountability modulate fit by influencing users' perceptions of information salience, credibility and legitimacy in particular decision contexts[8,12]. In the Pacific Northwest, because water resource managers have been able to follow the evolution of climate modelling over time, they trust the information and perceive the process as credible[8]. In some contexts, salience and interplay become more important in driving usability. For example, in a study of climate information use in the context of a boundary organization, it was found that credibility and trust were established quickly allowing interactions to focus primarily on improving information fit and promoting positive interplay[8].
Second, trust and two-way communication establish long-term relationships between producers and users, and promote better understanding of each others' contexts, needs and limitations[7,8,11,33,41,43,49]. In the Pacific Islands, ongoing collaboration between scientists and decision-makers facilitated the production of information tailored to user needs and operation context[12]. In the US southwest, scientist–stakeholder interactions played a significant role in building

capacity to use forecasts in decision-making, thereby enhancing information use[63]. These interactions and long-term relationships can critically accelerate dissemination of new knowledge through the many networks to which users belong[49].

Third, interaction can contribute to address barriers to climate information use such as levels of uncertainty and perceptions of accuracy and reliability. Here, interaction can help change users' minds by facilitating in-depth discussion of these issues and how they may affect decision-making, including potential trade-offs and risks[8,33,38,64,65]. For instance, better understanding of how climate information is produced and how it can be used for long-term drought planning critically increases usability[22]. Furthermore, White *et al.* found that explaining decision-making tools in more depth positively influences users' willingness to deploy them[66]. Finally, interaction may work to decrease mismatches between different forms of knowledge such as tacit (knowledge that is unarticulated and tied to senses, movement skills, physical experiences, intuition and implicit rules of thumb), and explicit (knowledge uttered and captured in writings and drawings)[67]. When the two kinds of knowledge are at odds, fit may become a problem, as in the case when explicit knowledge is rejected because it does not match expectations from users informed by their tacit knowledge. Here, interaction between users and producers may help to bring these two knowledge types closer together. For example, in the US southwest case described above, interaction around climate knowledge and long-term drought planning (explicit knowledge) brings scientists and managers closer together, allowing for better understanding of their specific jobs and of their experience[20], way of thinking, and intuitions (tacit knowledge). And because most people use a combination of tacit and explicit knowledge in their day-to-day decision-making, iteration coupled with reinforcing feedback loops as they get to know each other better may help ensure that these forms of knowledge synergize in positive rather than negative ways.

A conceptual model for usability

Drawing on the literature as a foundation, we propose a dynamic conceptual model to understand the path between usefulness and usability. The production and use of information in the model is akin to a market place where all available information is potentially useful as produced (hence where usefulness is a necessary but not sufficient condition), but will only be usable as users 'pick it,' that is, as users effectively incorporate specific information into a decision process. At each point in the range, information can go from useful to usable as it is translated, communicated and/or transformed to approach users' perceived needs. However, the point in the range where this transformation happens is not the same for all users, decisions, types of information or information production processes.

In our model, rather than operating independently, fit, interplay and interaction critically shape each other to increase or constrain usability of climate information. Hence fit, or the way users perceive their information needs and their ability to deploy knowledge, influences their willingness to use information. How users obtain information (for example, forms of communication, accessibility and format) and information characteristics — such as levels of uncertainty, reliability and accuracy — in turn influence users' perception of fit. However, fit is not static. Many factors and processes shape how perceptions of fit emerge and evolve: (1) new leadership or organizational shifts, focal events (for example, a crisis or unprecedented extreme event) or active learning through formal or informal interactions within a group or a network may alter how users perceive information fit; (2) improved formatting, better translation and communication of information and trust built through interaction can also change how users perceive and evaluate climate information; and (3) by interacting with producers, users may improve their understanding of how different kinds of knowledge fit their decision process in ways that they would not have imagined before.

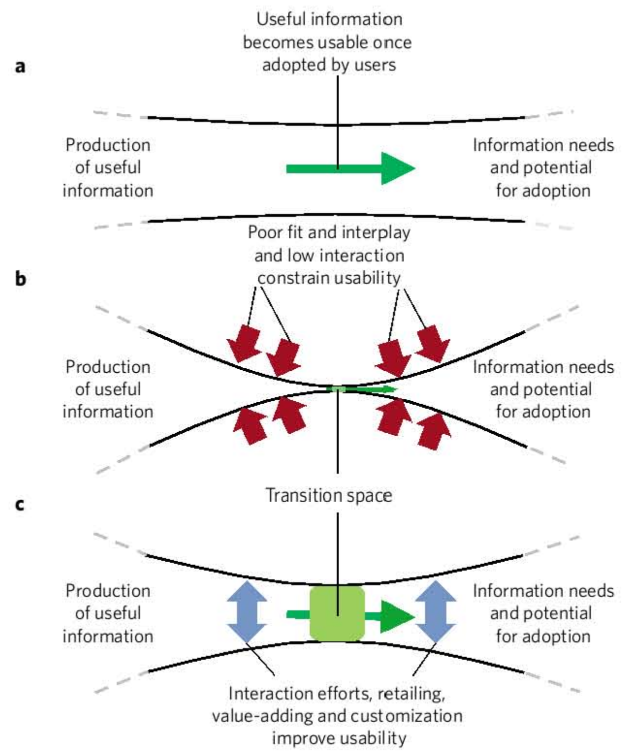

Figure 1 | The conceptual model. a, In principle, information moves from useful to usable by being deployed by users in decision-making. **b**, From a producers' perspective all information produced is potentially useful; information needs, fit, interplay and lack of interaction may restrict usability constraining the amount of information that moves from useful to usable. **c**, Interaction, retailing, customization and value-adding improve fit and interplay by changing users and producers' perceptions both of the information and the character of the information itself, widening the transition space and pushing information from useful to usable.

Second, the model accounts for interplay between new information and information already routinely used in decision-making. Users' behaviour, past experiences and culture influence interplay[8,20,56,68,69]. On the one hand, existing established routines, the way people access information, and the way they perceive risk may create path dependencies that make seeking and deploying new information harder[43]. Interplay may be particularly critical in cases where users build their professional identity around established practices and where users are particularly vulnerable to public accountability processes[56]. On the other hand, interplay can be positive when new knowledge complements and creates positive synergies with old knowledge, adding value to the whole decision-making process.

Third, as mentioned in many of the examples above, usability depends on the level and quality of interaction between information producers and users. In the model, interaction acts in two ways: as an independent variable when trust building in the process of knowledge generation improves usability, or as a moderating variable when interaction alters perceptions of fit or affects interplay. For example, through interaction users may better understand the current limitations of modelling efforts or the level of uncertainty germane to these efforts[5,29]. Producers may also improve their understanding of how different pieces of knowledge may be better employed in different decision environments (for example, improving users' access to specific kinds of data or information) or get a better feeling of the type and format of information users prefer in the context of specific decisions[7,8,66]. In this interactive context, climate information is tailored (formatted, translated and communicated) to meet specific user needs at the same time that trust building and accountability between producers and users is improving perceptions of information salience, credibility and legitimacy[12,70]. Here, interaction benefits usability not only by modulating fit as participants 'talk' and exchange explicit knowledge but also when their collective experience (tacit knowledge) positively influences the process of knowledge production and use[11]. Figure 1 depicts the conceptual model.

Strategies to improve usability. Now, we consider different strategies that narrow the gap between information production and use. We know from the literature that iterativity and co-production models of science production and use effectively increase usability, but are costly in terms of human, financial and technical resources, and are difficult to sustain in the long term without specific financial and institutional resources and incentives[11]. Creating boundary organizations that translate, mediate and communicate information into more useful and usable forms partly ameliorates these constraints[26,27,71–73]. Highly iterative modes of knowledge production are also limited in their ability to reach a large audience because of the disparity in size between the knowledge producer and user communities. To enhance reach and rates of adoption beyond these intense and dedicated producer–user relationships, innovation theory suggests creating systems of interacting actors/organizations (for example, private and public firms, universities and government agencies) that initiate, modify, import and diffuse science and technology[74]. This requires creating linkages (for example, joint research and personnel exchanges) between actors to support knowledge creation and technological innovation, and also maintaining flows of financial, legal, technological and scientific support to facilitate use and diffusion of those advancements. Alternatively, identifying the paths of information flow and institutional elements through which knowledge production, innovation and use occurs, and developing cross-chain interactions between them, creates synergies amongst old and new knowledge[75]. In either case, usability improves by structuring a knowledge production environment interconnected with and sustained by financial, legal, technical and information flows.

We know from cognitive research that the way users process information, analytically or experientially, is important to their understanding and use of that information[69]. For example, relating new information to ensembles of relevant past experience and statistical constructs taps into an individual's analytical processing. On the other hand, relating new information to personal or others' experiences and memories engages one's experiential processing. Attending to these two kinds of processing equally during producer–user interactions improves communication of information, highlight relevant personal experience, elicit affective responses, and provide contextual meaning[20,69] to information, thereby fostering usability.

Value-adding. Adding value to available information to better meet users' needs can positively influence usability[76]. In the context of information systems, value-adding refers to formal processes through which producers enhance the usefulness of a specific message[77]. In this case, producers, through a process of selection and analysis, convert data to information that can inform and educate users (that is, informed knowledge). In turn, synthesis and evaluation transform informed knowledge to decision-oriented (that is, productive) knowledge. For example, producers might add crop insurance data and planting and harvest patterns to climate information (that is, downscaled climate change impacts information and SCF), therefore increasing the advantages and value of using climate information for agricultural production or disaster prevention efforts. One disadvantage of value-adding, especially in traditional new-product-development processes, is the prohibitive costs for catering to 'markets of one'. To mitigate this challenge, von Hippel and Katz suggest deploying 'tool-kits' for user-driven innovation in situations where coordinated sets of 'end-user friendly' design tools enable users to develop need-related, low-cost product innovations for themselves[78]. Thus, climate knowledge producers can cater to heterogeneous users by producing science products that can be easily understood and customized by users themselves through toolkits tailored to specific sectors. However, the enabling institutional conditions and costs that make either of these mechanisms functional need further research[78].

Retailing, wholesaling and customization. In a knowledge producer–user context, retailing and wholesaling refers to supplying a subset of the original climate information products (for example, climate change model outputs and SCF) to groups of users with similar information requirements in a manner that is easily taken up by the end user. Whereas retailing serves users with individualized decision-making processes at a more localized scale (for example, farmers and water managers), wholesaling serves users at a broader scale who themselves influence other potential information users (for example, water or agriculture agencies and interest groups). Both strategies require that knowledge producers (or brokers) understand user information needs and how to appropriately package, contextualize and communicate subsets of existing information in an easy, user-friendly manner. In climate information systems, retailing and wholesaling could have significant advantages over one-size-fits-all climate information provision efforts, given not all climate information produced is usable to everyone. Examples of retailing climate information are evident in SCF application, where boundary organizations, traditional agricultural extension agencies, and urban planning agencies provide subsets of information based on user needs. For example, in Victoria, Australia, the Department of Primary Industries provides climate change and seasonal risk information via training programmes, conferences, and steering groups to help farm foresters manage climate risks. In these examples, retailing helps cater to the needs of multiple users, moderate perceptions of poor fit (for example, lack of salience), and increase participation of users in climate information uptake[79].

Lastly, customization refers to adjustments to meet an individual user's needs made at the end of the knowledge production process. Framing uncertainties of generic climate information such as 'percent chance of an event occurring (or not occurring)' is an example of customizing climate information to probability of events. This customization generates information more usable for decision-making such as influencing budgetary decisions or helping risk managers to conduct rapid assessments[80]. Taken together, these transforming strategies (interaction, value-adding, retailing, wholesaling and customization) act in the model to expand the amount of useful information that becomes usable in decision-making (Fig. 1c).

Conclusions and limitations

Climate-related risks pose serious threats to our social and ecological systems. As climate change is prioritized in societal and political agendas, we can reasonably expect that the need and demand for climate information will grow. However, the application of climate information in decision-making is neither easy nor straightforward. Some information is picked up easily and integrated into decision-making processes whereas other information — in principle useful information — does not make it into decision-making. In this Review, we identified and summarized the myriad factors influencing usability including institutional and organizational factors and individuals' perceptions, cognition, beliefs, values and experiences. Additionally, we highlight the critical role of interaction between producers and users in helping to overcome barriers to usability. In this model, usability depends on three interconnected factors: fit, interplay and interaction. By describing how information moves from useful to usable, the model helps to identify concrete actions that can improve usability such as varying levels of interaction, customization, value-adding, retailing and wholesaling.

Although improving fit and interplay through interaction has great potential to increase the usability of climate information, especially at the local and resource-management levels, there are limitations to the implementation of the model and other challenges that need to be addressed in future research. One challenge is the critical mismatch between the size of the producer and user communities. If the demand for climate information grows, that demand could critically outstrip the ability of producers to establish highly interactive relationships to increase usability. Producers can address this mismatch both by establishing remote relationships that learn from face-to-face ones and by increasingly relying on boundary organizations and objects to disseminate information. For example, the creation of highly interactive web-based mechanisms (for example, tool-kits) can potentially emulate some of the more desirable aspects of face-to-face interaction allowing for relatively high levels of customization and value-adding. Also, through boundary organizations, producers can both learn about overlapping needs and contextual constraints that different classes of users face using climate knowledge and enhance the range of products being offered (for example, retailing and wholesaling) to facilitate more widespread dissemination and uptake of information.

Another challenge is that whereas high levels of iteration critically influence usability, in practice, human, organizational and material limitations constrain both sides of the science–policy interface. For science production, the evidence suggests that we must rethink the ways in which we design and promote use-inspired basic and applied research programmes if we aim to produce usable climate information to meet societal risk and adaptive management needs. For users of climate information, it suggests the need for policy change to increase the range of incentives for the use of climate information and the need to build and sustain capacity for facilitating use.

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Author contributions

All authors contributed extensively to the work presented in this paper.

Additional information

The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to M.C.L.

Countering the Loading-Dock Approach to Linking Science and Decision Making: Comparative Analysis of El Nino/Sout....

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Countering the Loading-Dock Approach to Linking Science and Decision Making

Comparative Analysis of El Niño/Southern Oscillation (ENSO) Forecasting Systems

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This article provides a comparative institutional analysis between El Niño/Southern Oscillation (ENSO) forecasting systems in the Pacific and southern Africa with a focus on how scientific information is connected to the decision-making process. With billions of dollars in infrastructure and private property and human health and well-being at risk during ENSO events, forecasting systems have begun to be embraced by managers and firms at multiple levels. The study suggests that such systems need to consciously support the coproduction of knowledge. A critical component of such coproduction seems to be managing the boundaries between science and policy and across disciplines, scale, and knowledges to create information that is salient, credible, and legitimate to multiple audiences. This research suggests institutional

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mechanisms that appear to be useful in managing such boundaries, including mechanisms for structuring convening, translation, collaboration, and mediation functions.

Keywords: *science policy; boundary organization; coproduction; climate forecasting; institutions*

In the last twenty years, El Niño/Southern Oscillation (ENSO) events have risen from relative obscurity to phenomena that routinely command local to national attention. Their effects influence societies around the globe and spawn a range of natural disasters, changes in resource availability, and even political upheavals (Glantz 2003). As ENSO becomes better understood, scientists and policy makers have seen an enormous potential for using forecasts of ENSO events and their associated effects to assist emergency preparedness, agriculture, tourism, water management, fisheries, and energy sectors at international through local levels (National Research Council 1999). From regional planning bodies to national ministries to multinational firms to individual farmers, many actors already have used ENSO forecasts. Yet, such use is sporadic at best and there is growing demand for more effective use of scientific and technical information.

Such demand is part of a chorus of calls that science and technology (S&T) should play an increasingly central role not only in predicting climatic events but in the more general goal of meeting human-development needs while protecting the Earth's life-support systems (Cash et al. 2003; Kates et al. 2001; Lubchenco 1998; United Nations Educational, Scientific, and Cultural Organization 2000; United Nations 2002; World Bank 1999). These calls are balanced, however, by concerns that S&T-driven policy without connection to culture, ethics, and place can lead to more problems than it solves (Lansing 1991). Thus, one of the current central challenges is to better link S&T and decision making in ways that are more socially embedded and that attempt to better balance economic, cultural, and social needs. At the same time that there is this increasing demand that S&T should be better linked to decision making, there is little systematic understanding of what kinds of institutions can effectively achieve this (International Council for Science 2002). This article addresses these shortcomings by contributing to a nascent and growing body of research and practice that asks the following question: How can systems of research, observation, assessment, and decision support be better designed to address the complex and difficult challenges of sustainable development?

In this article, we hope to improve that understanding. Specifically, we seek to explore how institutional factors promote or constrain the production and use of ENSO forecasts both to improve ENSO forecasting itself and to illuminate the more general question of how to improve decision making through the better use of existing knowledge and technology related to the environment and Earth-society systems. To accomplish this, we trace the varied use of ENSO forecasts to the structure and functioning of the institutions and organizations that link scientific knowledge with individual, social, and political decision making. We study and compare two cases: ENSO forecasting in the Pacific Islands, mainly due to the efforts of the Pacific ENSO Applications Center (PEAC), and ENSO forecasting in southern Africa, centered on a number of institutions affiliated with the Southern African Development Community (SADC).

Situating our analysis in an emerging framework wrought from multiple disciplines, we outline and discuss this framework in the second section. The third section provides a brief description of the cases. The fourth and fifth sections present a comparative analysis of the two cases. The last section comprises a discussion of the implications of our findings both for theory and for practice.

Theoretical Framework: Coproduction across Boundaries between Science and Action

Earlier work on the determinants of effective scientific advice for policy has established several heretofore unconnected building blocks from which we draw a framework of analysis. Central to this framework are three interacting concepts. First, S&T systems are characterized by multiple boundaries—between science and policy, between disciplines, across organizational levels, between the public and private sectors, and between knowledges (Gieryn 1995; Jasanoff 1987). A fundamental challenge in S&T systems is to manage these boundaries, taking advantage of their benefits (e.g., protecting scientists from accusation of political bias) while minimizing their inefficiencies (e.g., producing knowledge that is irrelevant to decision making) (Cash 2001; Gieryn 1995; Guston 2001; Jasanoff 1987).

Second, countering the notion that technocratic solutions in which experts should be isolated from decision makers has been the concept of coproduction—the act of producing information or technology through the collaboration of scientists and engineers and nonscientists, who incorporate values and criteria from both communities (Guston 1999; Jasanoff and Wynne 1998).

This is seen, for example, in the collaboration of scientists and users in producing models, maps, forecast products, or other outputs that are valued by the researcher (e.g., they push their field forward, gain them status, satisfy curiosity, can be published, etc.) and the decision maker (e.g., they help solve a problem, chart potential options, protect the decision maker politically, etc.).

Third, research and practice suggest that S&T information is likely to be effective in influencing decision making to the extent that it is perceived by relevant stakeholders to be not only scientifically credible but also salient and legitimate (Andrews 2002; Clark et al. in review; Funtowicz and Ravetz 1993; Lindblom 1990; Wildavsky 1987). A critical challenge for S&T systems is to maintain threshold levels of salience, credibility, and legitimacy while managing tradeoffs between them. For example, attempts to increase one often decrease another, as in cases where public participation increases the salience of research to decision makers while decreasing the credibility of the information to peers in the sciences. Ideas about salience, credibility, and legitimacy are closely linked to concepts about producing socially robust knowledge that is not produced in a social vacuum but within the social and political milieu in which it is going to be used (Broad and Agrawala 2000; Gibbons 1999).

Critical to this framework, and what is innovative in our approach, is understanding the interaction of these three concepts and integrating them—how to manage boundaries to maintain salience, credibility, and legitimacy for audiences on different sides of boundaries so that socially useful knowledge can be produced and used (Cash et al. in review).

One of the effective approaches for resolving such tensions within S&T systems builds on the notion, identified by scholars of social studies of science, of boundary organizations: organizations that play an intermediary role between different arenas (Cash 2001; Clark et al. 2002; Guston 2001). Whether formalized in organizations specifically designed to act as intermediaries or present in organizations with broader roles and responsibilities, several institutional functions seem to stand out as characteristic of systems that effectively harness science and technology for sustainability by ensuring salience, credibility, and legitimacy across boundaries. These include (1) convening; (2) translation; (3) collaboration, especially to assure the coproduction and use of boundary objects; and (4) mediation. These four functions interact but should not be seen as hierarchical nor their implementation as linear. That is, systems do not start convening and then move to translation and so on. They appear in different mixes in different systems. One goal of this research is to test to what degree the existence of these features leads to effectiveness in linking science to decision making, what institutional mechanisms support these functions, and how these functions influence the salience, credibility, and legitimacy of information.

Four Critical Functions

Convening connotes the process of bringing parties together for face-to-face contact. This is hypothesized to be an important function, as it forms the background for relationships of trust and mutual respect. Convening also can provide the foundation for providing the three other functions outlined below. In studying this function, we sought information on how and in what contexts actors from different spheres were brought together.

Translation can be literal, as when information providers speak one language and users another. This is often the case in developing-country contexts in which the government operates in the language of the former colonial power and the users speak tribal languages or in which scientific outputs derived from United States or European sources are generally in English and users speak other languages. Translation also can be metaphorical, as when the actors on different sides of a boundary rely on such different core sets of assumptions that they cannot understand what the other is saying even when speaking the same literal language (Dryzek 1997). Boundaries often separate worlds defined by different jargon, causal maps, experiences, and presumptions about what constitutes salience, credibility, and legitimacy. For example, academic researchers often are accused of relying on jargon in their communication with actors outside academia. Moreover, each discipline within academia is steeped in its own jargon. From the outside, jargon is isolating and alienating, yet within a discipline, jargon makes for efficient language use and allows a crispness of definition that assures that everyone inside understands what is being discussed. To understand this variable, we investigated the mechanisms for translating information across boundaries and the relative effectiveness of different mechanisms.

Collaboration is a function that brings actors together in an effort—by different experts or experts and decision makers—to coproduce applied knowledge (e.g., models, forecasts, and assessment reports). Such efforts are manifest in analyses, research and development (R&D), or assessments that are interdisciplinary, cut across multiple levels, or involve multiple different perspectives along the continuum of expert to decision maker. One class of collaboration produces what have been termed boundary objects in the social studies of science literature and are closely linked with the idea of coproduction. Boundary objects are outputs that "are both adaptable to different viewpoints and robust enough to maintain identity across them" (Star and Griesemer 1989, 387). Different actors collaborating in the coproduction of outputs receive different benefits from the collaboration: information useful for a decision maker or research that is publishable for a scientist. Institutions that can support collaboration increase the likelihood that useful, robust, and credible information will be produced (Gibbons 1999). In investigating collaboration, we looked for evidence of mechanisms used by organizations to support, encourage, and facilitate collaboration across multiple boundaries.

Mediation is a process by which different interests are represented and evaluated so that mutual gains can be crafted and value created in a way that leads to perceptions of fairness and procedural justice by multiple parties (Andrews 2002; Susskind 2000). Often, it is not disagreement over fact but over goals that drives conflict, and resolution can only be achieved through mediation and negotiation rather than more information or better understanding (Ozawa and Susskind 1985). Mobilizing science and technology for sustainability often requires active mediation of those conflicts (Andrews 2002; Jasanoff 1987; Ozawa and Susskind 1985). If it is agreed that the construction of knowledge takes place in a social and political context and that such a context is characterized by multiple boundaries, mediation might have a central place in the dynamic of producing policy-relevant information. This reasoning was used in the structure and activities of the World Commission on Dams, an assessment effort that explicitly designed its process around professional mediation and facilitation exactly because it was addressing issues that were characterized by conflict and polarized perspectives (Khagram 2003). In studying mediation, we investigated institutional mechanisms that supported conscious acknowledgement and addressing of differences, conflict resolution activities, and third-party involvement in settling or avoiding disputes within the S&T system.

Understanding these four functions and their relationship to managing boundaries and producing salient, credible, and legitimate information provides a framework from which we can begin exploring ideas about how systems of research, observation, assessment, and decision support can be better designed to address the complex and difficult challenges of sustainable development. Toward this end, we undertook a comparative analysis of two systems of ENSO forecasting, one in the central Pacific Ocean and one in southern Africa. That research is described in the remainder of this article.

Case Studies

Methods

Data for the study were collected from extended, semistructured telephone interviews with fifteen climate experts and forecast users in the Pacific and southern Africa. The interviewees were chosen for the range of perspectives they could provide on the development and implementation of climate forecasts. The sample included key actors in regional ENSO forecasting centers, such as the Pacific ENSO Applications Center (PEAC) in the Pacific and the Drought Monitoring Centre in Zimbabwe, as well as users of those forecasts, such as emergency managers in the Pacific Islands and farmers in southern Africa.

The interviews were divided into several sections, each containing a number of lead questions on a topic followed by probes designed to help clarify, deepen, and/or broaden the discussion. The interviewees were asked to describe their organization and their position in it; the critical challenges facing their organization; the structure of the climate-information network as they see it; the salience, credibility, and legitimacy of the forecast information provided by or used by their organization; and what they believed contributed to salience, credibility, and legitimacy. Although all topics were covered in some depth in each interview, the interviews were not rigidly conducted; the interviewees were encouraged to discuss whatever issues they found most important. The interviews were conducted between December 2001 and August 2002, and the average length of an interview was one hour.[1]

In addition to the semistructured interviews and informal personal communications, we obtained data on each system through examination both of peer-reviewed published materials and of gray literature (e.g., agency reports, workshop proceedings, etc.) as well as material from Web sites.[2]

As noted below, the two case studies are not perfectly comparable because of vast differences in the regions, but we are able to glean qualitative lessons from examining differences between them.

The Cases

As documented widely in the last twenty years, ENSO events produce a wide range of social, economic, and environmental effects (Betsill, Glantz, and Crandall 1997; Glantz 2000; Glantz 2001; National Research Council

1999). Societies around the globe feel the effects across numerous sectors: agriculture and food security, fisheries, diseases, human settlement disruption, and aberrations from typical storm activity.

While many societies have had long traditions of using a variety of different indicators to predict the weather associated with ENSO events (Orlove, Chiang, and Cane 2000), it is only since the mid-1970s that scientists have devoted significant resources to understanding and predicting ENSO. As ENSO appeared both on scientific and policy agendas, multiple regional efforts began to link the emerging forecasting capabilities to on-the-ground decision making. Numerous organizations, such as the United States National Oceanic and Atmospheric Administration (NOAA), the International Research Institute for Climate Prediction at Columbia University's Lamont Doherty Earth Observatory (IRI), the United States National Center for Atmospheric Research (NCAR), the United Kingdom's Hadley Centre for Climate Prediction and Research, Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO), and the World Meteorological Organization (WMO), have dedicated research funding to understanding ENSO. They have invested in understanding the complex ocean-atmosphere dynamics that underlie ENSO events and their social and environmental effects, building tools that can predict the onset and severity of ENSO events, integrating traditional methods of climate forecasting, and discovering and implementing ways of making predictions useful to decision makers at multiple levels and for multiple sectors.

A growing body of literature has examined the effects of forecasting on responses to ENSO events. For example, Betsill, Glantz, and Crandall (1997) examined the 1991–92 ENSO event in southern Africa, analyzing the potential cost savings from receiving earlier forecasts. The work also highlighted several of the cross-scale problems with the 1991–92 forecasts, such as only informing high-level bureaucrats of the impending event with few mechanisms for disseminating information to lower levels (i.e., to farmers through the agricultural-extension system).

Several researchers have examined the particular difficulties of applying uncertain and imperfect information about complex causal phenomena. Barrett (1998), for example, identified the critical importance and the difficulties of linking the forecast of the climate event with forecasts of effects that matter to decision makers on the ground. In Australia, Hammer and his colleagues (2001) outlined the importance of interdisciplinary approaches that stress learning and the usefulness of simulations.

Orlove and Tosteson (1999) analyzed ENSO forecasting and application in five countries, including Zimbabwe. They concluded that measures to link national and regional forecasting systems to international systems "indicate a rapid (if late, relative to other cases) coevolution of information and institutions that have made the climate more favorable for application of ENSO forecasts in Zimbabwe. However, greater efforts must be made to assure closer articulation with end-users" (43). A team of researchers from Norway's Center for International Climate and Environmental Research came to similar conclusions about the connection to potential forecast users in Zimbabwe, finding both a lack of broad dissemination of forecasts and a need to improve the capacity of farmers to use the forecasts to adapt to predicted climate variability (O'Brien et al. 2000). Further investigating the challenge of linking forecasts to users, Patt and Gwata (2002) examined credibility, legitimacy, and institutional constraints that limit forecast use, suggesting the importance of participatory forecast development and iterated trust-building communication between forecasters and users (see also Patt 2001). Exploring constraints as well through in-depth survey techniques, Phillips and her colleagues (2001) cite not only gaps in credibility between indigenous forms of knowledge and new forms produced by the emerging climate-science community but also constraints on credit, seed availability, and other factors that make even credible forecasts less salient (Hammer et al. 2001).

Several recent studies have examined the distributional effects of forecasting. Broad, Pfaff, and Glantz (2002), for example, found that different interest groups (e.g., industrial fisheries and artisanal fisheries) had differential access to recent ENSO forecasts resulting in heterogeneous distribution of benefits and costs (see also Broad 2000; Broad and Agrawala 2000). Finally, NOAA, a central funder of climate-forecasting activities, has undertaken a variety of self-evaluations (International Research Institute for Climate Prediction 2000) that describe the building and maintaining of a growing network of climate forecasters, scientists, and stakeholders, while at the same time acknowledging the need to more systematically understand the institutional dimensions of linking forecasts to decision making:

> The full potential of evolving climate forecast capabilities will be realized only when climate forecasts are routinely and systematically applied to practical problems in multiple sectors, both public and private, and at different levels, from local to international. The mere existence of forecasts does not necessarily translate into effective adjustment actions until decision makers have determined how early-warning information can best be incorporated into the context of their requirements. Equally, developers of forecast systems need to be informed by users of these requirements, including optimal methods

> from the user perspective for providing and presenting information. (Buizer, Foster, and Lund 2000, 2137)

The research examining the use of seasonal climate forecasts has come to resemble the findings in two other related areas as well: communicating information about health and safety risks and technology transfer. The field of risk communication developed out of the experience of governments trying to persuade people to engage in lower-risk types of behavior, such as wearing seatbelts while driving, or to accept new technologies that were perceived as particularly dangerous, such as nuclear power (Wynne 1996). Formal risk analysis often produced robust estimates of the differential safety of different technologies and behavior patterns, and policy makers initially believed that people would react to that information, changing their behavior accordingly as soon as they learned the numbers (Leiss 1996). To the dismay of economists, who propounded solutions to risk problems that relied on people's own preferences and values, the simple provision of risk information proved inadequate (Zeckhauser and Viscusi 1996). The maturation of the risk-communication field saw first the use of carefully tailored messages to try to convince people of the accuracy of the risk estimates and eventually the recognition of the need to treat the information users as partners in the process of developing appropriate responses within an appropriate institutional framework (Fischhoff 1995). The information users need to understand is not only the basic risk numbers but also the process through which they were generated, to the point where they can evaluate the numbers critically and selectively apply them to their lives.

The study of technology transfer has undergone a similar evolution. As Agrawala and Broad (2002) discuss, the literature reveals a series of four conceptual models describing how technology moves from its development to its use. The appropriability model assumes that technology that is useful and appropriate will sell itself with little need for producer push to transfer it to a new context. The dissemination model provides a caveat that the technology developers will need to spread information but that once users learn of the new technology, they will take it up. The knowledge-utilization model requires not merely the dissemination of the information but the demonstration of its effectiveness. Finally, the contextual-adaptation model recognizes that new technologies are not adopted as if they were ready-to-wear fashion but rather sewn, in bits and pieces, into the fabric of the users' social setting and existing practices. According to this last model, effective technology transfer requires users to understand the new technology not simply to the point of being able to take it out of the box and turn it on but rather to the point of being able to take it apart, put it back together slightly differently, and fix it when it breaks. Achieving that level of understanding requires a sustained relationship between producers and users.

The many studies of forecast communication and use have begun to show that the information they convey both resembles risk information for which participatory communication (coproduction) is necessary and constitutes a new technology to be transferred, which again requires a sustained dialogue.

Our research builds on these studies, illuminating some of the institutional mechanisms that address some of the constraints and challenges that other researchers have identified. We further try to understand the robust finding across these different research efforts that even in cases where the science is right, decision makers do not listen or change behavior. Our work contributes to this growing body by outlining the conceptual connections between boundaries, salience, credibility, and legitimacy and the importance of mechanisms that foster coproduction. To do so, we turn our attention to our case studies.

We examined two regional systems that are particularly amenable to comparison: the ENSO research and applications system in the central Pacific Ocean, encompassing Hawaii and the United States–affiliated island states, and the ENSO forecasting system in southern Africa. Both systems began maturing at approximately the same time, after the 1992–93 ENSO event. Both receive funding and technical support from NOAA and other international organizations, and both attempt to link science originating in developed countries with decision making in developing countries. While similar in these dimensions, both systems also vary in a number of important institutional dimensions, thus allowing us to compare how institutional factors might contribute to effectiveness at linking science and decision making. Naturally, in systems as complex as these, there are also differences in the two systems that we cannot control and that are unrelated to the institutional dimensions we investigate. Political dynamics, inherently different levels of signal-to-noise ratio in the two settings (stronger ENSO signals and teleconnections in the Pacific versus southern Africa), and general level of development differ in our two cases. At the end of the article, we discuss how these differences influence our conclusions.

Pacific ENSO Applications Center

In the early 1990s, the Office of Global Programs (OGP) at NOAA began to explore the utility of new forecasts for coastal-zone managers on

Hawaii and the United States–affiliated Pacific Islands (USAPI).[3] With OGP funding, a partnership between OGP, the Social Science Research Institute at the University of Hawaii, and the Pacific Basin Development Council (PBDC—a regional association of the USAPI governments) held a scoping meeting early in 1992. Organized and driven by actors representing the continuum from climate research, social-science research, and potential users of climate forecasts, the meeting brought together a range of perspectives to describe the current state of the science, but more importantly, to ask the following question: How should forecasts be produced so that they might be useful to managers in the region? This scoping work led to the birth, in 1994, of the Pacific ENSO Applications Center (PEAC).[4] In addition to the original partners, PEAC included the participation of the NOAA National Weather Service/Pacific Region (NWS/PR), the University of Hawaii/School of Ocean and Earth Science and Technology (UH/SOEST), and the University of Guam/Water and Energy Research Institute (UOG/WERI).[5] PEAC's mission is to conduct research and forecasting for the benefit of the USAPI and the islands' various economic, environmental, and human-services sectors.

The Southern African Drought Monitoring Centre

In 1991–92, southern Africa experienced a severe drought with wide-ranging effects on food production and availability and direct effects on the livelihoods of over 100 million people in the region. At the time, regional ENSO forecasting was in its infancy, and while several forecasts were produced through the National Weather Service/Climate Prediction Center (NWS/CPC) and Australia's Bureau of Meteorology, they had little effect on food security, agriculture, and drought-preparedness activities (Betsill, Glantz, and Crandall 1997). With both the experience of the 1991–92 event and the improving skill of regional ENSO forecasting, NOAA, WMO, regional decision makers, and scientists began structuring an ENSO forecasting system that could better take advantage of the emerging science. The Southern African Development Community (SADC), an already existing regional economic-development association of southern African states, took the lead in organizing such a system in partnership with NOAA, WMO, USAID, the World Bank, and the National Meteorological Services (NMSs) of member countries.[6] One of the principal new organizations that originated from this partnership was the SADC Drought Monitoring Centre (DMC),[7] supported by the United Nations Development Program (UNDP) and WMO and housed in Harare, Zimbabwe. Like PEAC, the DMC has helped shape the

ENSO forecasting system in the region, has collaborated with existing institutions and built new institutions, and has structured relationships between a diverse set of actors and organizations. These include those noted above and the IRI, United Kingdom Meteorological Office (UKMO), SADC's Regional Early Warning Unit (REWU), Regional Remote Sensing Unit (RRSU), and the Famine Early Warning Systems Network (FEWS-NET).

A Comparison of Boundary Functions

Although in a number of dimensions the Pacific and southern African systems are similar, their institutional structures and activities differ enough to allow systematic comparisons of characteristics that contribute to their effectiveness. In this section, we outline how the four different functions—convening, translation, collaboration, and mediation—are manifested differently in the two cases.

Convening

In the PEAC case, scientists, forecasters, and decision makers (for example, representatives of all the governors of the USAPI, water managers, fisheries managers, emergency management, and representatives from many state, federal, and island agencies) met regularly at the beginning of the process. Such broad collaborative participation galvanized an iterative process that fostered periodic evaluation of the needs of the users of forecasts and the capabilities of the climate scientists and forecasters. Using NOAA funds, PEAC played the central role as convener, institutionalizing participation of multiple players in such a way as to take advantage of critical expertise at critical times. At PEAC scoping meetings, crossing boundaries between scientists, forecasters, and decision makers was achieved by bringing key actors representing those groups together as joint collaborators in designing the scope of an ENSO research and applications system in the Pacific. PEAC thus presents an innovative vision of how to convene stakeholders: rather than have the stakeholders outside of PEAC and invite them to the table when issues arise, include them within the PEAC planning process from the very beginning. Other stakeholders, as they became interested in PEAC, also were invited to join. In traditional stakeholder practices, the boundary organization reaches out to obtain the input from people on both sides of the relevant boundaries. In PEAC, by contrast, those people were part of the boundary organization itself, with a role in making decisions about how it would function. PEAC was the funded institutional setting in which climate scientists, meteorologists, hydrologists, epidemiologists, and economists collaborated on research and forecasting outputs that captured the important uncertainties and dynamics of ENSO events.

This feature of PEAC—that it convened through inclusion in the organization rather than simply inviting others to the table—also highlights how its accountability was divided among several communities. PEAC was accountable, for example, to its funder, NOAA, through contractual arrangements and the granting process. Funds could have been withdrawn or additional funding denied if PEAC did not perform in accordance with its obligations. On the other side of the boundary are the decision makers—agency bureaucrats, technicians, and elected officials—all actors who could have withdrawn from their relationship with PEAC. Such dual accountability arrangements forced PEAC to address the interests, concerns, and perspectives of actors on both sides of the boundary, thus increasing salience, credibility, and legitimacy.

In southern Africa, the SADC's DMC is itself a small organization, working in the building compound of the Zimbabwe Department of Meteorological Services. Like PEAC, the DMC organizes events in which the convening function takes place. The most important of these events is the biannual Southern African Regional Climate Outlook Forum (SARCOF). Coordinated by the DMC in collaboration with NOAA, IRI, WMO, and the RRSU, SARCOF brings together experts and stakeholders from across the entire region to produce a forecast in September before the planting season and reconvenes in December to make corrections.

The majority of SARCOF participants are meteorologists from the SADC region's National Meteorological Services (NMS), as well as from the IRI. Before the September SARCOF, the DMC sponsors a multiday capacity-building workshop for young meteorologists from the NMSs. In this workshop, the scientists use a common statistical methodology to develop tercile rainfall forecasts for their home country. For each country, the scientists use principal-component analysis to define two to three subnational regions in which the influence of climate drivers is similar. For each subnational region, the scientists then select the most significant drivers (such as tropical Pacific or North Atlantic sea-surface temperatures) to construct a statistical model for rainfall in the early (October, November, and December) and late (January, February, and March) seasons. Within each region and seasonal period, the scientists are able to assign probabilities in terciles (for above-normal, near-normal, and below-normal rainfall).

The scientists bring these national forecasts to the SARCOF meeting, where members of the early-warning organizations and other stakeholders join them. The latter include people from NGO and development organizations (such as the World Food Programme), specific economic sectors with the countries (such as hydropower planners), and academic researchers. Two main items of business dominate SARCOF. First, the nonmeteorologists make presentations about their concerns and information needs. Second, and more time-consuming, the forecasters meet among themselves to iron out differences between their national forecasts based on the principle that climate does not respect political lines on the map. After a day or two of negotiation, the scientists present their consensus forecast to the others at the meeting, leaving time for discussion of the forecast's implications. SARCOF concludes with a press conference.

Translating

As in many systems for linking S&T to decision making, arenas on different sides of boundaries within the PEAC system were defined by different languages. One of the critical roles that PEAC has played is translating across these boundaries to facilitate mutual comprehension in the face of such differences. Such translation is seen in the collaborative efforts to produce forecasts in which final outputs used a language that could best be understood by target audiences. In this case, the language of historical analogy was more understandable than the language of probabilities. PEAC used scientists who were facile in both languages and could translate between them and provided the many meetings to identify what language worked best.

In southern Africa, the DMC has done little translating, relying on national organizations for that. Certainly, translation is necessary in the literal sense, as within the SADC region, there are three European (English, Portuguese, and French) and dozens of African (e.g., Afrikaans, Shona, !Xhosa, and Zulu) languages spoken. In the figurative sense, however, there may be a need for greater work by the DMC. It currently expresses the information in its forecasts using models and jargon that the meteorology community easily can understand but that other users have a difficult time deciphering, such as the tercile format of the forecasts (O'Brien et al. 2000). Reflecting comments made by all interviewees and existing literature, one official, a project director of the SADC regional early-warning system, stated:

> In terms of . . . communication with the users with these forecasts, we need to work on the language, the information content that we put out to the users to be able to, because, at the moment, sometimes the language, an ordinary farmer might not understand probabilities and so on. So we really need to work on those.

One of the more difficult challenges in this regard is integrating mathematical and model-derived scientific prediction with local knowledge. As a Zimbabwe NMS official noted:

> We realize that they also have got traditional forecast systems that they rely on, especially when you are looking at some of the small-holder farmers that prevail in southern Africa. So, we're saying we need to understand their systems a little bit better before we can actually come in with this [forecast] information to try and influence the way they do things.

Collaborating

Through participation mechanisms that fostered joint production and packaging of outputs during the forecasting process, the PEAC system was able to create products that were salient to a range of decision makers. Historical and statistical analyses allowed managers to better compare potential future events to past events in which management actions were not taken and negative outcomes ensued.

Multiple actors contributed to the construction of the forecasts, including NWS/CPC scientists, natural and social scientists at the University of Hawaii and the University of Guam, managers from multiple sectors, and representatives of the governors' offices. Each actor clearly benefited in a different way from the collaboration: receiving information on predicted rainfall for an agricultural-extension officer; hearing warnings of impending storms for an emergency manager; learning predictions of where fish might be for the fishing industry; and producing a publication in a peer-reviewed journal for a scientist. Though the forecasts had different value and meaning for each of these actors (an important part of being a boundary object), PEAC was able to coordinate and mediate activities such that there was enough overlapping meaning that a robust forecast could be produced.

The collaboration fostered by the DMC occurs primarily among forecasters from different agencies and countries rather than including potential end-users in generating useful information. One report from the October 2002 SARCOF meeting is consistent with this and confirms individual observations by interviewees:

> First, there was a sharp divide between forecasters and forecast users. There were no users invited to the consensus forecast group, and no climate expert was involved in any of the four users' working groups (health, food and agriculture, water and energy, and disaster management). Even though the users' group presentations had a lot of demands in common, no climate person made

> any effort to share perspectives about the feasibility of satisfying users' needs. For example, beginning and duration of rainy season was clearly something desired, but users left with no knowledge of whether climate scientists can (or want to) provide that information to them. (Patt, personal communication)

Efforts have been made by DMC and the national meteorological offices to communicate these kinds of probability forecasts through workshops, meetings, and other media, with inconsistent results and persistent confusion. As one Zimbabwe NMS official states (reflecting survey results from Phillips, Makaudze, and Unganai [2001] and other comments by interviewees):

> But when it comes to the local level, maybe the actual farmer who we want to benefit at the end of the day, we have actually realized that the way we communicate the forecast at times is very difficult for them to make an operational decision or a strategic decision as to what to do.

Such efforts, however, focus on communicating existing science to potential users of the information and are not true collaborations in which scientist and decision maker coproduce information.

For some constituencies, linking with actors outside the SADC system has been productive in attaining salient climate information. Primarily white large-land holders in Zimbabwe have turned to both their Commercial Farmers Union (CFU), which has an internal technical and research division, and to private consultants for sources of salient information. This was also seen in parts of the paprika-producing sector, which was constituted both by large- and small-land holders. Consultants and the CFU relied on some information originating in places like DMC and SARCOF but then were able to fine-tune it according to the specific needs of clients and constituencies. Such participation of consultants and technical expertise within the CFU provided intermediary functions that, currently, the SARCOF process does not provide.

Mediating

Part of PEAC's role is to mediate between the different interests, perspectives, and missions of the organizations and individuals that make up the network of the Pacific ENSO forecasting system. What kind of institutional mechanisms support mediation and what form does it take?

First, the actors involved in the founding of PEAC were individuals with already existing credibility and legitimacy in multiple spheres who represented long-standing institutions in the region. Mr. Dick Hagemeyer was the director of the NWS/PR and personally established weather-observation stations on several of the USAPIs in the1950s. Chip Guard had been the director of the Joint Typhoon Warning Center for four years when it was located on Guam and was a research associate at the University of Guam. Mike Hamnett was the director of the Social Science Research Institute at the University of Hawaii and had a long history of working on disaster management in the region (including being in the Peace Corps in Papua New Guinea and Kapingamwarangi in Pohnpei state). Eileen Shea had been an NOAA program officer in the region, and Jerry Norris was the executive director of PBDC coordinating activities for multiple countries.

Second, these leaders realized early in the process that conscious mediation would be a critical activity for any effective research and applications system. This is evidenced, for example, in a description of one of the first scoping meetings in 1992 when managers and scientists were brought together for the first time:

> She [a cofacilitator] and I facilitated a dialogue between the scientists and decision makers about . . . the beliefs of scientists about information and about certainty and uncertainty and probability and then the beliefs and needs of bureaucrats about the same thing. And we had the scientists characterize the bureaucrats and the bureaucrats the scientists, and then we brought them all back in the room together and said, this is what they said about you, and this is what they said [laughter], and it was interesting that, you know, everybody thought the other one needed certainty. (University of Hawaii social-science researcher)

PEAC organizers, climate scientists engaged in the process, and decision makers shared similar observations.

If two of the functions of mediation are to get actors in different arenas to understand the different perspectives and to find common ground, the exercise described above accomplished both. Scientists began to understand that managers were comfortable making decisions under uncertainty, and managers began to understand the concerns scientists had about making scientific claims in the face of uncertainty. This illustration is representative of myriad ways that PEAC relied on active and conscious mediation to bridge boundaries and facilitate the coproduction of useful and valued information.

Though PEAC undertook the mediator role, it also realized the importance of relying on existing intermediaries that also could play that role. Thus, one mechanism for linking forecasters and users of forecasts was to engage local people who already played trusted intermediary roles. This institutionalized a connection between PEAC and local decision makers while avoiding the problem of outsiders trying to break in to existing communities:

> And that's why paratrooper scientists are no good. I mean, they don't know what to do in the local setting. You need people who have worked with a variety of people on the ground who can get plugged in fairly quickly to the middle people. So it's not the farmers you worry about. It's the people that direct the agricultural extension who work with farmers that we've worked with. It's not the individual water consumers. It's the Water Utility and the Civil Defense Agency. (University of Hawaii social-science researcher)

Paralleling the relative lack of institutional mechanisms for translation in southern Africa, there were also relatively few mechanisms for actively engaging in mediation. Conflicts of interest characterize several significant parts of the system: between small- and large-land holders, exacerbated by the political climate in Zimbabwe in 2000–2002 in which the government was engaging in aggressive agricultural-land redistribution; between farmers and credit institutions, in which banks restricted credit in response to ENSO forecasts, making adaptation by farmers more difficult; and between national governments and NMSs and the DMC, in which political leaders were hesitant to allow the dissemination of forecasts that predicted negative outcomes. Each of these and the more benign conflicts across discipline and scale boundaries often require conscious and skilled mediation to facilitate the legitimacy of the process. One kind of mechanism that seems to be lacking in this regard is using actors who, as individuals, cross boundaries easily. There seem to be few people with credibility and legitimacy in climate forecasting who also have credibility and legitimacy in agronomics or agricultural decision making. This lack of mediation might be one reason why farmers in the CFU turned to private consultants or in-house technicians. Another reason may be race. Government employees tend to be black Africans, whereas white decision makers dominate many of the stakeholder organizations, such as the commercial farming sector. In many countries, there is still incomplete trust between whites and blacks.

A Comparison of Salience, Credibility, and Legitimacy

The functions of convening, translating, and collaborating have long been known, in scholarly literature if not in practice, to be critical features of functioning systems that link research and decision making. (The multiple and pervasive presence of systems that focus only on convening, or one-way translation, speak to the difficulty of institutionalizing these kinds of functions.) The importance of mediating in S&T systems only recently has been the focus of scholarly attention (Ozawa and Susskind 1985) and even less has been the focus of concerted efforts by practitioners.

What makes these functions critically important? In contentious public decision making characterized by uncertain science and emerging technologies, the charge of lack of credibility ("we don't believe this"), legitimacy ("the process has been corrupt"), and/or salience ("science answered the wrong question") can be devastating for finding solutions to complex problems. Each of the four functions outlined above plays a role in trying to create and maintain adequate levels of salience, credibility, and legitimacy. In the remainder of this section, we compare the two cases, analyzing how institutionalized convening, translating, collaborating, and mediation contribute to salience, credibility, and legitimacy.

The Pacific

Through the use of the four functions outlined above, PEAC's ENSO forecasts were timely and included information useful to a wide range of audiences. It increased credibility by bringing multiple types of expertise to the table. Thus, climate modelers, hydrologists, and oceanographers could produce an output that was credible from global to local levels and enhanced legitimacy by providing multiple stakeholders with greater and more transparent access to the information-production process. Thus, stakeholders from multiple arenas at multiple levels engaged in the process and found the process fair and legitimate.

This kind of structure was in contrast to an existing culture of linking science to decision making, summed up by a PEAC member's comment about the NWS, an agency that was not heavily involved in climate forecasting when PEAC was being formed:[8]

> National Weather Services, in general, have . . . the loading-dock approach to forecasting. You take it out there, and you leave it on the loading dock and you say, there it is. And then you walk away and go back inside. (University of Hawaii social-science researcher)

Although deciding how to present a forecast is critical, when to release forecasts is a critical part of salience as well. Information that is too early or too late for a decision maker's timeframe lacks salience. As a civil-preparedness officer on one of the USAPI recounted:

> The last El Niño happened in ‘97–‘98. And it was really bad; it was the worst we’ve ever had. But we received the information in October. And so we started our public education right after that. [The PEAC scientist] came down to Palau, and then he gave us the information. So, right after that, we started our public education. And then, by the next year, the following year, around February, then it hit us. So there was a very good lead time there . . . it worked out pretty well, so that when the event came, it happened, and the people were so prepared, and then the people were not tired of hearing the word El Niño. (An emergency management officer in the Republic of Palau)

In this case, the salience of the forecast was influenced by whether or not it was released within a critical window of time in which there is enough lead time to make changes but not so much that people lose interest. If it is too late, the manager cannot take appropriate actions. If it is too early, however, there is a risk of fatigue by the public that might counter gains made by early warnings. For PEAC, there was a valuable lesson in the commentary by this civil-preparedness officer, a lesson that ultimately was learned through the institutionalized participatory meetings between the scientists, forecasters, and managers. Others in the system further commented that through the regional meetings, there was the opportunity to discuss concerns about timing and other requirements:

> We said, well, what would you have us do differently? They said, well, I think maybe tell us a month early or something. And we said, how about if we told you in June? They said, no, no, no, too early. They said, your scale is probably as good in June but maybe not. And if we start crying about the wolf in June, people are going to forget about it by November. (University of Hawaii social-science researcher)

In both of these cases, participation of the end users of forecasts and of forecasters themselves in regular meetings before the preparation of the forecast was critical to producing a forecast that was understandable to decision makers and timely.

The region covered by PEAC is millions of square kilometers, large enough that variations in large-scale patterns influence different islands differently. Furthermore, each island has its own topography, soil structure, ecology, and hydrology, which influence microclimatic dynamics and local weather. For example, variance in precipitation between leeward and windward sides of an island may dwarf the variance in precipitation resulting from an ENSO event. A PEAC scientist captured the importance of place-based understanding in the following way:

> Tailoring is imperative. You must talk about Yap things on Yap, Chuuk concerns on Chuuk, and Pohnpei problems in Pohnpei. It must be personalized. Many times, we get meteorological training programs that pertain to weather in the continental United States, not tropical weather. We feel it's not very useful to us. And, that's just the way the islanders look at things that aren't specifically tailored to them. A discussion of a water shortage on a Guam river won't get much attention on Pohnpei. But talk about a Pohnpei river, and it gets attention. (University of Guam climate scientist)

Clearly aware of these kind of pitfalls, PEAC addressed this challenge through its collaborative relationships that resulted in participation of national and international climate scientists from organizations from multiple levels: for example, IRI and the NWS/CPC; the UOG/WERI; and local islands' water-, weather-, or emergency-management agencies. Such collaborations resulted in increasingly place-based forecasts that integrated large-scale models of climate systems with the data collected through local monitoring and observation systems. These kinds of collaborative participation to link global phenomena and local realities appear in this description of a briefing to the Pohnpei legislature:

> After I talked to them about the event itself, the meteorology in layperson's terms and what to expect, the University of Guam PEAC hydrologists got up and started showing them what the effects would be on raising and lowering the water table and the river flow. We had to treat atolls much differently than we treated mountain islands. Some countries or states have only atolls, some have only mountain islands, and some have both. (University of Guam climate scientist)

Such institutionalized collaboration of multiple disciplines at multiple levels resulted in a package of information that had credibility for academic scientists and at the local level. The key in producing these outcomes was the structured participation of many actors, bringing many different bases of expertise to the table with a clear goal of producing a locally credible forecast partly derived from globally credible models.

Southern Africa

One of the primary motivations behind the formation of the DMC and the SARCOF process was to produce a forecast that would be legitimate and credible for users, especially for food-security planners (Orlove and Tosteson 1999). By including representatives from all of the NMSs in the process of creating a consensus forecast, SARCOF could generate a product that all of the SADC countries would be willing to use. That, in turn, would facilitate greater cooperation in emergency planning. As an NOAA/OGP program manager states:

> [A]ll the fourteen countries in Southern African Development Community have a stake in the administration of Drought Monitoring Centre . . . So they all have their interest in there, you know, and, so whatever DMC puts out is . . . recognized by all the member states in those countries.

SARCOF also is supposed to increase the credibility of the forecast, both by expressing it probabilistically and by including all of the climate scientists in the region in a transparent process. Finally, it was hoped that the SARCOF process would improve the salience of the forecasts:

> [In SARCOF] we develop some forecasts from a meteorological point of view, but then invite various users . . . where we actually say this is how we're going through the process of developing this forecast. And the users then get to participate in the process, at least listening through how we go about, you know, blending different techniques, and then come up with what we describe as a consensus forecast. (Drought Monitoring Centre official)

Where the DMC and the SARCOF process is not as successful as hoped, however, is in translating the information into layperson's terms that still reflect the probabilistic character of the information and in generating collaborative outputs. This, in turn, has a real effect on both the legitimacy and salience of the information.

First, many users simply do not understand how to interpret the tercile forecast information. Many of the SADC member countries have poorly developed systems for communicating forecasts to users and so simply pass on the forecasts that the DMC provides them. This then places the burden of creating understandable information on the DMC, something that it so far has refused to accept.

Second, the one-way flow of information that the DMC fosters—from forecasters to users—interferes with both the salience and the legitimacy of the forecasts. At the SARCOF meetings, stakeholders have the opportunity to suggest how the forecasts could be more salient for their needs. This has included the need for forecasts of the beginning and ending dates of the rainy season and greater local specificity. So far, the DMC has incorporated few if any of these suggestions, decreasing salience. Moreover, the DMC has not even stated why it is not including them, and this decreases legitimacy. If users came to understand that a forecast of the dates of the rainy season was simply not possible, they would at least know that their concerns had been heard. By failing to draw stakeholders into the process of the forecast generation and instead seeing the stakeholders as simply the end users of the information, the DMC has decreased its own legitimacy.

Discussion

Both the Pacific and southern African ENSO forecasting systems evolved with similar general institutional structures intended to provide salient, credible, and legitimate information about climate variability. Both are designed to connect scientists and decision makers at global to local scales, and both systems are structured around regular and iterated meetings that can bring multiple participants together to the same table. Despite these similarities, this research suggests that each system has used different kinds of institutional mechanisms, resulting in different outcomes. We understand that there are other differences between the systems that can explain different outcomes of decisions relating to climate-affected sectors (such as greater technical constraints and greater political corruption in southern Africa), but we attempted, through our interviews and data collection, to try to at least qualitatively trace causal connections. We believe that, especially given the greater constraints in places like southern Africa, the tentative findings about institutions are all the more relevant.

Perhaps the most striking difference between the two systems has been PEAC's relative success in producing decisions compared to the southern African system. In institutionalizing a close ongoing dialogue between scientists and the users of forecasts, information was tailored to decision makers' needs and the specific context in which they operate. Even before the official formation of PEAC, it was critical to the organizers of the incipient effort that a true dialogue be created and that scientists and users be brought together with equal standing for setting agendas, designing products, and evaluating success. By structuring participatory roles at critical times in the process, PEAC facilitated a legitimate process that engaged multiple stakeholders, produced salient outputs that met users' needs, and created credible forecasts that integrated global climate knowledge with local-scale knowledge. As such, PEAC's institutional structure and focus on the functions of convening, translation, collaboration, and mediation resulted in a system antithetical to the loading-dock approach of connecting science to decision making. The result has been decisions made by a wide range of managers from sectors including utilities, emergency preparedness, water management, and so on. At least from their perspective, the information-production process better prepared them for the 1997–98 El Niño event as compared to the 1982–83 event.

In the southern African system, SADC and DMC have not used institutional mechanisms that bridge the boundary between forecasters and users as well. While SARCOF generated a high degree of legitimacy among some participants, the unidirectional nature of much of the forecasting process has made it more difficult to establish legitimacy in certain sectors and at subnational levels and to produce salient outputs for many intended users and credible linkages between global and local knowledge. The result has been, in many sectors, unused information—information produced but not used.

The difference in degree of dialogue seen in the two cases seems to arise from the different mechanisms of communication that the two systems used. Both systems focused on convening functions to bring multiple actors to a common forum to engage questions about forecasting. However, convening mechanisms, while perhaps necessary, seem to be insufficient for effective communication. PEAC, for example, devoted additional resources to institutional mechanisms for translation and mediation functions. In southern Africa, these functions were less institutionalized and less used. Part of this results from the focus that the science agencies in southern Africa have had on producing scientifically credible outputs, sometimes at the expense of engaging users, and thus decreasing the potential salience and legitimacy of the process. With some sectors ignoring some forecasts, or in fact, never even seeing them, relatively fewer decisions to prepare for effects of ENSO events occurred. Thus, there seems to be an association between these lacking institutional mechanisms and lack of use of existing forecasts. For true dialogue to take place across boundaries that separate different languages, worldviews, and interests, these cases suggest that it is critical to focus on translation and mediation that can result in the constructive sharing of information and the agreement on mutual goals and methodologies. Such strategies as engaging intermediaries who already have legitimacy and credibility across boundaries and specifically focusing activities at meetings on mediation were mechanisms that were used successfully in the Pacific and less so in southern Africa.

For PEAC, the forecast itself was an item about which collaboration occurred between disciplines, between scientists and decision makers, and across levels. The participants coproduced the forecasts collaboratively, deciding what variables went into the forecasts, how they were presented, and how to integrate knowledge from multiple sources. Such use of a boundary object allowed for two-way education to occur, for trust to accrue over time between different groups, and ultimately, for the production of credible and salient outputs. To some degree, the DMC used a similar model in the building of consensus forecasts during the SARCOF meetings. These tended, however, to be weighted toward forecast producers, including forecasters from international and national organizations and scientific and management agencies with technical expertise. As such, SARCOF forecasts served the function as a boundary object for a narrower set of participants than did the PEAC efforts. The critical boundary that was not bridged in these exercises was that between the forecasters and users of forecasts, such as farmers, the health sector, and emergency managers. Thus, SARCOF missed opportunities to educate users about forecast products (e.g., how to understand probabilities), tailor forecasts to the local needs of decision makers, and integrate knowledge of global and regional climate with local knowledge of climate and weather to make them more credible. Not surprisingly, these potential target audiences did not make decisions with input from the forecasts, with negative results for the agriculture and food-security sectors.

Despite these differences in institutional mechanisms and the resulting levels of salience, credibility, and legitimacy that are attributed to these different systems, the southern African system and PEAC share many of the same fundamental building blocks. Such building blocks could be better developed in southern Africa relatively easily. For example, the SARCOF meetings could be restructured to provide better links between forecasters and users, focusing more on applications than forecasts and consciously mediating between different groups. Given the rapidity of transformation of the system in the ten years from 1990 to 2000 (especially in the face of political instability, fewer resources, and an ENSO signal that is not as clear as the signal in the Pacific) and the common links that the Pacific and the southern African systems share (e.g., NOAA, IRI, NWS), learning and adaptive change should be feasible.

Notes

1. The interview protocol, which had been vetted and pretested, and the transcripts of the interviews are available from the authors by request.

2. Drought Monitoring Centre, http://www.dmc.co.zw/; Southern African Development Community (SADC), http://www.sadc.int/; SADC Regional Early Warning Unit, http://www.sadc-fanr.org.zw/rewu/rewu.htm; Famine Early Warning Systems Network (FEWS-NET),

http://www.fews.net/; National Oceanic and Atmospheric Administration (NOAA), http://www.noaa.gov/; NOAA Office of Global Programs, http://www.ogp.noaa.gov/; Commercial Farmers Union, http://www.cfu.co.zw; East-West Center, http://www.eastwestcenter.org/; Social Science Research Institute (Hawaii), http://www.ssri.hawaii.edu/; Pacific ENSO Applications Center (PEAC), http://lumahai.soest.hawaii.edu/Enso/; Office of Hawaiian Affairs, http://www.oha.org/; Southern African Regional Climate Outlook Forum, http://www.dmc.co.zw/sarcof/sarcof.htm; International Research Institute for Climate Prediction, http://iri.columbia.edu/; and World Meteorological Organization http://www.wmo.ch/.

3. The United States–affiliated Pacific Islands are American Samoa, Guam, the Commonwealth of the Northern Mariana Islands, the Federated States of Micronesia, the Marshall Islands, and Palau.

4. See http://lumahai.soest.hawaii.edu/Enso/ for more information.

5. The name of the Water and Energy Research Institute was changed to the Water and Environmental Research Institute sometime in the late 1990s.

6. Member countries include Angola, Botswana, Lesotho, Malawi, Mauritius, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zambia, and Zimbabwe.

7. See http://www.dmc.co.zw/ for more information.

8. The United States National Weather Service/Pacific Region (NWS/PR) was not heavily involved in climate forecasting when PEAC was actively providing information and forecasts for the 1997–98 El Niño. The NWS/PR has now adapted many of the techniques of PEAC in its forecasting and outreach, and in fact, now funds PEAC.

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Overview

Co-production in climate change research: reviewing different perspectives

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Notions of 'co-production' are growing in popularity in social science and humanities research on climate change, although there is some ambiguity about the meanings of the term and how it is being used. It is time to critically and reflexively take stock of this expanding area of scholarship. A comprehensive review of over 130 scientific publications first mapped the scholars using co-production, relative to characteristics like their discipline, nationality, and research themes. Second, it looked at how this diversity of scientific perspectives has opened up a multiplicity of meanings of co-production. While most discussions of co-production stop at a basic distinction between descriptive and normative uses of the term, this review unpacked eight conceptual lenses on co-production, each discernible by its particular emphases, academic traditions, logic, and criteria of success. There are two important implications of this work. On one hand, it urges self-reflexive transparency when using co-production concepts. The multiple meanings attached to co-production add richness to the concept and open it up to different uses. However, it is important that scholars clearly communicate how they use the term and are mindful of what they 'buy into' by using the concept in certain ways. On the other hand, there are tensions between the different perspectives as well as opportunities for combining them into a compound concept of co-production. In this way, co-production is reconceptualized as a prism, where each aspect allows different but complimentary insights on the relationship between science, society, and nature.

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INTRODUCTION

Notions of 'co-production' are growing in popularity in social science and humanities research on climate change. The past 10 years has seen a surge in the use of the concept in this literature, appropriated by scholars across numerous disciplines, with different emphases, and toward different ends. But, arguably, this opens up some ambiguity about the different meanings of the term and how it is being used. We critically take stock of this expanding area of scholarship steered by the research question: *Who is using the concept of co-production in climate research, and how are they using it*? Through a literature review of over 130 publications, we aim to provide a broader and more nuanced mapping than is normally afforded to this concept, which usually stops at a descriptive/normative divide.

Climate research scholars, such as Linda Prokopy and colleagues or Eva Lövbrand (e.g., Ref 1–3), draw a basic division between two areas of

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co-production research. The first area regards co-production as the deliberate collaboration of different people to achieve a common goal. Jasanoff ironically describes this as the 'film credit' version.[4] The second area has a science and technology studies (STS) perspective and examines how science and society constantly shape each other in unexpected and unintended ways. The former area looks at the preconditions for co-producing knowledge and social orders relevant for climate adaptation and mitigation. We call this area *normative* as it aims to elaborate guidelines (in the most general sense) of how different actors *should* define and co-produce relevant knowledge. Elinor Ostrom and colleagues were the first to use the term co-production in the 1970s, and they used it in this sense.[5,6] They studied how public services were co-produced through collaboration between public and private actors, questioning public–private boundaries and demonstrating that citizens are not merely passive clients of services provided by government agencies. In climate research specifically, the normative approach is most prominent in the work of Maria Carmen Lemos and colleagues,[7–10] who are concerned with the co-production of 'demonstrably usable' knowledge for policy making through interactive and iterative scientific processes: 'the interactions between scientists and stakeholder participants influence how scientists pursue science and how stakeholders understand the possibilities and limits of science, the range of uses to which the scientific knowledge may be put, and the practical value of such knowledge […] defined across three dimensions: interdisciplinarity, interaction with stakeholders, and production of usable science' (Ref 7, p. 58). The second area of co-production research describes and analyses how the co-production of various artifacts, settings, knowledge, social orders, and power relationships happens. We call this area *descriptive* because it mainly uses the co-production idiom for *interpreting* the shifting relationships between science, society, and nature—including around climate change—rather than intervening to actively change these relationships. This research is represented by authors like Sheila Jasanoff, Bruno Latour, Bryan Wynne and others.[11–14] They are concerned with the different ways that science, technology, and society make and remake each other. Co-production in this way is interested in 'the *emergence and stabilization* of new techno-scientific objects and framings […]; the resolution of scientific and technical *controversies*; the processes by which the products of techno-science are made *intelligible and portable* across boundaries; and the adjustment of science's *cultural practices* in response to the contexts in which science is done' (Ref 15, p. 38; italics in original).

We want to go beyond this basic distinction and map a richer picture of the terrain of climate change co-production. We see co-production as a complex meeting place where several different academic traditions and practices converge, overlap, affect each other, come into conflict, or cooperate toward describing and effecting co-production. This mapping work allows a greater appreciation for the richness of the co-production concept and the complementary ways it can be used. There are two important implications of this work. On one hand, it urges transparency and care in how co-production concepts are used. It is important that scholars clearly communicate how they use the term and are mindful of what they 'buy into' by using the concept in certain ways. On the other hand, we look at tensions between the different perspectives and explore opportunities for combining them into a compound concept, or prism, of co-production. We progress with this mapping in two ways. We start by asking who the scholars using co-production are, relative to characteristics like their discipline, nationality, and how they engage with climate topics. We then move to look at how this diversity of scientific perspectives has opened up a multiplicity of different meanings of co-production, and obtain eight overlapping but different perspectives. We finish by discussing the implications of this work and introduce the co-production prism.

METHOD

This study reviewed 131 academic publications discussing climate change co-production. We selected publications for this corpus that contained both the search words 'climate' and 'co-production.' Climate and climate change had to be the central focus of the publication for it to be considered. For instance, it was not sufficient that climate change was noted in passing or listed as one of many environmental challenges in a broader discussion of sustainability. Co-production, on the other hand, did not need to be the central theme for a publication to be considered. We were not only interested in how co-production is discussed in-depth but also how the term is used as part of other discussions, even as a passing reference. For this reason, it was sufficient for co-production to be referred to just once or twice for a publication to be included in the corpus. Moreover, we extended our 'co-production' word search to include different stem words, with and without the hyphen (e.g., co-produce, co-producing), and to include some related terms that we considered to be often used interchangeably or synonymously: co-design, co-create, co-develop, co-construct, and joint knowledge production. These search criteria tightened our focus but also excluded other insightful literature that borders this area of focus. There are a number of high-quality publications on co-production that do not explicitly discuss climate as a central focus (see e.g., Ref 16 and 17) or that discuss climate themes closely related to co-production but do not use the term or related terms (see e.g., Ref 18 and 19). For us, the focus on the terms was important because it is the ambiguous use of terms, and the weight of thinking behind them, that interested us. A focus on broader themes would constitute a different paper.

Our literature search was steered by three concurrent approaches. First, we conducted a search using the Google Scholar and Web of Science search engines, looking up each variant of the co-production search word until relevant publications stopped appearing. Second, amongst those publications selected for the corpus, we scanned the references for relevant publications. Finally, we undertook a targeted search of nine journals known to publish social and human science of climate change, which had already yielded relevant publications, including *AMBIO*, *Climatic Change*, *Climate Policy*, *Climate Risk Management*, *Environmental Science and Policy*, *Global Environmental Change*, *PNAS*, *Weather Climate and Society*, and *WIREs Climate Change*.

This review was framed by a number of decisions. First, we focused on published academic literature—book chapters and journal articles. As we were interested in the concept's uptake within academia, we excluded gray literature, although a review of the gray literature might be a worthwhile follow-up study. This would further plumb the depths of the unpublished academic literature and reveal the perspectives on 'co-production' of other societal actors that are constantly invited to participate in such initiatives. Second, we focused on the concepts of co-production used by social science and humanities scholars, rather than in a more technological sense. There are quite a few publications (24 of the first 520 hits on a Google Scholar search for 'climate co-production') discussing co-production relative to the byproducts of industrial applications, such as the co-production of electricity and synthetic fuels (see e.g., Ref 20), which were excluded. Third, we focused on publications in English. Fourth, we did not exhaustively try to account for every publication on climate change co-production. Our search stopped when: (1) we reached a saturation point where no new perspectives emerged; (2) the corpus included all of the most widely cited publications on this concept; and (3) the corpus was comprehensive enough to enable tentative comments on which scholars are using this concept. In this way, we can claim that the review is comprehensive but not complete.

WHO IS USING THE CO-PRODUCTION CONCEPT IN CLIMATE RESEARCH?

Our first layer of analysis brings to light some tentative descriptions of which scholars are using the co-production concept, relative to when they published, in which disciplinary fields and countries, and on which basic climate themes. Given the limitations of the corpus, we do not aim to provide a sophisticated statistical analysis but, rather, distil some emergent indications. See the full corpus of readings in Appendix.

Timing of Publications

We analyzed how many of the 131 publications in our corpus were published per year and found that climate change co-production has been written about for at least 20 years (see Figure 1). The earliest publication that we identified was by Wynne in 1996[14]; then, over the following 10 years (1996–2006), we found just 13 publications on this subject, published at a rate of 1 or 2 per year, although many of these have emerged as the most important and cited in the field. From 2007, we found a notable increase in the number of publications on climate change co-production, with 118 publications in the period 2007–2013. Moreover, accepting the incompleteness of our corpus, our analysis cautiously suggests an increasing trend in publications per year, with the most papers (23 papers) published in 2015. Our search stopped with publications published in 2016, although some of these were early releases online, which may not be formally published until 2017.

Disciplinary Location of Authors

We moved on to analyze the disciplinary fields discussing climate change co-production. We started by looking at which journals published the publications in our corpus and found that they were spread over 54 different academic journals and 15 books. Leaving the books aside, we clustered the journals into eight broad categories according to disciplinary and subject themes. Most publications we read were in '*climate specific*' journals with a general social science and humanistic leaning, including *Climate Risk Management*, *Climatic Change*, *WIREs Climate*

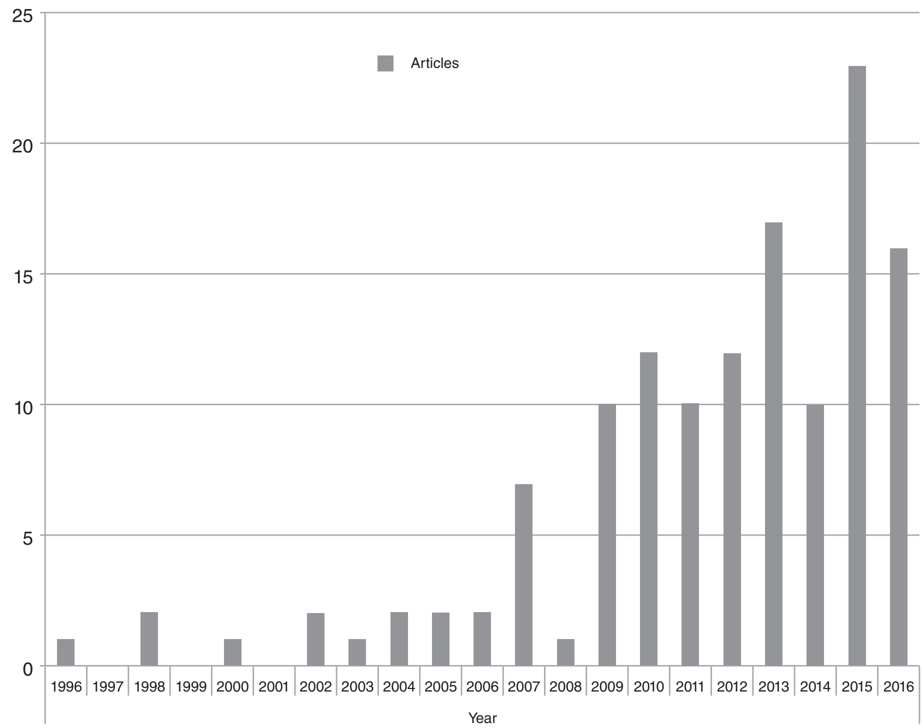

FIGURE 1 | Publications on climate change co-production published per year.

Change, and *Weather, Climate and Society*. The next highest number of publications were found in journals focused on '*global environmental studies and sustainability*'—notably *Global Environmental Change* and journals like *Ambio*—followed by journals looking variously at '*planning, policy analysis, resource management and governance*' in titles like *Environmental Science and Policy* and *Environmental Policy and Governance*. A fourth category, grouped under the theme '*social theory and social studies of science*,' included publications in journals like *Science, Technology and Human values*, or *Theory, Culture and Society*. A fifth set of journals grouped under the theme '*ecology and politics*' included journals like *Ecology and Society*, while a sixth category contained '*geography*' journals like *Geoforum* or *Applied Geography*. Finally, we found some articles in '*general science*' journals like *Science* and in '*other*' journals like *Natural Hazards*.

It was more difficult to ascertain authors' actual disciplinary backgrounds without contacting each directly, something we saw beyond the more conceptual focus of our work. Very few have a clear published statement of their disciplinary identity—in publications or on websites—but by looking at both avowed disciplinary background and departmental affiliations, we can make some coarse and indicative statements of the main fields writing on this topic. The most important contribution came from environmental sciences (including environmental studies or governance), with 52 publications having at least one author affiliated to that field. Other significant contributions came from authors in planning and public administration (including resource management, policy analysis, and institutional studies—45 papers), geography (including human and natural geography—39 papers), political science (26 papers), and science studies (including STS and the history of science—26 papers). Other contributing disciplines included political/social ecology, anthropology, and sociology. Some papers were written in interdisciplinary collaboration with natural scientists, including from agricultural science and technology (13 papers) and meteorology and climatology (11 papers).

Geographic Location of Authors

We checked where authors were based geographically. The papers in our corpus were written by scholars from 33 countries, with most papers written or cowritten by authors based at institutions in the United States (65 papers) and the United Kingdom (33 papers). From a regional perspective, most papers were written or cowritten by researchers based in the United States and Canada (73 papers) and Europe (78 papers). Just 23 papers were written or cowritten by scholars based at institutions in other regions like Australia and Oceania, Asia, Latin America, or Africa. We have to bear in mind that our sample comprised only English-speaking journals and does not include research on climate change co-production written in other languages. This might explain the dominance of authors from English-speaking countries.

We further analyzed which regions these papers focused on or where the research was conducted. Where they focused on a particular initiative, in which country did that initiative take place? Just under a third of the papers did not have a regional focus but discussed conceptual, political, or epistemological issues of climate change co-production more generally or at a global scale (40 papers). When there was a regional focus in the papers, authors were mainly concerned with issues within their own regions or countries (65 papers). Only a small proportion dealt with issues in other countries (12 papers). Given the great number of US-based scholars, it is not surprising that most papers deal with issues in the United States (39 papers). Another region that came up often is the Arctic and Polar region (12 papers). Authors working in Australia and Oceania, Asia, Latin America, or Africa predominantly focus on their own regional issues.

Climate Research Themes Engaged with

We analyzed the papers with regard to broad recurring themes that they engaged with. We found that most papers are concerned with climate change adaptation (74%), another 8% are equally concerned with adaptation and mitigation, and only 2% have a focus on mitigation; 16% of the papers deal with conceptual issues such as the emergence of global climate governance or the role of media. We noted a stark difference between the lenses on co-production. Almost all papers using a normative lens deal with adaptation either alone (94%) or together with mitigation (4%). In contrast, the papers using a descriptive lens predominantly address conceptual issues (63%) and, to a lesser extent, adaptation (32%). From this, we can only build a tentative hypothesis for the predominance of adaptation in the text corpus. While mitigation appeals to some basic global strategy and efforts, adaptation can be approached more independently at a more regional and local level. As co-production is about creating meaningful knowledge for particular contexts of action, it might appeal more to people interested in adaptation. Yet, basically, there seems to be no reason why co-production should not be interesting for mitigation research. Adaptation was discussed with regard to water management (including flood control), agriculture and rural communities, and energy supply (29 papers). Some papers discuss the management of these resources with a focus on resilience (9 papers). Another topic that interested authors writing about adaptation is the production of climate services (7 papers), that is, 'the generation, provision, and contextualization of information and knowledge derived from climate research for decision making at all levels of society' (Ref 21, p. 587). The papers discussed how climate services and underlying scenarios can be improved by co-producing their knowledge base together with relevant 'users.'

A number of papers (20 papers) are concerned with interpreting the emergence of global climate governance and the different roles of climate science in this governance. They review the structure of transnational climate governance and climate science (for instance, the UNFCCC, the IPCC, and the Copenhagen summit).[22–25] Some of these authors challenge the role, authority, and assumptions of science and knowledge production in the current structure and call for a transformation that connects better to place-based experiences, meanings, and values (e.g., Ref 24 and 26).

Finally, some papers (6 papers) discuss the role of the media in co-producing climate knowledge that influences public perception and opinion on climate change and its anthropogenic causes (e.g., Ref 27–29). Here, a focus was on the United States where media seems to focus predominantly on climate controversy and uncertainties instead of consensus.[28,29] Moreover, a certain ambivalence around the role of the media becomes manifest. On one hand, it is important in communicating climate change knowledge (e.g., Ref 30). On the other hand, media (unintentionally or intentionally) creates 'misinformed public' and delegitimizes other (nonacademic) forms of knowledge.[29]

HOW IS THE CO-PRODUCTION CONCEPT USED IN CLIMATE RESEARCH?

Our review found that there is no one common vision of co-production in climate research. Rather, the co-production literature represents an intersection, or meeting place, where a number of different perspectives from across the social sciences and humanities converge. Each perspective offers a particular vantage point on co-production, offering a different conceptual 'lens' to make sense of the complex and changing relationships between science, society, and nature. Indeed, this conceptual meeting place is itself highly overlapping, messy, and in flux, not unlike other popular conceptual meeting points around 'resilience' or 'sustainability' for instance. The different perspectives are not always clearly defined or delineated, and many authors (purposefully or not) combine several different lenses in looking on co-production. As a malleable concept, co-production is molded to each author's use, drawing on the elements that he or she sees as important. For example, an author (see e.g., Ref 31) might use co-production mainly as a way to empower traditional communities for adaptation, but also implicate co-production as important for social learning and adaptive institutions. In this way, one publication can reveal insights on more than one lens.

In this section, we try to better understand the messy meeting place of co-production by unpacking the different conceptual lenses employed. Usually, this unpacking work stops at a broad division between the *descriptive* use of co-production for critically diagnosing problems at the science–society interface and the *normative* use, offering solutions through new modes of interfacing science and society. But our review reveals a much more complex terrain. On one hand, some perspectives span this descriptive/normative divide. Scholars discussing co-production as a new mode of science, like Mode 2[32] or post-normal science[33] for instance, often use these perspectives to both diagnose problems with current scientific practice and suggest how it should be changed. On the other hand, we found that these two broad categories—descriptive and normative—themselves comprise many different perspectives. In all, we inductively delineated eight conceptual lenses, or ways of looking at co-production, two mainly descriptive and six mainly normative. This delineation is based on our own synthetic interpretation of what has been written and may not always agree with what the authors themselves intended, but it nonetheless serves an important heuristic function. These lenses are distinguishable by: (1) the aspect of co-production that they emphasize, (2) their academic tradition, (3) how they are used and the work that they do, and (4) their criteria for evaluating 'good' co-production. This section starts from the descriptive/normative division and discusses each of these eight lenses in turn according to these four dimensions. An important starting point is to recognize that these eight lenses are not equally as widely used by scholars; some have a more prominent role at this meeting place than others (see Figure 2).

Descriptive Lenses of Co-Production

The Constitutive Lens

The constitutive lens, so labeled by Jasanoff,[15] is broadly concerned with how our understandings of nature and society constitute each other, how these understandings coevolve, and their mutual influence. The way we represent the natural world shapes the way we choose to live in it and govern it. More specifically, this lens is concerned with how systems of thought emerge at the boundary of nature and society and are held in place, becoming stable and powerful for understanding our place in the world. In climate research, this lens focuses on how scientific representations of climate change redefine the boundary between natural and social worlds and redefine our understanding of natural and social orders. It was referred to in 19 of the papers in our corpus. For instance, Miller used this lens to describe how the emergence of global climate models and the Intergovernmental Panel on Climate Change in the 1980s saw a fundamental change in the representation of climate, 'from signifying an aggregation of local weather patterns to signifying an ontological unitary whole, capable of being understood and managed at scales no smaller than the globe itself' (Ref 34, p. 54). Jasanoff, in turn, argues that this representation of climate change as a global phenomenon detaches it from local meanings and ways of living with the weather: 'To know climate change as science wishes it to be known, societies must let go of their familiar, comfortable modes of living with nature' (Ref 26, p. 236).

This lens is shaped by influences from various academic traditions, which also come together in climate research. Some scholars from STS draw on Latour's 'actor network theory'[35] to represent climate change as interconnected elements traversing social and natural worlds. It cannot be framed as a purely natural or social phenomenon because the two are inextricably linked. For example, Mayer describes how shifting scientific understandings of climate change, from gradual to nonlinear and rapid, are linked to its shifting social framings as a 'danger to national security.'[36] Related to this, political scientists have long looked at how science's view of nature shapes governance regimes, with Dahan and Aykut, for instance, describing the 'scientifico-political' negotiation of the 2°C climate mitigation target in Copenhagen in 2009 and how these negotiations stabilized around that number.[37] Anthropologists have also explored the relationship between nature and culture, with ethnoclimatologists asking to what degree our

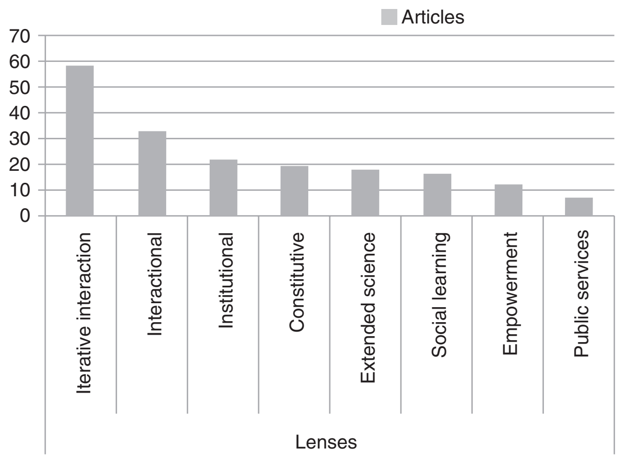

FIGURE 2 | Number of articles employing the eight lenses. Note that some articles employ two or more of the lenses and are counted multiple times, explaining why the addition exceeds the 131 papers in the corpus.

representations of climate are produced by our direct experience with weather, or by our social organizations and institutions, or co-produced by both.[38] Finally, geographers look at how a sense of place is continuously coconstructed by changes in natural and cultural elements of the landscape, with a changing climate playing an important role.[39]

The constitutive lens is used as an analytical tool for studying current scientific practices and interpreting how they affect social and natural orders. It can diagnose the problematic ways climate science (re)represents climate and how this shapes our understanding of ourselves in nature across other social spheres. Boykoff and Smith use this lens to analyze the framing of climate change in the US and UK media, diagnosing how science is (mis)used in these framings and the impact on public perception.[27,28] Ryghaug uses the lens to analyze the opposing forces that mold climate policy in Norway, noting that it is only to a small extent shaped by scientific recommendations, with key influences from the mass media and other public discourses.[40] The article diagnoses this as a problem of communication at the science–policy interface. In this sense, good or successful use of the constitutive lens relates to the quality of the analysis it steers, the diagnosis of science's role in rebuilding representations of climate, and the social orders for living with this climate.

The Interactional Lens

The interactional lens focuses on 'the *accommodations* between scientific and other forms of social life *at moments of manifest conflict and change*' (Ref 15, p. 28, italics added). Basically, this lens is interested in how science and society make and remake each other in dynamic processes. With this, it is about conflicts over different forms of knowledge and over issues of demarcation of science and society, facts and values, or knowledge and power. This lens challenges notions of science as being separate from society and analyses emergence and change, rather than stability or continuity.[2,24] This lens is quite widely used in the climate change literature, with 33 papers in our corpus employing a form of co-production influenced by this lens.

Jasanoff introduced the term 'interactional' co-production.[15] For her, this perspective mainly builds on the epistemological approach of the Edinburgh school of sociology of scientific knowledge. But other academic fields also use this lens and add their respective colors, such as anthropology, ethnography, history of science, philosophy of science, geography of science, political ecology, and social studies of science.[11,14,24,41–43] Scholars using the interactional lens challenge established demarcations between science and society and the privileged status of scientific expertise.[3,25]

The interactional lens is used to look at the processes by which climate science has emerged and claimed political authority in producing knowledge of the global climate change phenomenon. Scientific attempts to render the global climate governable have created and stabilized a particular global order.[14,25,34] Unsurprisingly, many studies using the interactional lens focus on the IPCC and UNFCCC conferences as sites and results of co-production.[24,34,37] They also analyze the interaction between universalized climate knowledge and local contexts of meaning making.

Based on the same IPCC knowledge, national governments have pursued different climate policies in line with their own traditions, beliefs, and value systems.[2,3,26,44] At the same time, decision makers steer this science to their purposes through funding programs, as Lövbrand demonstrates with regard to EU climate policy.[2] Meanwhile, climate skepticism challenges established climate governance and raises issues of trust, relevance, and legitimacy.[29,44] The 'Climategate' incident called into question the IPCC's exclusive authority over climate knowledge and exposed science for not being a separate, value-free field of social activity.[26,45] The multiple ways of making climate cognitively and emotionally accessible challenge the universal, standardized tools and approaches of climate science and its exclusive social authority.[26,45] The interactional lens also makes visible how different social categories, such as power, interests, gender, and class, become naturalized and invisible in the mundane practices of science–society interfaces, for example, the representation of women in climate change campaigns.[46]

As the interactional lens aims to provide 'the possibility of seeing certain "hegemonic" forces not as given but as the (co)products of contingent interactions and practices' (Ref 15, p. 36), the successful use of this lens is particular to its context. It is an analytical, interpretative tool for better seeing certain social phenomena. In this vein, co-production exposes and challenges dominant narratives in climate governance. However, it remains contested whether or not the two descriptive lenses—constitutive and interactional—have a social mission themselves or remain purely descriptive (Ref 2, p. 226–27).

Normative Lenses of Co-Production

The Iterative Interaction Lens

This lens promotes the iterative interaction of science providers and users along an interdisciplinary research process designed to produce more useable climate information; 'the interactions between scientists and stakeholder participants influence how scientists pursue science and how stakeholders understand the possibilities and limits of science' (Ref 7, p. 58). Seen this way, co-production is a process to better reconcile the supply and demand for climate science across the 'useability gap'[47] and go beyond a 'loading dock' model where science is 'dropped off' for users to take up.[48] Its emphasis is less on fundamentally restructuring new modes of climate science, which completely integrate nonscientists into the research process, and more on ways of tailoring scientific information to the decision-making context through regular consultation.[9]

Unlike the other lenses, the iterative interaction lens was purposely developed for climate research, stimulated by the US National Academy of Science calls in 2001 for 'the timely delivery of useful [climate information] products through a direct and accessible user interface.'[49] Its early proponents came from political science, geography, and environmental science[7,47,48,50,51] and were influenced by STS work on the context[13] and economy[52] of science and how they influence usefulness. They also drew on literature on collaboration at the science–policy interface from interactive science,[53] Mode 2 science,[54] and boundary work[55] for instance. This lens is by far the most widely used in climate research, with 58 papers in our corpus referring to it.

The iterative interaction lens is largely used to analyze climate science projects and practices, especially in the United States (30 papers in our corpus), to assess the degree to which they produce useable information and build a body of theory and practice on user–producer interaction and institutions. For example, a number of papers assess the NOAA Regional Integrated Sciences and Assessments (RISA) program looking at how certain initiatives have co-produced useful climate information, analyzing the barriers to interaction that they faced and the success of organizational approaches to overcoming them.[8,32,56–58] This has given rise to a rich literature on how to bridge producer/user institutions and how to create the conditions for interaction with boundary organizations for instance.[1,47,51,59,60] More recently, this lens has become a starting point for thinking about how to transform climate science into value-added 'climate services,' a growing market for climate information products tailored to clients' needs.[32,58,61,62] Through the iterative interaction lens then, the success of co-production is assessed relative to the usability of climate information products in a decision-making context.

The Extended Science Lens

This lens looks at ways of doing science differently by including the knowledge and values of nonscientists as integral to the process of scientific knowledge production. It begins from an assumption that complex environmental challenges such as climate change cannot be adequately dealt with by normal disciplinary science alone but need new extended forms of scientific practice. This calls for research that goes beyond integrating scientists across various disciplines (interdisciplinarity) to also integrate nonscientists embedded in other knowledge systems, and with a stake in the issue, as coinvestigators. That implies an epistemological revision of the institutions, norms, languages, methods, tools, and measures of robustness employed by science. For instance, post-normal science scholars[42,43] question 'truth' as a guiding scientific principle when faced with significant uncertainty and prefer principles of 'knowledge quality.' This opens up for other research process and product quality criteria than scientific ones, ranging from incorporating indigenous protocols to fitness-for-function. In the climate literature, our corpus included 18 publications influenced by the extended science lens.

This lens is inspired by many different approaches emerging across the philosophy and social studies of science under the umbrella of 'sustainability science,' most prominently Mode 2 and transdisciplinarity science,[63] post-normal science,[42] a new contract with society,[64,65] or civic science.[66] They all call for a new mode of science, yet each has a slightly different focus. All stress the importance of creating a more robust and socially accountable science that is problem-driven, better reflects complexity and uncertainty, and includes a diversity of perspectives. Most of them are concerned with the democratization of knowledge production. By extending the peer community, it is believed that more and other knowledge forms and values can enter scientific world making and associated decision-making.

Most climate research using the extended science lens is interested in climate change adaptation.[48,67–69] Related scholars link co-production to the participatory and democratizing practices of Mode 2, transdisciplinarity, or post-normal science that might ultimately generate robust climate knowledge.[32,70–72] Co-production in this sense is supposed to overcome the knowledge–action gap by creating useful and place-based knowledge[48,67,69] and by motivating people to act, who are otherwise not interested in science.[73] Some hold climate change to be a typical post-normal problem[25,33,74] where 'facts are uncertain, values in dispute, stakes high and decisions urgent' (Ref 42, p. 744), revealing that post-normal science has a descriptive as well as a normative side. Carrozza discusses post-normal science and co-production as methods to create meaningful democratization of science.[25] She suggests 'that the concept of co-production can offer possibilities to investigate why and how the nexus knowledge–governance become controversial, while the notion of post-normal science could offer specific criteria to manage and to respond to such controversies—and in particular to improve the quality of information in the context of the policy-making process' (Ref 25, p. 13–14). The success of extended science co-production is measured against the social robustness, accountability, and legitimacy of scientific knowledge in the face of uncertainty.

The Public Services Lens

The first use of co-production as a scholarly concept is attributed to the study by Ostrom and colleagues of institutional economics in the joint production of public goods and services by government agencies and citizens: 'the process through which inputs used to produce a good or service are contributed by individuals who are not "in" the same organization. […] Co-production implies that citizens can play an active role in producing public goods and services of consequence to them' (Ref 6, p. 1073).

While this perspective is a fertile field of study, we found relatively limited discussion in the climate literature; just seven papers in our corpus used this lens. Some scholars adopt this lens to look at how citizens can collaborate with government agencies on local climate adaptation. Vedeld and colleagues analyze how local governments in Tanzania and Senegal, with relatively few resources and a weak institutional mandate, are managing flooding risks with citizens.[75,76] Others, like Tompkins and Eakin, draw on this lens to explore the potential for private enterprises producing public adaptation goods.[77] Others still invoke this lens to promote collaboration across governmental and nongovernmental sectors for producing climate information as a public good.[78]

The public service lens is used to suggest ways by which government institutions can be reorganized to enable citizens and private enterprise to actively co-produce public services. For example, Vedeld and colleagues, endorsing multilevel governance, argue that a strong mandate and resources should be supplied to city and subcity levels of governments in Tanzania and Senegal as the appropriate level of nested governance to adapt to the impacts of a changing climate.[75,76] At this scale, they focus on 'the encounters at the interface between public officials and diverse citizen groups (and private sector) related to forms of collaboration (engagement/disengagement) and forms and degrees of participation in service delivery…' (Ref 75, p. S177). Arguably then, co-production is assessed under this lens relative to the efficient and effective provision of public services.

The Institutional Lens

This lens looks at how processes of knowledge co-production can build capacity for adaptation within governance institutions. It is part of a wider study in political ecology and environmental science about ecological resilience and societal capacity to adapt to change, particularly models of adaptive governance.[48,50,79,80] This literature has important influence on academic and political discussions around climate adaptation, and this lens was seen to influence 22 of the papers in our corpus. Through the institutional lens, knowledge co-production is a thread in a process through which institutions learn to live and adapt to change, '…a dynamic process based on social learning between and within institutions…' (Ref 81, p. 919). It is defined as a 'collaborative process of bringing a plurality of knowledge sources and types together to address a defined problem and build an integrated or systems-oriented understanding of that problem' (Ref 79, p. 996). *Within institutions*, like local government for example, co-production is an 'institutional trigger or mechanism' to enable learning and empower local peoples' agency to act and innovate new technologies in the face of change.[79,82,83] *Between institutions*, co-production processes can help lubricate cooperation between institutions working in different sectors (horizontally) and at multiple scales (vertically),[84] sharing information,[48,50] building trust, and operationalizing relationships between governance actors.[85] These multiscale partnerships are seen as important for devolved governance at the 'local' scale where climate impacts are arguably experienced most acutely.[86]

The institutional lens is often used to assess the role of co-production in building adaptive capacity in governance regimes. For instance, Wilder and colleagues assessed how co-production contributed to adaptive capacity between institutions at the US–Mexico border.[81] Newsham and Thomas looked at conditions for adaptive capacity-enhancing knowledge co-production with agricultural communities in Namibia,[87] and Chhetri and colleagues looked at how Nepalese communities co-produced agricultural technologies with government agencies.[86] The lens is also used to compare governance regimes across different countries.[84] In any case, successful co-production through this lens is arguably measured by its contribution to adaptive capacity in institutions.

The Social Learning Lens

The social learning lens looks how co-production facilitates social learning about climate issues. It focuses on the complex relations between social or policy learning and the co-production of climate knowledge that stakeholders find relevant or useful. While most authors look at social learning almost exclusively with regard to climate adaptation, there is no reason why learning should not also be applicable for mitigation. In all, 16 papers in our corpus made some reference to co-production as social learning.

This lens builds on work of organizational studies,[88] policy research,[89,90] environmental systems research,[91] and management theory.[92] Related scholars are interested in how social learning can enhance adaptiveness and resilience in the face of climate change, and which institutional settings influence and facilitate social learning.[56,79,84,93] According to Collins and Ison (Ref 94, p. 367; italics in original), 'the act of *jointly* identifying the nature of improvements and co-producing knowledge—a key requirement for adaptation—arises from processes of social learning.' However, social learning means different things to different scholars. Some see it as a form of social practice by which 'learning occurs through situated and collective engagement with others' (Ref 94, p. 370); that is, 'iterative action, reflection, and deliberation of individuals and groups engaged in sharing experiences and ideas to resolve complex challenges collaboratively' (Ref 79, p. 995). Others describe it as a property of systems.[84]

The social learning lens is used to promote the joint co-production of knowledge and acquiring of competences, that is, learning to learn.[79,93] Learning appears as a means to co-produce useful and adaptive knowledge that feeds on and bridges universal abstract climate science and local or indigenous forms of knowledge.[56] For instance, Armitage and colleagues analyze co-production processes performed together with indigenous groups in Canada's Arctic,[79] Bartels and colleagues with farmers in the Southeast United States,[56] or Tschkert and colleagues with rural communities in Ghana and Tanzania.[83] Authors also use the lens with a focus on teaching. Bartels and colleagues looked at co-production as a means to teach farmers useful knowledge on climate change in interaction with other experts and scientists.[56] Colston and Vadjunec are interested in the role of schools as sites of teaching climate change and how they become boundary institutions where science, policy, and the public negotiate climate knowledge.[95] In the social learning lens, co-production is assessed by its ability to create a setting for learning to learn—which in most papers means learning to adapt better to climate change and become resilient.

The Empowerment Lens

The empowerment lens looks at the ways co-production recognizes and empowers traditional environmental knowledge (TEK) systems. Related scholarship is mainly concerned with climate change adaptation of indigenous people and how adaptive knowledge can be co-produced in a way that respects traditional forms of knowledge making. This use of co-production was seen to influence 12 publications in our corpus.

Conceptually, the lens is influenced by anthropology,[96] philosophy of science,[97] and STS[98] that distinguish different forms of knowing about the world. Resource management approaches identified TEK as elements of managing natural systems and building resilience.[99] In contrast, political science and development studies critically query what traditional or indigenous knowledge actually is and how it really differs from Western scientific knowledge.[100,101] Related authors are conscious that empowerment co-production transcends a mere appreciation of traditional knowledge[102] and simple knowledge integration 'given the fundamental differences in the epistemological roots of these knowledge systems' (Ref 93, p. 118). Climate researchers are faced with both the claim of indigenous people to be included in ecological monitoring and natural resource management as well as the legal requirement to do so in some countries (such as the United States or Canada).

Now, co-production becomes an experimenting field to meet the methodological challenge of creating processes of mutually respectful knowledge production.[31,79,93,103] It is hoped that 'new climate change knowledge co-produced from assessment reports and from TEK offers the best possible avenue for adaptation plans to both preserve cultural diversity while pragmatically addressing the impacts of climate change' (Ref 104, p. 297). With this also comes a political agenda of 'enfranchising people with representative decision-making and resource rights and responsibilities' (Ref 102, p. 93). Related research has a main focus on the Arctic and Polar region[31,79,104,105] and also on the Pacific region[99,106] and the Asian highlands.[102] The success of this lens is measured against the empowerment of TEK systems in climate governance.

A Crosscutting Concept: Boundary Work

At the complex meeting place of overlapping perspectives on co-production, we found 'boundary work' to be a cross-cutting concept that traversed several lenses and was appropriated in a certain way by each lens, adding to the messiness of this literature. That is, boundary work was not used as a lens itself but rather as a tool or method for doing the work of different lenses. We did identify other emergent cross-cutting concepts related to 'place,' 'uncertainty,' and 'time scales' for instance, but our review found that boundary work came through strongest. It was discussed relative to co-production in 54 articles in our corpus, 15 descriptive papers and 39 normative. Boundary work's conspicuous nature may come from its close links to the dominant iterative interaction co-production lens (30 papers) or because it is an explicit and distinct concept of its own while other concepts are more inherent and pervasive of co-production.

'Boundary work' refers to the notional boundary between scientific and other social institutions across at least five lenses. *Descriptively*, the interactional lens employs this concept to interpret how abstract boundaries are put up to demarcate science from politics in 'boundary spaces' and how, through 'boundary work,'[107,108] these boundaries are continuously renegotiated for issues like climate change.[24,37,109] This helps us study the coevolution of science and politics and emergence of 'boundary objects,' like the 2°C goal, which are as much a product of science as political debate.[37] Mahony discusses boundary work as a mode of social ordering, delegating certain forms of authority to science or politics.[24] A useful distinction can also be made between boundary work as the deliberate social work of delineation on one hand[107] and as the incidental work that occurs at the science–policy boundary on the other, the daily practices of navigating and working at the boundary.[108] These incidental practices further introduce normative imperatives for 'how to work better' at the boundary.

Normatively, an emphasis is placed on bridging these boundaries, mainly with boundary organizations 'that play an intermediary role between different organizations, specializations, disciplines, practices, and functions, including science and policy' (Ref 110, p. 15). Through the institutional and empowerment lenses, boundary organizations play an intermediary role, bridging governance institutions working in different arenas, levels, or scales and facilitating the co-production of knowledge.[48,50,79,104] Through the iterative interaction lens, boundary organizations help facilitate partnerships between science producers and users,[32,57] with some authors discussing 'boundary chains' of connected boundary organizations that span the range between the production of knowledge and its use.[8] Finally, through the extended science lens, authors discuss boundary objects, from numbers to maps or graphs or other artifacts, which act as a common focus and a bridge across different knowledge systems.[33,48,50]

DISCUSSION

Based on the literature on climate change co-production, we began from the different perspectives on co-production as divided into two groups (descriptive, normative) and further subdivided them into eight lenses (constitutive, interactional, iterative interaction, extended science, public service, institutional, social learning, and empowerment). With it, we gained insight into how the co-production idiom is used in this particular text corpus and how these lenses relate to each other. Some authors make their use of one or several lenses explicit and transparent. Others just refer to co-production in passing. We underscore that it is important for scholars to self-reflexively communicate how they use the term and be mindful of what they 'buy into' by using the concept in certain ways. The lenses each follow a different academic tradition, embodying a different logic and different criteria of success, all of which influence the process of co-production. Failure to clearly articulate which perspective is steering a co-production process can both confuse the way this process is carried out and what is learned from it. Moreover, it is more difficult to compile lessons across different studies in the literature when authors are speaking past each other. What may be considered a failed initiative through one lens, looking at the usefulness of the final information output, might be considered a success through another lens, looking at the social learning emerging from the process. Indeed, we joined other scholars like Lövbrand[2] who have distinguished tensions between lenses that can be difficult to reconcile and could pose a trap for unwitting users.

Lövbrand advises against an overly optimistic application of what we have called the normative lens.[2] She detects fundamental tensions between a 'logic of ontology' ascribed to the descriptive lens and a 'logic of accountability' related to the normative ones. The *logic of ontology* advocates a way of co-production that is reflexive and emancipatory, allowing the public to engage with the societies they want to live in (Ref 2, p. 227). It stands against traditional disciplinary science that, by claiming authority over facts, closes down deliberation on values and meaning, hiding power relationships and its own normative assumptions from public review and criticism. By contrast, co-production under a *logic of accountability* sets for itself the goal of making research more useful and applicable in order to solve social problems. Lövbrand warns that if we make the value of research 'dependent on user groups' testimony that the proposed research is useful to them, we run the risk of reifying the instrumental forms of co-production that scholars of science and society are so eager to challenge' (Ref 2, p. 227). Understood this way, co-production risks black-boxing elements of the knowledge process that needed closer scrutiny in the first place. For instance, there is lively debate on what constitutes TEK[100,101] or how public engagement also creates 'unengaged publics'[25] and media coverage 'misinformed publics'[29] as well as challenges to the romantic and nonreflexive use of participation.[94] Moreover, there is not only a tension between the different lenses but also within lenses. For instance, different approaches within the extended science lens can lean more toward the logic of ontology or accountability.

Accepting these tensions, the overlapping nature of the co-production meeting place makes the lenses more complimentary than exclusory. As each lens permits only one narrow observation on the complex processes of co-production, certain scholars (deliberately or not) define co-production in a way that combines several lenses to provide a more comprehensive view. For instance, some research on adaptive governance (see e.g., Ref 79) has discussed co-production as a way to simultaneously: (1) enable social learning and (2) empower marginalized stakeholders to (3) build adaptive capacity within institutions for (4) collaboratively managing public services. There is a coherence to this combination of four normative lenses that 'makes sense' and allows us to see co-production as a multifaceted phenomenon.

We see great potential in the complimentary use of co-production lenses when conducted in a reflexive and transparent way and argue that there is a need for more research that combines descriptive and normative lenses. The descriptive work may be able to add analytical sharpness to the more normative applications of the concept. For example, scholars promoting the co-production of useful climate knowledge emphasize that knowledge quality and usefulness are anchored in a decision-making context and the 'everyday interaction between scientists, policy-makers, and the public' (Ref 7, p. 59). Here, we can see how a careful contextual analysis using the interactional lens could provide a sharper perspective on what constitutes usefulness in a context. Likewise, we agree with others who see the critical perspectives offered by the descriptive lenses as an important point of departure for organizing an extended mode of scientific inquiry, like post-normal science.[25] Indeed, this invites study into the 'co-production of co-production' to explain the recent popular uptake of this concept and to try and understand what kinds of knowledge, public, objects, and subjects are being co-produced, with what effects. And how does the coevolution of the different lenses we have discussed act to reformulate or co-produce the co-production concept over time?

In recognizing the compound nature of co-production, we propose recrafting co-production as a conceptual prism of eight lenses (see Figure 2), recomposed of the eight different uses of the concept. In first taking apart and then reassembling co-production theory, this exercise fashions a conceptual lens that brings to light and helps understand different aspects of climate change co-production at the science–society interface. It presents eight sides to the co-production challenge. This prism can guide co-production inquiry so that it does not need to be limited to any one facet but can be opened up to integrated study along different dimensions, with equal regard for describing the processes indirectly shaping climate science as for normatively prescribing co-production approaches to mediate these different processes. The prism offers eight complimentary perspectives for understanding the role of climate science in a context and designing a co-production process and practices to better integrate climate information with decision making in that context (Figure 3).

The obvious pitfall to combining lenses is that with more lenses comes ever more detail, and 'noise'; making it more difficult to implement a cogent analysis. There is a danger that analyzing co-production along eight different dimensions could lead to a schizophrenic research process that confounds and dilutes any findings. Moreover, with these lenses synthesized from one scientific literature, we cannot contend that they represent the totality of perspectives on co-production, and that only by using all eight would one get a full vision of the co-production problem. Rather, the prism concept aims to serve a heuristic function, reflexively pointing out complimentary perspectives to explore.

CONCLUSION

In this paper, we set out to map the use of co-production concepts in social science and humanities research on climate change and discovered a complex meeting place where several different academic traditions and practices converge, overlap, and influence each other. We tried to set some order to this messy terrain by singling out which scholars are using this term, in which disciplines and countries, and then synthetically demarcating eight diverse perspectives on co-production. Our intention is that this mapping work helps scholars and practitioners be more reflexive and clear about how they use

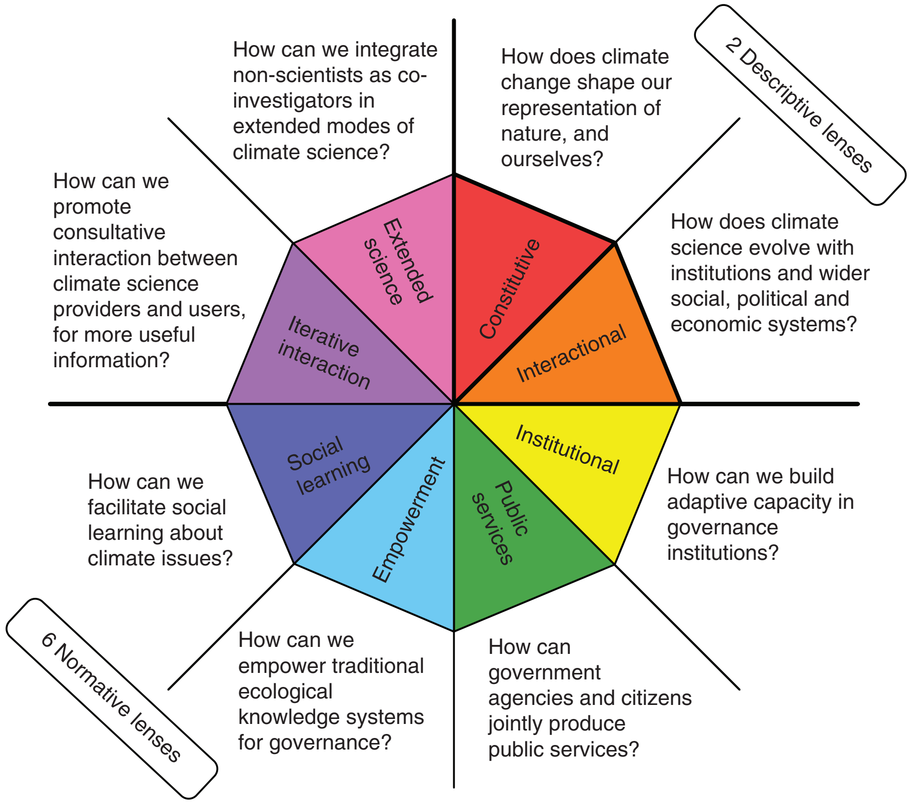

FIGURE 3 | The co-production prism comprising eight unique perspectives on climate change co-production, two mainly descriptive and six mainly normative.

the concept, recognizing the differences (and sometimes the tensions) between co-production perspectives and measuring the success of co-production with appropriate criteria. But it is equally our intention to nurture the creative use of this rich concept through the combination of different co-production lenses for new and surprising insights. It is to this end that we conceptualize co-production as a prism.

Co-production scholarship is in no way limited to the issue of climate change; it pervades a much wider category of literature on sustainability (e.g., Ref 17). But climate research is arguably a good place to start exploring uses of this concept because (1) research on climate change has grown in parallel with research on co-production; (2) climate science is a good case of universalized knowledge that is argued to be reintroduced to local contexts; (3) at least one concept of co-production originated from climate research; and (4) there is a large and varied literature on climate change co-production. Notwithstanding the possibility that there are novel perspectives on co-production outside of climate research, we suggest that our mapping work in the climate literature is quite representative of human and social science literature on co-production in other spheres of environmental governance, like water management for instance.[16] The prism concept of co-production can likely travel to these other fields as well.

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APPENDIX

The Corpus of Climate Change Co-Production Readings

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REVIEW

A How-to Guide for Coproduction of Actionable Science

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Abstract

Resource managers often need scientific information to match their decisions (typically short-term and local) to complex, long-term, large-scale challenges such as adaptation to climate change. In such situations, the most reliable route to actionable science is coproduction, whereby managers, policy makers, scientists, and other stakeholders first identify specific decisions to be informed by science, and then jointly define the scope and context of the problem, research questions, methods, and outputs, make scientific inferences, and develop strategies for the appropriate use of science. Here, we present seven recommended practices intended to help scientists, managers, funders and other stakeholders carry out a coproduction project, one recommended practice to ensure that partners learn from attempts at coproduction, and two practices to promote coproduction at a programmatic level. The recommended practices focus research on decisions that need to be made, give priority to processes and outcomes over stand-alone products, and allocate resources to organizations and individuals that engage in coproduction. Although this article focuses on the coproduction of actionable science for climate change adaptation and natural resource management, the approach is relevant to other complex natural-human systems.

Introduction

In the loading dock approach to linking science and action (Cash *et al.* 2006), science producers interact with resource managers, decision makers, or policy makers (henceforth *managers*) in a linear transaction. In one variant of this approach, the manager contracts a scientist for a specific product, which is delivered to the manager's desk (a small loading dock), and may later be used to inform management decisions. In another variant, a funder not affiliated with the manager (e.g., the U.S. National Science Foundation) might award a scientist a grant to develop a science product regardless of whether the manager has asked for it. The scientific product sits in the peer-reviewed literature (a big loading dock) until the manager finds it. In the latter variant, the scientist might take the additional step of outreach or science communication – i.e., making managers and those who influence managers (stakeholders, lawmakers) aware that the products exist. The loading dock approach works best in situations in which the manager knows what questions to ask, and the scientific answers readily apply at the spatial scale (a political or property boundary) and temporal scale (next year's budget, or a multiyear planning schedule) faced by the manager.

Some problems are not well served by the loading dock approach. For example, the problem of adaptation to climate change involves complex phenomena (such as range shifts, phenotypic plasticity, and evolutionary potential of many interacting species in response to multiple, highly uncertain, climate scenarios) that occur at spatial scales beyond the manager's sphere of influence and at temporal scales beyond the manager's budget or planning cycle. We became acutely aware of the limitations of the loading dock model during our work as members of the Advisory Committee on Climate Change and Natural Resource Science (ACCCNRS), which advises the Secretary of Interior on operation of the National Climate Change and Wildlife Science Center (NCCWSC) and eight regional Climate Science Centers (CSC). In their first years of operation (2009-2013), the NCCWSC and the CSCs generated and compiled hundreds of vulnerability assessments (USGS 2016), usually at the specific request of managers. Nonetheless, a reaction of many managers was "What do I do with these vulnerability assessments? Why did I ask for them?" Many vulnerability assessments remain on the loading dock, yet to support adaptation decisions. It became obvious to the CSCs, NCCWSC, and ACCCNRS that neither decision makers nor scientists working alone can specify what science products are needed, how they should be developed, and how they should be applied to climate adaptation.

As a result, the CSCs and NCCWSC have adopted a fundamentally different model, known as coproduction (ACCCNRS 2015). Although actionable science can, theoretically, be produced by scientists working alone, we believe that coproduction offers a more reliable route to actionable science for complex challenges such as managing the risks of climate change. Managers can explain the decision or planning issue at hand, the legal, political, social, and fiscal constraints, and explain how scientific information affects their decisions and downstream decisions. Scientists can ensure that the right product is developed and that managers understand how to appropriately use the information. Stakeholders (industry, landowners, potential downstream users of the information, and other persons who might be affected by the decisions) can provide insights on practical constraints and alternative courses of action that might affect the decisions and the science needed. Because various parties bring potentially unique contributions, they can better define the research goals, methods, and products if they work in concert than singly.

For the purposes of this article, we define *actionable science* as data, analyses, projections, or tools that can support decisions in natural resource management; it includes not only information, but also guidance on the appropriate use of that information. We define *coproduction* as collaboration among managers, scientists, and other stakeholders, who, after identifying specific decisions to be informed by science, jointly define the scope and context of the problem, research questions, methods, and outputs, make scientific inferences, and develop strategies for the appropriate use of science. We use the term *partners* to collectively refer to these coproducers.

Although the scientific literature on actionable science is limited, it is unanimous in concluding actionable science must be credible (scientifically sound), salient (relevant to a management decision), and legitimate (fair and respectful of stakeholders' divergent values), and that it is most reliably produced by iterative collaboration between scientists and managers (Cash *et al.* 2003, 2006; Lemos & Morehouse 2005; NRC 2009; Dilling & Lemos 2011; Kirchhoff *et al.* 2013; Meadow *et al.* 2015; Nel *et al.* 2016). Here, we try to translate these descriptions of coproduction into concrete recommended practices. For brevity and clarity, we express each recommended practice using imperative sentences directed at specific partners (e.g., "Scientists: do this"). We organize our recommended practices under three guiding principles, adapted from the six principles of effective decision support developed by NRC (2009). Our guiding principles are entirely consistent with the recommendations for science-practitioner interactions offered by Jacobs (2002), the five principles of knowledge exchange offered by Reed *et al.* (2014), and the 10 heuristics to guide scientist-practitioner collaborations offered by Ferguson *et al.* (2014). Meadow *et al.* (2016) note that these "principles are just that – guiding principles that need specific strategies to enact." Therefore, each principle is followed by recommended practices or strategies.

The first two guiding principles and eight recommended practices focus on individual coproduction efforts. Each of these eight practices is an activity associated with successful coproduction in case studies described by Cash *et al.* (2003, 2006), Lemos & Morehouse (2005), NRC (2009), Bowen *et al.* (2015), Lebel *et al.* (2015), Mukhopadhyay *et al.* (2014), Schuttenberg & Guth (2015), Wyborn (2015), and Nel *et al.* (2016), six case studies in our ACCCNRS report (Beier, Behar *et al.* 2015), and our experiences as participants or observers in efforts that incorporated elements of coproduction. Every activity or idea associated with successful coproduction in two or more case studies is reflected in one or more of our principles and practices; there was no instance in which a key conclusion of one study was contradicted by another study. The third guiding principle and final two recommended practices focus on the larger issue of supporting the enterprise of coproduction.

By advocating for wider use of coproduction and providing practical advice to managers, scientists, and funders, our goal is to increase society's ability to address the more challenging issues of our day, such as climate change. Readers should focus on the spirit of these recommendations and adapt the details to their particular situations.

Guiding principle #1: Coproduction begins with decisions that need to be made

Because research needs are rarely known (and almost never clearly specified) in advance, collaboration is a logical way to identify those needs. Cash *et al.* (2003)

compared two or more attempts to generate actionable science in each of five thematic areas (farm productivity, aquifer depletion, drought forecasts, ocean fisheries, and transboundary air pollution). In each case, Cash *et al.* (2003) concluded that effectiveness suffered when scientists assumed they knew what questions managers needed to answer, or when managers assumed that scientists knew how to provide usable answers to their important questions. In contrast, effectiveness increased when partners took management decisions as their starting point and jointly defined and produced science to support those decisions. For example, at the outset of an effort to coproduce a plan to conserve rivers and wetlands in South Africa, partners iteratively deliberated to identify 37 decision-making contexts and the types of scientific guidance needed in each context; as a result, the scientific guidance has been applied in 25 of these contexts during the first 3 years of the project (Nel *et al.* 2016). The first three recommended practices are intended to help ensure that science is focused on management decisions.

Recommended practice 1. Managers: Approach scientists with a management need, goal, or problem, rather than a request for a product.

For complex issues, managers must work with scientists and stakeholders to cospecify the project elements before the problem and decision can be fully articulated. This is especially true when managers need science to adapt to climate change, resolve conflicts among conservation goals, and integrate conservation goals with competing goals. For example, managers might initially assume they need scientific knowledge about impact of climate change on particular resources. However, after discussions with scientists, they may learn that uncertainty about impacts cannot be reduced in time for the intended decision. After additional discussion, the managers might realize they need more information about which alternative adaptation strategies are most robust to uncertainty, which actions can best manage risk, or the relative costs of alternative strategies. Managers acting alone might come to this realization, but collaboration between scientists and managers is more likely to ensure that the right questions are asked and addressed, producing useful outcomes with fewer delays and at a lower cost. Managers might not have requested vulnerability assessments (above) if the parties had discussed what decisions would be informed by science, how scientific understanding would be used, model uncertainties, the format of model outputs, and how uncertainty and format of the outputs would affect actionability.

Recommended practice 2. Scientists: Before suggesting specific products, make sure you understand the decision to be made, and the environment in which the decision will be made.

Although the CSC were created specifically to provide science "geared to the needs of fish and wildlife managers as they develop adaptation strategies in response to climate change" (Salazar 2009), about 90% of initial CSC projects focused on downscaled climate predictions and vulnerability assessments and less than 10% on developing, evaluating, or operationalizing adaptation strategies (Beier, Hunter *et al.* 2015). We suspect this mismatch was partly driven by scientists assuming that managers needed more accurate projections of climate change impacts at finer spatial resolution. But a particular adaptation decision may hinge less on assessment of impacts than on assessment of how well various options will reduce vulnerability and minimize risk. Sometimes no-regret strategies can be devised that do not require projections. Even when projections are useful, they are almost never the end point (NRC 2009). To generate actionable science, the scientist must understand the type of decisions a manager can make, the fiscal, policy, social and political constraints on the manager, and incentives and disincentives faced by the manager.

Recommended practice 3. Partners: Invest in at least one in-person meeting of all potential partners and stakeholders to specify the types of decisions to be made and the types of scientific information needed to support those decisions.

Before this in-person meeting (identified here as the Goal-Defining Meeting), the convenors should identify the types of decisions needing scientific support, the types of scientific information that might be relevant, the timeframe needed for completion, and key stakeholders. Then, the convenors schedule a meeting to which they invite the key decision makers, scientists in the appropriate disciplines, implementers, and (when appropriate) funders and other stakeholders. The invitation should state the tentative goal and agenda of the meeting. Stakeholders with different values and objectives should be invited, as long as they are willing to contribute to the goal of the project (e.g., to support decisions that promote conservation). Stakeholders might include land owners, community groups, associated agencies, business interests, or others who affect or are affected by potential decisions and actions. Organizers should use some combination of semistructured interviews, expert opinion, and snowball sampling (whereby early invitees nominate additional participants) to create a diverse and representative stakeholder collaborative (Reed *et al.* 2009).

Sometimes conservation advocates, agencies, or scientists oppose inviting participants who may not share the goal of the project – e.g., inviting real estate developers or mining industry representatives to participate in a project to codevelop a conservation plan. However, in our experience this has never been a problem if the purpose of the meeting is clearly stated. For example, Beier (2008) described efforts to coproduce eight wildlife corridors in densely populated southern California, United States. Most invitees from industry declined to participate, but appreciated that the process was transparent, honest, and inclusive. When industry representatives did participate, they brought useful local knowledge and insight into options for implementation. Beier (2008) concluded that partners have nothing to lose and much to gain by inviting anyone who wants to advance sound decisions and their implementation.

At this meeting, participants should produce a clear goal statement so that success can be assessed later. In some cases, it may be necessary to modify tentative goals that emerge as infeasible, or expand the menu of policy options beyond those initially envisioned (Lovbrand 2011). Participants should refer to the goal statement throughout the process. If the goals must be revised during the process, partners should seek consensus. Goals should be specific, measurable, achievable within time and budget constraints, and realistic.

This meeting may require 1-2 full days. The agenda should include questions such as those listed in Table 1. It may help to have a skilled facilitator lead the meeting. A summary of the meeting, and each subsequent meeting, should be promptly sent to all partners.

Table 1 Questions that could be used as agenda items at a Goal-Defining Meeting for a coproduction project

- What is the issue at hand? What questions are being addressed? What topics are included or excluded from consideration?
- What decisions are being made? Are they flexible or limited in scope?
- Who will use the scientific information (including downstream uses) and how will they use it?
- In what form, process, or product will the data be most useful to the users?
- Given that decisions must be made before the science can be "settled," what is a realistic expectation of what is possible and useful within the available time and budget?
- What is necessary to make data accessible to all projected users? Who will own the data or other products? Where will the products reside?
- What would success look like for all parties?
- What alternatives are available to achieve success? What is gained or lost by pursuing one alternative over another?
- What variables does the decision maker care about? What resolution of data? What spatial extent? What level of precision is realistic, achievable, and adequate for the decision? If such precision is not feasible, should the project be abandoned or modified?
- What is the planning time horizon? Is this horizon appropriate for the purposes agreed on by the stakeholders?
- How will uncertainty be addressed? To what extent can multiple projections (e.g., emission scenarios, general circulation models) bracket uncertainty?
- Is a technical advisory group or steering committee needed for this project? If so, who should serve?

Guiding principle #2: Partners should give priority to processes and outcomes over stand-alone products

NRC (2009) admonished producers of actionable science to "give priority to process over products." This rhetorical overstatement was intended to nudge scientists away from their traditional focus on products that are left on a loading dock. Giving priority to process does not mean that shabby products will be tolerated – there is a dire need for quality scientific products relevant to management and adaptation. Rather, it points out that facts (scientific products) do not speak for themselves but require guidance for their proper interpretation and use. A focus on process, outcomes, and adequate interaction must be explicitly built into project design from the beginning. An emphasis on process not only affirms that good process leads to good product, it points out that decision-support *services* are fundamentally different from decision-support *products*.

Recommended practice 4. All partners: For a large, complex project, engage a subset of key people to serve on a technical advisory group that will adjust goals, review key methodological decisions, and coproduce inferences. Recruit a smaller steering committee to manage the project calendar, products, and workflows.

The Goal-Defining Meeting will not be able to map out every detail of the project. Surprises will occur and adjustments will need to be made. It could be cumbersome for all participants from the first meeting to manage these surprises and many participants would not want to do so. Many participants at the first meeting may be agency heads who are one step removed from using science to make decisions; they may prefer to have end-users on their staff serve on the technical advisory group. If the first meeting is run well, participants will trust the small technical advisory group and steering committee to keep the project on track. Spencer *et al.* (2010) and Nel *et al.* (2016) illustrate how a technical advisory group and steering committee can avoid stakeholder burnout and maximize the ability of stakeholders to provide meaningful input at each stage of coproduction.

Recommended practice 5. All partners: Over the course of the project, iteratively discuss key assumptions, models, approaches, data sources, and criteria.

At the Goal-Defining Meeting (see Practice 3 and Table 1), partners should have resolved many issues, but may still have divergent opinions on scientific models and products, and difficulties encountered along the way may require adjustment. Addressing these issues will often require three additional in-person meetings (or sets of meetings): the Work Plan Meeting, the Science Implementation Meeting, and the Rollout Meeting.

At the Work Plan Meeting(s), scientists explain alternative scientific approaches to achieve the goal, discuss the key assumptions, data needs, and costs of each approach, and describe strengths and limitations (including uncertainties) of available data. Under the direction of the steering committee, the scientists should provide a written overview and agenda, so that invitees can decide whether to participate. Participants (typically the technical advisory group) discuss these issues to reach consensus on the scientific approaches to be used. If pilot or demonstration work is needed to evaluate competing approaches, more than one Work Plan Meeting may be required. During this discussion, it may be necessary to revisit some issues, such as spatial extent, focal species, key processes, or resolution of data or outputs, that had been tentatively agreed at earlier meetings.

At the Science Implementation Meeting (see Recommended Practice #7), draft scientific products are presented and discussed in relation to the decision-making contexts defined earlier. The meeting should occur early enough to allow time for significant adjustments if needed. At this meeting, participants should discuss how various draft or hypothetical outputs would inform particular management or policy options. Participants should request that the scientists provide specific guidance on proper use of science in particular contexts.

At the Rollout Meeting, scientists describe the information and appropriate use of the information in decision making, and key decision makers explain how they intend to use the information. All the participants from the initial meeting should be invited to participate. At least 1 hour should be allotted for questions and discussion. Training programs may also be appropriate.

After engaging in a lengthy Goal-Defining Meeting (Table 1), it is easy for scientists to overlook the need for these additional meetings. For example, the Southeastern CSC engaged in a 2-day meeting with potential users of downscaled climate information to conserve plants and animals in Puerto Rico. The managers were pleased that scientists solicited and honored requests for specific climate variables (e.g., duration of longest rain-free period), but were dismayed that there were no additional opportunities to develop context-specific guidance on use of the products before the downscaled climate variables were delivered.

Recommended practice 6. Decision makers: Explain to scientists how risk is evaluated and managed in your organization. Help scientists appreciate how you make informed decisions (not perfect decisions) despite uncertainty about current or future conditions and the outcomes of interventions. Explain the context in which decisions are made, the limitations on your authority, and to whom you are accountable. If multiple agencies are responsible for decisions, make sure that scientists provide the array of scientific information that each agency needs to act independently.

This practice is an important part of all four types of in-person meetings. In our experience, scientists will not fully grasp this information the first time they hear it. Repetition, through multiple speakers, smaller breakout groups, working lunches, and/or end-of-day summary sessions, can help scientists understand. For example, an effort to define key connectivity areas among significant natural areas in California involved 220 participants representing 62 federal, state, tribal, regional, & local agencies (Spencer *et al.* 2010). At the start of the discussion, all scientists and most managers wanted the scientists to develop importance scores for each connectivity area. Over the course of several meetings, the scientists learned that different management agencies needed different scientific information to make decisions, that each institution had unique values (not always the values other parties assumed), and these differences affected how each agency would use a given type of scientific information. As a result, eventually it was decided that a single importance score would be counterproductive. Instead, the scientists were asked to provide a dozen key descriptors of each linkage area, allowing each entity to interpret importance in light of its own mission and values.

Recommended practice 7. Scientists: Honestly convey the meaning of uncertainty in your results, but (respecting the fact that decisions must be made) clearly convey the main implications of your research. In addition to providing information, an equally important task is to provide clear guidance on appropriate use of that information. Expect managers to challenge your science. Be open about your policy preferences.

This practice is also an important part of all four types of in-person meetings. Managers may have overly optimistic ideas of the quantity and quality of the scientific information available, and may not fully comprehend the implications of key assumptions and the limitations of scientific models when this information is first presented. Once again, breakout groups, repetition by another scientist, working lunches, and other mechanisms can help, and will lead to a better project.

An important activity (and a major focus of the Science Implementation Meeting) is to work with decision makers to develop decision trees or tables describing the most appropriate way to apply the information in each anticipated decision-making context (Nel *et al.* 2016). Because local environmental conditions and social processes affect management decisions, scientists must provide flexible guidance that accommodates local knowledge and stakeholder values.

Scientists should make it easy for resource managers and decision makers to understand key assumptions and the logical chain of analyses. Indeed, scientists should expect managers to challenge assumptions, offer alternative interpretations of analyses, propose alternative approaches, and demand flexible options. Although some scientists might tend to interpret this as pressure to compromise their scientific credibility, in most instances these demands are entirely consistent with the values of science, namely transparency, respect for evidence, logic, and openness to correction. Scientists should embrace these opportunities to improve their science.

Scientists should also freely express their values and policy preferences. All the other partners will have expressed their personal and agency values and preferences, and will not expect or believe that individual scientists are value-free. Scientists increase their credibility by frankly disclosing their preferences and opinions, insisting on transparency and rigor, working to find common ground, respecting the ideas of nonexperts, and being open to all evidence and inferences supported by evidence (Noss 1999; Alagona 2008).

Recommended practice 8. Scientists, funders, boundary organizations: Evaluate coproduction products, processes, and the actionability of the science of individual coproduction projects, and disseminate these findings. As project evaluations accumulate, revise these recommended practices.

Coproduction is still under development, and there is much to be learned to improve the process. Table 2 provides a list of questions that can be used to evaluate a project that attempted to coproduce actionable science. The evaluation should occur after partners have attempted to apply the new science and can provide meaningful answers to these questions. Ideally, evaluation should be embedded into a project from the outset, and budgeted for.

We suggest two ways to evaluate a project. First, a group of key participants, or independent evaluators, can provide a retrospective evaluation, as Nel *et al.* (2016) did 3 years after a major coproduction project. Another option would be to convene a meeting among partners several months or years after the Rollout Meeting (typically the contractual end of the project). In either case, addressing the questions in Table 2 will help determine how well the project delivered actionable science, and how future projects could better produce actionable science. Although the ultimate success or failure of the project (e.g., resilience of biodiversity to changes in climate and land use) may not be evident for decades, the evidence can be considered in a results-chain model (which links actions to desired impact through a series of intermediate steps; CMP 2008). Results of each project evaluation should be disseminated via white papers, peer-reviewed publications, webinars, websites (e.g., www.cakex.org), or scientific and professional meetings such as the biennial National (U.S.) Adaptation Forum (www.nationaladaptationforum.org). Some boundary organizations are beginning to conduct such evaluations, a few of which have been published (e.g., Ferguson *et al.* 2016).

Table 2 Questions to address in evaluating a project to coproduce actionable science

- How well did scientists and managers specify the problem statement at the outset?
- In retrospect, would different scientific information and processes have been more useful? What steps could have better set up the project at the outset?
- Did the project give appropriate priority to process and products? Was the process collaborative, communicative, and positive for both scientists and managers?
- If scientists provided postcontract advice on the appropriate use of the information, was this continuing engagement properly budgeted for?
- Were the scientists appropriately rewarded by their employers, and by the satisfaction of contributing to better decisions?
- What practical steps could have been taken to provide better guidance on appropriate use of the scientific products?
- Did the scientific information and process lead to better decisions (or was it capable of doing so, even if constraints precluded a better decision)? How should future projects be managed to better meet this goal?
- What obstacles to collaboration were encountered in shaping the goals and final results?
- Is the product being used in the way it was envisioned? If not, why not?
- Was a mechanism created to insert new scientific results and learning that occurred by observing the outcomes of decisions made using the products?

As evaluations of individual projects accumulate, systematic reviews or meta-analyses should be used to draw general lessons, and most importantly, to revise this how-to guide. Fazey *et al.* (2013: their table 4) provide 80 questions that can be adapted to evaluate coproduction as a knowledge system. Although a randomized and replicated experiment to evaluate the hypothesis that coproduction is the best route to actionable science may be infeasible, careful grouping of case studies (e.g., Cash *et al.* 2003) could provide meaningful comparisons. Ideally, revision of this how-to guide would be coproduced by scientists, managers, and stakeholders, and subject to peer review.

Guiding principle #3: Build connections across disciplines and organizations, and among scientists, decision makers, and stakeholders

Decisions on complex issues can require combining information on available technological and policy options at different scales of decision making, and information on the likely ecological, economic, and societal costs and benefits of those options. This requires integration across disciplines, sectors, and scales. Linking information producers and information users is especially challenging because the cultures and incentives of science and practice are different, and those differences need to be respected (NRC 2009). All partners must invest goodwill, respect, commitment, time, and resources to develop the interpersonal interactions that are critical to coproduction (Cheruvelil *et al.* 2014).

Recommended practice 9. Funders, universities, and governments: Create and grow the capacity of boundary organizations dedicated to coproduction of actionable science.

A boundary organization is an entity that serves as a convener of science producers, science users, and other affected parties, and as a translator and a facilitator of productive tension among these groups (Guston 2001; Cash *et al.* 2003; NRC 2009). Boundary organizations related to conservation and climate adaptation include the Intergovernmental Panel on Climate Change, International Platform on Biodiversity and Ecosystem Services, Regional Integrated Sciences and Assessments Program, CSC, Landscape Conservation Cooperatives, U.S. State Agricultural Extension Programs, and NGOs such as EcoAdapt, Conservation Biology Institute, and Geos Institute. Many universities also sponsor boundary organizations.

We recommend support for boundary organizations dedicated to coproduction of actionable science, because such enterprises incur extraordinary expenses to build and maintain good relationships across disciplines and sectors. Support for coproduction activities must be built into the base funding of boundary organizations because these activities extend beyond the normal 2- or 3-year duration of individual projects. Boundary organizations with broad geographic scope will find it challenging to develop long-term relationships with partners, especially with leadership turnover in partner entities. Accordingly, the budgets of boundary organizations should be structured to minimize turnover in key personnel within the boundary organization, train staff to serve as facilitators, conveners, and communicators, support staff travel, and provide high-quality virtual-meeting facilities. These investments are necessary to build a regional community of researchers and science users, to support individual projects, and to generate the political support that will sustain the boundary organization.

Recommended practice 10. Funders, managers, universities, agencies, and NGOs: Create incentives for academic scientists to consider coproduction of actionable science as a rewarding line of work.

Table 3 Questions to be used by funders to evaluate a proposal to coproduce actionable science

- What decisions will the project inform? Does the proposal explain how the research will inform multiple, specific decision-making contexts?
- Has the need been articulated by managers or other users? Does the research team include managers?
- How well does the proposal incorporate the recommended practices for coproduction?
- Does the budget include adequate funding for collaborative activities?
- Does the proposal provide flexibility to modify goals and activities in response to stakeholder input?
- What mechanisms are in place to ensure collaboration between those who will use this research and the researchers conducting the project?
- Does the project team have the appropriate expertise, or is there a plan to procure it?
- What outreach is planned to disseminate the product to those who need it? Will users be trained on how to use the product? Will appropriate staff be assigned to make the products user-friendly?
- How will the project be evaluated for both process and product?

A straightforward incentive would be for a funder to issue a request for proposals to generate competing proposals to coproduce science to address important management decisions. The request for proposals should encourage academic applicants to recruit managers as coprincipal investigators, and advise applicants that the questions in Table 3 will be used to evaluate proposals for funding.

Universities and research laboratories should modify promotion and tenure criteria to consider a peer-reviewed publication focused on coproduction of actionable science as equivalent to more than one "pure science" publication. Considering the extra effort involved, time lag from project inception to publication, and benefits to society, a multiplier of at least two seems reasonable.

Regardless of how their employers reward coproduction, many academic scientists may find coproduction of actionable science personally satisfying and professionally rewarding (Brugger *et al.* 2016). For example, Beier (2008) felt that a coproduction effort that led to a conserved wildlife corridor that included a highway crossing structure was a more satisfying legacy than any increase in h-index that might have occurred from avoiding the time-demanding coproduction process. Coproduction can also be professionally rewarding. For example, participation in multiple coproduction efforts resulted in two well-cited peer-reviewed papers that summarized the lessons from those efforts (Beier *et al.* 2008, 2011). Although the same amount of time invested in traditional research would have yielded more papers, coproduction was not a professional black hole, and can be part of a diversified portfolio of professional activities.

Conclusion

The actionability of science depends on how well the knowledge system carries out four functions, namely convening, translating, collaborating, and mediating (Cash *et al.* 2003, 2006). Coproduction is not the only route to actionable science; alternatives include the loading dock model, contractual research, knowledge exchange, user-inspired basic research, boundary organizations, research scientists embedded in management agencies, training scientists to communicate to managers, and social learning (Cash *et al.* 2003, 2006, Kirchhoff *et al.* 2011, Cook *et al.* 2013; Meadow *et al.* 2015). Because coproduction and boundary organizations are the only approaches that deliberately target all four critical functions, we argue that these two closely allied approaches should be more widely used. We believe coproduction is especially appropriate for problems involving multiple spatial and temporal scales, problems where neither scientists nor managers can specify needed science products in advance or situations in which managers need ongoing guidance on proper use of science in a variety of decision-making contexts.

To the best of our knowledge, this is the first attempt to provide a set of coherent recommended practices that scientists, managers, funders, and institutions can use as a recipe to coproduce actionable science for resource management. Our terse statements gloss over many of the complexities. For example, the recommendation that universities modify promotion criteria would involve major cultural shifts in some institutions. Similarly, some natural scientists may require training in facilitation, needs assessment, or social science (although many "fall into" these skills by persistent engagement in issues they care about; Brugger *et al.* 2016).

Although it is unlikely that any recipe produces perfect results every time, this set of recommendations fills an urgent need for practical guidance. Coproduction is expensive, time-consuming, difficult, and ambitious, and it will sometimes fall short of achieving actionable science, especially in the initial attempts (Lovbrand 2011). Nonetheless, even partial success is better than not having tried at all, especially if rigorous evaluations provide lessons to guide future attempts.

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Moving Climate Information off the Shelf: Boundary Chains and the Role of RISAs as Adaptive Organizations

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ABSTRACT

While research focusing on how boundary organizations influence the use of climate information has expanded substantially in the past few decades, there has been relatively less attention to how these organizations innovate and adapt to different environments and users. This paper investigates how one boundary organization, the Great Lakes Integrated Sciences and Assessments Center (GLISA), has adapted by creating "boundary chains" to diversify its client base while minimizing transaction costs, increasing scientific knowledge usability, and better meeting client climate information needs. In this approach, boundary organizations connect like links in a chain and together these links span the range between the production of knowledge and its use. Three main chain configurations are identified. In the *key chain approach,* GLISA has partnered with other organizations in a number of separate projects simultaneously, diversifying its client base without sacrificing customization. In the *linked chain approach,* GLISA is one of several linked boundary organizations that successively deepen the level of customization to meet particular users' needs. Finally, by partnering with multiple organizations and stakeholder groups in both configurations, GLISA may be laying the groundwork for enhancing their partners' own capacity to make climate-related decisions through a *networked chain approach* that facilitates cooperation among organizations and groups. Each of these approaches represents an adaptive strategy that both enhances the efficiency and effectiveness of participating boundary organizations' work and improves the provision of climate information that meets users' needs.

1. Introduction

Boundary organizations play an important role in the effort to increase use of scientific knowledge by decision makers. Defined as organizations that stabilize the science–policy interface while assisting the interaction between science producers and users (Kirchhoff et al. 2013a), boundary organizations not only protect the boundary between science and policy, but also bridge and broker knowledge between scientists and decision makers. While research on boundary organizations' role in increasing use of climate information has expanded substantially in the past few decades, there has been

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relatively less attention on understanding how boundary organizations themselves innovate and adapt to different environments and users (but see McNie 2008).

This article focuses on the role of one specific kind of boundary organization, the National Oceanic and Atmospheric Administration (NOAA)-funded Regional Integrated Sciences and Assessments (RISA) program. Created in the late 1990s to both produce and broker climate information, the RISA program has been hailed as one of the most successful climate science boundary organizations in the United States (Dilling and Lemos 2011; Feldman and Ingram 2009; McNie 2013; NRC 2010). At present, 11 RISAs serve a diverse range of climate information users (e.g., water managers, farmers, city managers and planners, forest managers, energy producers, public health managers) by supporting better planning for and in response to climate-driven impacts (Anderson et al. 2010; Pulwarty et al. 2009). In practice, this means that RISA research teams simultaneously carry out research relevant to their regions and actively organize users and events to increase the usability of climate information.

As both producers and brokers of climate knowledge, RISAs have faced many challenges, including those related to knowledge salience and legitimacy (Bales et al. 2004; McNie 2013); how knowledge produced by RISAs and others fits and interplays with users' decision-making processes (Corringham et al. 2008; Furman et al. 2011; Lemos et al. 2012); the level of resources available on both sides of the boundary (Kirchhoff 2013; Lemos et al. 2012; McNie et al. 2007); institutional barriers to knowledge production (Lemos and Morehouse 2005); complexity of knowledge production and use across scales (Kirchhoff et al. 2013a); and a lack of understanding and awareness of information availability (Bolson et al. 2013).

To overcome these challenges, RISAs have been innovative in "adapting" their activities and creating different models of knowledge production and user interaction to bridge the science–policy divide. In this process, they have produced customized knowledge for regional users, have bridged and brokered knowledge produced by others, and have translated and tailored climate science to local contexts (Feldman and Ingram 2009; Guido et al. 2013; Hansen 2002; Hartmann et al. 2002; Jacobs et al. 2005; Lemos et al. 2012; McNie 2008, 2013; Pagano et al. 2002; Rice et al. 2009).

In this article we explore a new approach pursued by one RISA program created in 2010, the Great Lakes Integrated Sciences and Assessments Center (GLISA), organized jointly between the University of Michigan and Michigan State University. We call it the *boundary chains* approach. In this model, GLISA has sought to improve usability of climate information and to minimize transaction costs by connecting a series of boundary organizations like links in a chain. Together, these links span the range between the production of knowledge and its use. Each link of the chain complements the others, both in terms of resources (e.g., technical, human, and financial) and other less tangible capacities (e.g., trust and legitimacy). They build on each other's strengths, share costs, and pool resources while maintaining accountability to each other.

In the following sections, we discuss the boundary chain approach in more detail, using empirical data collected in the context of GLISA's work. Section 2 focuses on the boundary organizations' scholarly literature that informs and supports our analysis (especially that addressing the RISA program). Section 3 reviews the RISA program and briefly describes GLISA and its operating context. Section 4 explores the boundary chain model, focusing on the experience of GLISA. We conclude in section 5 and suggest how these models might evolve in the future.

2. Boundary organizations: Narrowing the gap between science production and use

In the midtwentieth century, philosophers and scholars in the social studies of science struggled to demarcate science from other intellectual activities [e.g., Popper's (1965) "falsifiability criterion" and Merton's (1973) institutionalization of the social norms of science]. Ultimately, these analytical efforts fell short, as they failed to reflect the broader social context and practical ways in which science is routinely parsed from nonscience (Gieryn 1983). In the 1980s, Gieryn (1983, 181–182) argued persuasively that the problem of demarcation was not about defining the characteristics of science; rather, it was about efforts by scientists to set their work apart from nonscientific activities. Gieryn defined these efforts as "boundary work." In addition to distinguishing science from "nonscience," boundary work also established a social boundary for science. It was not long until the boundary idea was extended beyond differentiating science from nonscience to dividing scientific activities from politics or policy. For example, work by Jasanoff (1990) explored how blurring the boundary between scientific advisors and regulatory agencies can lead to productive policy making.

In an idealized model, boundary organizations play two main roles: they bridge across the science–policy divide while protecting each side from potential negative effects, such as the politicization of science or "scientization" of politics (Ehrlich and Ehrlich 1996; Sarewitz 2004). They accomplish these goals not only by acting as an impartial player/broker between science producers and users and being accountable to both sides but also by allowing each side to maintain their separate identities (Guston 1999; Lynch et al. 2008). In general, boundary organizations have at least three characteristics: 1) they involve information producers, users, and mediators; 2) they create and sustain a legitimate space for interaction and stimulate the creation of products and strategies that encourage dialogue and engagement between scientists and decision makers; and, 3) they reside between the worlds of producer and user with ''lines of responsibility and accountability to each'' (Guston 1999, p. 93).

Empirical research focusing on boundary organizations related to climate science—especially work centered on RISAs—has shown that interaction across the production–use divide (e.g., participatory dissemination, iterative models of production, and use) critically affects knowledge usability (Bales et al. 2004; Feldman and Ingram 2009; Hansen 2002; Hartmann et al. 2002; Kirchhoff 2013; McNie 2013). For example, interaction between scientists and users increases use and dissemination of forecasts among networks (Roncoli et al. 2009), may encourage scientific outreach (Frank et al. 2012), and builds trust (Lemos and Morehouse 2005), legitimacy (Carbone and Dow 2005; Lemos and Morehouse 2005; Pagano et al. 2002), and capacity for using the information in decision making (Kirchhoff 2013; McNie 2013) while simultaneously enabling the production of information tailored to a user's needs and operational contexts (Cash et al. 2006). In the context of these interactions, understanding how knowledge fits users' decision needs (*knowledge fit*) and how it connects (or not) to other kinds of knowledge users already employ (*knowledge interplay*) is important to increasing usability (Lemos et al. 2012). In fact, better understanding of how decision environments shape the usability of scientific knowledge remains a wide gap in this literature (Bolson et al. 2013; Furman et al. 2011; Vogel and O'Brien 2006). Finally, interactions that both facilitate convening, translating, and mediating, as well as collaborative processes increase the salience, legitimacy, and credibility of information (Cash et al. 2006).

Yet, despite the positive role boundary organizations play at producing usable information, they face a number of fundamental challenges, such as the mismatch between the size of the producer and user communities, constraints and disincentives that limit the ability of scientists at universities and research organizations to engage with user communities, and constraints users face to engaging with scientists (Dilling and Lemos 2011). In addition, within a given boundary organization's ''jurisdiction,'' the increase in the number of producers and users of climate information may pose an extra burden on climate researchers tasked with providing users with specific products or with evaluating the quality of different sources of information. First, as the demand for information increases, sustaining or expanding intensive producer–user relationships critical to usability can overwhelm the availability of a limited group of producers/brokers to meet the informational demands of an ever-expanding pool of potential users (Bidwell et al. 2013; Kirchhoff et al. 2013a). Part of the challenge in serving user needs is the inherent difficulty of knowing what constitutes the ''right measure'' of bridging versus boundary-protecting activity that both preserves boundary stability and increases science's usability by society (Gieryn 1995; Guston 2001). Second, the tenure and promotion system at many research-focused organizations more often rewards disciplinary-specific basic research over the more interdisciplinary use-inspired basic or applied research produced or brokered by boundary organizations (Dilling and Lemos 2011). Third, these intensive producer–user relationships are not easily sustained by users or producers unless both are willing participants and have the commitment and capacity to do so (Kirchhoff 2013). Overcoming these obstacles requires creativity and leveraging resources that minimize the workload and risks for both organizations and individuals.

3. RISAs as boundary organizations

The RISA program, established by NOAA, facilitates integrated and interdisciplinary, place-based research and assessment (Pulwarty et al. 2009; Simpson 2009). The RISAs are experiments in novel approaches to address the paucity of climate information use in decision making despite the rapid advancement in climate information products and models. Specifically, RISAs have four main goals: 1) advance the understanding of policy, planning, and management contexts; 2) develop regionally relevant knowledge on impacts, vulnerabilities, and response options through interdisciplinary research and participatory processes; 3) innovate products and tools to enhance the use of science in decision making; and 4) test diverse governance structures for managing scientific research (for more information see http://cpo.noaa.gov/ClimatePrograms/ClimateandSocietalInteractions/RISAProgram.aspx). RISAs bring together natural, physical, and social scientists to work alongside regional, state, and/or local clients to identify critical issues, decision-making needs, and information gaps, and to ultimately coproduce usable climate information to meet identified needs (Pulwarty et al. 2009).

Empirical research on RISAs as boundary organizations suggests that there are three main reasons why they are relatively successful: 1) they facilitate effective two-way communication and coproduce user-driven knowledge (Bales et al. 2004; Feldman and Ingram 2009; Lemos and Morehouse 2005; Rice et al. 2009); 2) they produce credible, salient, and legitimate information (Hansen 2002; McNie 2013); and 3) they are stable and long-term (Kirchhoff et al. 2013b; McNie 2013). In particular, RISAs benefit from NOAA's long-term commitment, as each RISA's initial 4–5-yr awards are often extended through periodic competition-based renewals. While there is no guarantee of success (proposals for continuation can be denied or moved to a different home organization), the RISA programs have been remarkably stable for the past 15 years. The longevity of RISAs supports the creation of decision-relevant research programs and the formation and maintenance of dedicated user networks (Anderson et al. 2010; Feldman and Ingram 2009; Pulwarty et al. 2009). In turn, these long-standing client networks help the RISAs identify, develop, and continue to refine information to meet client needs (Anderson et al. 2010; Corringham et al. 2008; Guido et al. 2013; Hansen 2002; McNie 2013) and overcome barriers to information use (Kirchhoff 2013; Rice et al. 2009). But RISAs are also resource intensive and limited in the range of users they can serve, especially considering the potential for a growing demand at the regional level.

GLISA as an adaptive boundary organization

In 2009/10, NOAA launched a competition for two new RISA regions alongside recompeting awards for some of its existing programs. One of the new awards was for GLISA. Drawing on resources based at the University of Michigan and Michigan State University, GLISA serves potential users of climate information in a region that spans eight U.S. states (Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York) and the province of Ontario in Canada. GLISA's climate science efforts involve both developing tailored, locally scaled climate science for potential users and engaging in dialogue with them.

From the outset, the GLISA core team (project codirectors and co-principal investigators) actively considered interactive approaches for producing and disseminating information, building upon what could be learned from the experience of other RISAs. Taking advantage of both published empirical research on RISAs and knowledge from the tight network of RISA scientists and stakeholders, GLISA sought to innovate on two fronts. First, it developed an adaptive approach organized around a flexible research program that is committed to solicit, review, and select research proposals through a small grants competition (up to $50,000, 1-yr duration) held annually. The competition sought proposals from other organizations that involved both creating usable science and bridging/brokering it to regional users (for more information, see section 4).[1] This approach recognized that research needs and emphases evolve over time in response to both science advancements and changing input from stakeholders.

Second, GLISA chose to add value to existing climate knowledge (e.g., tailoring and customizing) to meet regional stakeholders' needs, rather than developing its own in-house climate research. Accordingly, GLISA's climate science team: 1) identified best practices for the use of climate information in decision making in the Great Lakes region; 2) created an archive of climate projections for the Great Lakes region from multiple sources, organized metadata to facilitate their use by scientists and stakeholders, and created an avenue for their uptake through ongoing interaction with users (e.g., meetings, phone conversations, e-mails, coproduction); and 3) developed a web portal to facilitate the delivery of these resources. Meanwhile, GLISA's social science team assessed stakeholders' contexts and networks and the development and application of climate science in the region. They also initiated a series of comparative assessments for the different stakeholder groups served by GLISA. As a part of this approach, GLISA's online presence includes a compilation of available resources and a collaboration space for project teams (www.glisa.umich.edu). Next, we discuss the work being carried out in the context of these relationships and how they can represent a viable path not only for other RISAs but also for other boundary organizations.

4. Boundary chains: Pooling resources and spreading costs

GLISA's first grant competition in 2011 focused on funding climate-related research projects, requiring each of them to include a stakeholder-driven component to their core activities. In this competition, GLISA funded four small grants in the Great Lakes region, ranging from assessing the impacts of climate change on Great Lakes evaporation and lake levels to a modeling framework for informing the decision makers' response to extreme heat events. GLISA also collaborated in a fifth project funded by the Charles Stewart Mott Foundation to a local nongovernmental organization (NGO), the Huron River Watershed Council, to create a stakeholder group around water management challenges in the Huron River watershed. GLISA's portion of the project specifically

[1] To the best of our knowledge, the only other RISA that implemented a small grants competition is the Alaska Center for Climate Assessment and Policy, but in that case the competition was focused on in-house applied research projects.

focused on adding climate impacts to the range of problems the water management group targeted. While the results in terms of stakeholders' involvement in the four more traditional scientific projects were mixed (see http://www.glisa.umich.edu/ for more details), the interaction with the Huron River Watershed Council offered the best promise of close and sustained iteration with stakeholders.

Following GLISA's adaptive management approach, the core team evaluated the effectiveness of the first competition in terms of actively fostering the usability of climate information. Originally, the goal of funding these projects was to leverage GLISA's limited resources to add value to existing climate-related research (by funding a stakeholder-driven component) in the Great Lakes region, rather than developing in-house applied research projects. However, one significant limitation of partnering with ongoing research-driven projects was the relatively limited opportunity it afforded for building long-term iterative relationships between producers and users of scientific knowledge. Such relationships often depend on factors such as trust and ongoing communication between producers and users as well as a willingness of all involved to interact and invest in the coproduction of usable science. The experience with the first competition showed that while the small grants competition succeeded in leveraging GLISA resources to include stakeholders, it fell short from critically increasing knowledge usability, especially when compared with the outcome of the Huron River Watershed Council partnership.

Learning from this experience and after considering different ways to overcome the transaction costs involved in building long-term relationships in the context of limited human, technical, and financial resources, the idea of partnering with other boundary organizations that already have ties to stakeholders emerged as a testable approach. In this model, rather than serving as a central boundary organization for all producers and users of climate information in the Great Lakes region, GLISA supports and partners with other boundary organizations to leverage their long-term relationships with stakeholders. The rationale was that such partnerships would reduce the transaction costs of increasing climate change usability by spreading costs, pooling resources, and fine-tuning roles over time to provide the level of fit and support necessary for meeting stakeholder information needs.

a. Three models of boundary chains

Conceptually, the GLISA experience advances three configurations of boundary chains beyond the more conventional relationship in which boundary organizations directly connect with each information user (Fig. 1). In the

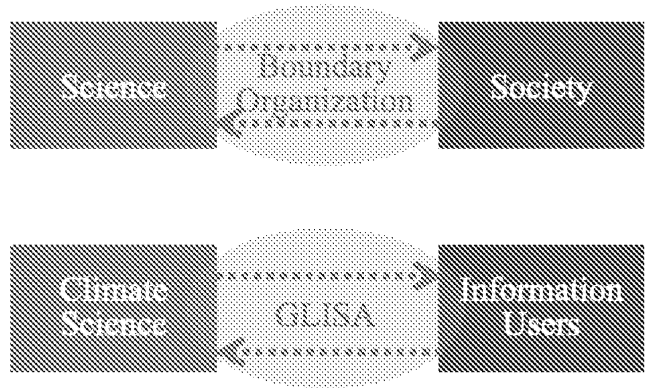

FIG. 1. Traditional boundary organization arrangement.

key chain arrangement (Fig. 2), boundary organizations maximize their limited resources by collaborating with a range of other boundary organizations that increase the potential diversity of users served (e.g., water and forest managers, urban planners). In each of these links, knowledge use can range from building awareness of potential information products to the actual creation of specific products customized for specific users and uses. However, in the context of these relationships, it might be necessary to engage more than one link to efficiently close the gap between producers and users, leading to the second configuration: a *linked chain* arrangement (Fig. 3). In it, some end users may require several steps of customization or filtering through different boundary organizations (links) before information can be applied (e.g., to their decision support tools). In these instances, each link (boundary organization) gets one step closer from the two bookend functions of science production and science use. Ultimately, the links forming each of these individual chains may benefit from interactions with each other, leading to the development of our third configuration, the *networked chain* arrangement (Fig. 4). This arrangement maximizes each boundary organization's potential role as a true bridging organization, connecting the needs of an organization down one chain with the resources of an organization down another chain. Over time, it may even be possible to imagine cultivating such a relationship network as a means of maximizing regional institutional capacity to apply climate information. In all three conceptualizations, the way the links are arranged can add flexibility and reach to boundary organizations, allowing them to become more adaptive to changing conditions (e.g., evolution of information needs, emergence of new information needs, nonlinearity in climate impact and response). In other words, boundary chains offer the potential for a high level of customization of information without sacrificing diversity (of users or their information needs, or of the kinds of interactive approaches used to address those needs).

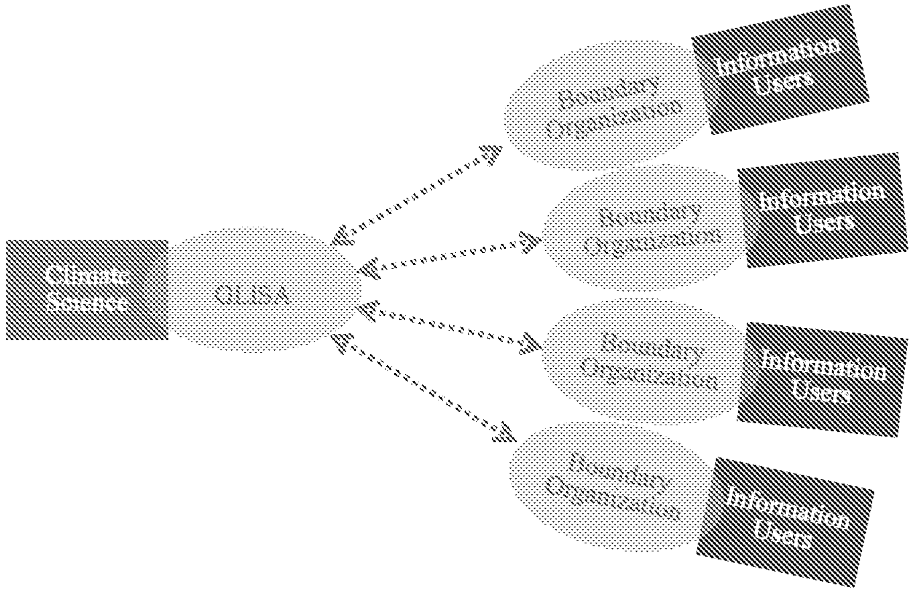

FIG. 2. Key chain arrangement.

In practice, GLISA initiated two boundary chains by building partnerships across two parallel processes. The first is a dedicated small grant competition focusing on building partnerships with boundary organizations already working with stakeholders in areas that intersect with climate change impact. The second is through opportunistic relationships with other boundary organizations that sought GLISA as a partner outside of the formal funding mechanism. In the next three subsections, we discuss the boundary chains' experience and speculate on the potential evolution of the process into a broader network that is more sustainable over time.

b. *Broadening the diversity of users: The key chain approach*

In 2012, GLISA launched a second grants competition, this time focusing on other organizations that could support and enhance its mission of coproducing climate information and increasing information usability. As a result of that competition, GLISA awarded six 1-yr grants of financial and informational support to organizations that have experience interacting directly with policy and decision makers in the Great Lakes region, in effect creating a key chain of boundary organizations (Fig. 2). The funded organizations and their projects in this round of competition were 1) Michigan State University Extension (MSU Extension), to provide technical support for master plan development processes in Benton Harbor and Marquette, Michigan; 2) Illinois–Indiana Sea Grant, to support the city of Chicago's efforts to incorporate changes in winter weather events into their ongoing climate adaptation work; 3) the Northwest Michigan Horticulture Research Station (NMHRS), to provide assistance to the local tart cherry industry, which was greatly affected by variable spring weather in 2012; 4) the Toronto and Region Conservation Authority, to support both farmers and those responsible for municipal shoreline management in the Region of Peel, Ontario; 5) the Nature Conservancy, to perform an expert solicitation to better understand the performance of agricultural best management practices (BMP) under climate change; and 6) the Huron River Watershed Council, to continue the work started with the Charles Stewart Mott Foundation funding. Each organization took on the role of brokering knowledge to and/or coproducing knowledge with their stakeholders. A summary of GLISA's boundary organization partnerships is provided in Table 1.

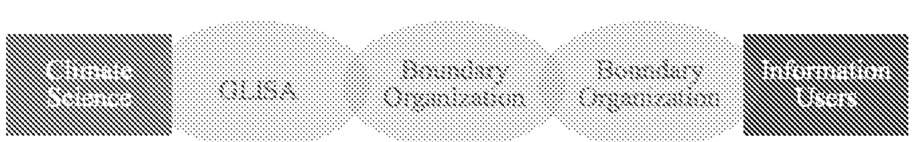

FIG. 3. Linked chain arrangement.

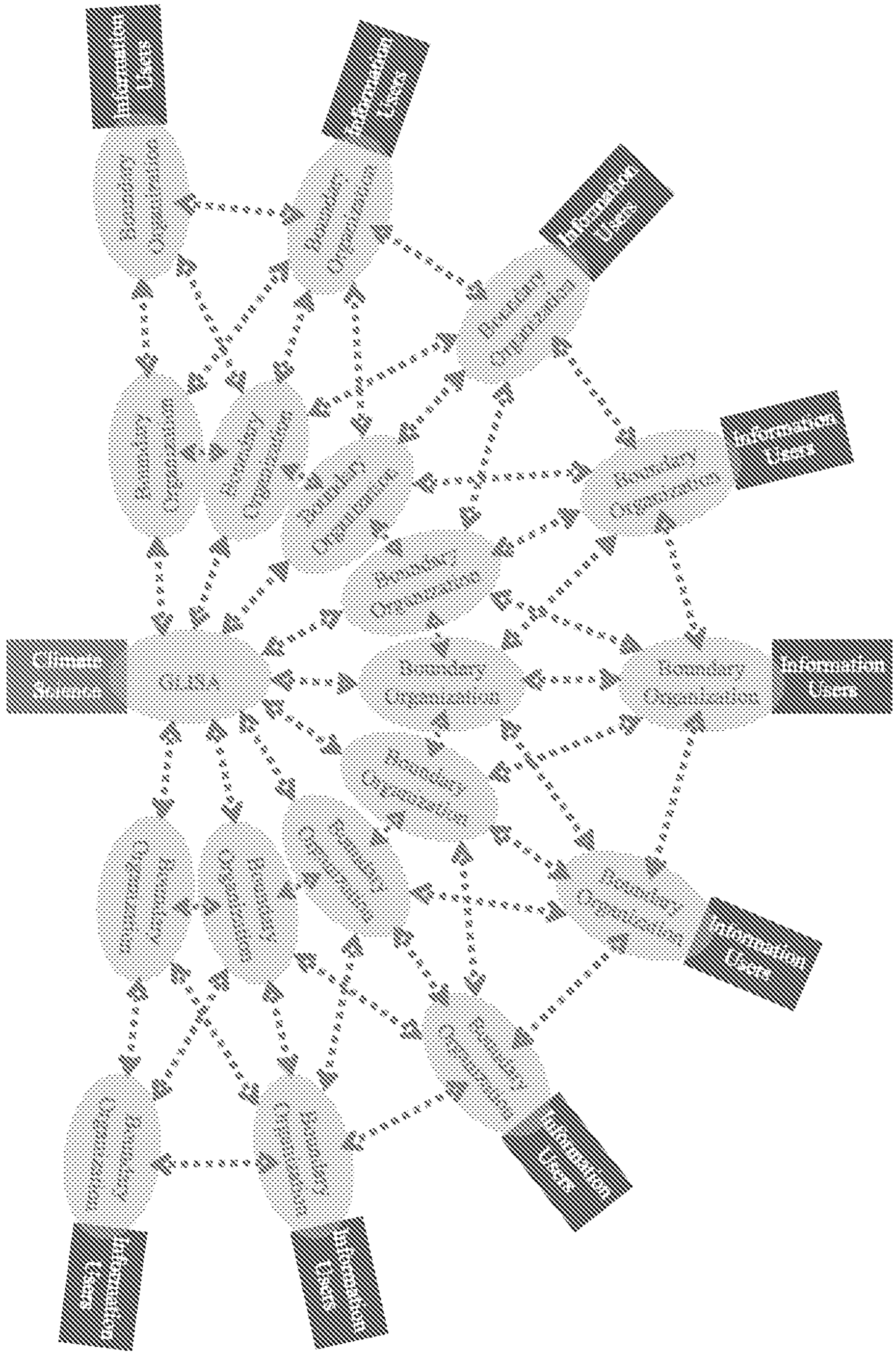

FIG. 4. Networked chain arrangement.

Whereas some of these organizations did not define themselves initially as traditional boundary organizations, by subscribing to the terms of the competition's request for proposals, they agree to act as de facto boundary organizations in their relationship with GLISA and with the stakeholders with whom they work. Hence, as part of the second competition, awardees committed to participate in a step-by-step evaluation of the interaction between GLISA climate scientists and representatives at each linked boundary organization as well as between each linked boundary organization and the stakeholders they target. This includes collecting information both before and after interactions with GLISA data, and allowing GLISA social scientists to observe the interactions between GLISA climate scientists, partner organization staff assisting with information brokering, and stakeholders. GLISA social scientists have been following these interactions, tracking the processes of

TABLE 1. Summary of GLISA boundary organization partnerships.

Boundary organization partner	Project goals	Stakeholders	Bridging events and coproduced outputs
GLAA-C	Bring researchers and practitioners together to support the creation of actionable programs for climate adaptation in cities in the Great Lakes region	Ann Arbor, Dayton, Flint, Kingston, Thunder Bay, and Toledo	Workshops held throughout the region featuring GLISA climatologists; local historical and future climate projections and socioeconomic data (through Headwaters Economics)
Huron River Watershed Council	Bring stakeholders in the watershed together to understand how their communities can maintain quality of life under different climate change scenarios and to provide the information needed to make adaptation decisions	Managers of water, in-stream flows, and natural infrastructure in watershed communities	Six monthly meetings, presentations about local historical and future climate, Ann Arbor and southeast Michigan climatologies, and fact sheets and reports for three sector groups (water infrastructure, in-stream flows, and natural infrastructure)
Illinois–Indiana Sea Grant	Easily understandable wintertime climate change indicators that Chicago and other cities can use to monitor wintertime impacts and the efficacy of adaptation planning	City of Chicago	Presentation and report to city officials based on interviews and input from GLISA climatologists; freeze–thaw cycle and "wet snow" projections
MSU Extension	Assess community vulnerabilities and strengths and prioritize adaptation strategies through a discussion-based, deliberation-with-analysis process	City of Marquette and SWMPC	Public input sessions in both cities with GLISA presentations and reviews, historical trends on Great Lakes ice cover, precipitation, lake levels, and temperature and climate sensitivity maps
NPS Climate Change Response Program	Bring together park officials and other experts to develop and explore four divergent but plausible scenarios of future climate and associated ecological responses to support current and future decision making needs	Isle Royale National Park	Presentation and discussions at workshop including GLISA and other experts and park officials, local historical and future climate projections (e.g., climate summary table, least change scenario, matrix of plausible scenarios), and a NPS report about the process
NMHRS	Compile information to help the tart cherry industry make choices about risk mitigation and resource appropriation, foster understanding of climate variability and extreme events	Michigan tart cherry farmers	Workshops, panels, and presentations at annual industry Northwest Michigan Orchard and Vineyard Show; relevant local historical and future climate projections (e.g., date of plant "side green")
Nature Conservancy	Assess the implications of climate change for agricultural BMP for conservation, use expert solicitation to recommend changes to existing models that incorporates BMP performance under changing climate	Agriculture and water quality modelers, groups working to minimize the impact of farming on water quality	Final report and recommendations for modeling based upon expert and stakeholder feedback
Toronto and Region Conservation Authority	Pilot a method for risk identification and analysis based on future climate ensembles, scope adaptation options for climate change impacts/hazards facing the region	Port Credit and farmers in the Region of Peel	"Keep it Growing in Peel" farmer workshop and two workshops for Port Credit risk identification; presentations, assessments, and risk assessment methodology

information brokerage comparatively as they evolve in different contexts. This involves, first, carrying out in-depth interviews and surveys with GLISA staff, their boundary organization partners, and the potential users of climate information; and then compiling updates at 3-month intervals throughout the year and at the close of the funded year to gauge development over time. By acting as a bridge between GLISA climate scientists and their stakeholders, these organizations are also able to maintain accountability across the chain. On the one hand, by adding value to and tailoring climate scientific knowledge in response to their partners' requests, GLISA scientists are accountable both to other climate scientists and to the partners in the chain. On the other hand, by procuring knowledge and "customizing" it (in terms of communicating and application) to their stakeholders, partner organizations are accountable to their stakeholders while keeping the boundary protected.

Preliminary observations of these projects suggest that linking to other boundary organizations successfully leverages and bolsters GLISA's services through the diversity of roles and support opportunities that have emerged through these links. Moreover, these initial activities are, at a minimum, fostering awareness of climate impacts and of GLISA's products among a wider range of stakeholders than possible under the one boundary organization model, as well as improving information usability. The extent to which these activities will continue to foster and deepen climate information use by decision makers is part of an ongoing evaluation. However, even this early in the process, we already can identify two distinct paths in the interaction among GLISA, other boundary organizations, and groups of stakeholders.

In the first path, the interaction between GLISA climate scientists and stakeholders progressed relatively quickly toward a quasi-service model in which tailored information is shared with potential users. For example, MSU Extension worked closely with GLISA to explore adaptation priorities for the city of Marquette in Michigan's Upper Peninsula and the Southwest Michigan Planning Commission (SWMPC). GLISA provided information requested by SWMPC and Marquette on temperature, precipitation, ice cover, and lake levels. MSU Extension used these data as input for SWMPC and Marquette to perform climate change self-assessments based on Sea Grant's "A Self-Assessment to Address Climate Change Readiness in Your Community: Midwest Region" (Sea Grant 2012). The data were also used to develop vulnerability maps that the cities are using for communication and planning purposes. In addition to information, community engagement sessions were completed in Marquette and Benton Harbor to obtain feedback from residents about their vulnerability concerns and preferences about adaptation options. MSU Extension and GLISA collaborated closely not only in tailoring climate information for these events, such as developing historical climatologies and future projections to address locally relevant vulnerabilities, but also in designing the structure of the engagement process so that it was sensitive to the interests and experiences of local residents and officials. For example, following challenges with disruptive attendees of an initial public meeting in one location, MSU Extension, GLISA, and local clients adjusted the subsequent event to have a more structured format than the first. Accordingly, GLISA changed how local climate impacts were presented as well how to frame discussion of future changes more positively, focusing more on observed changes rather than the more controversial projections of future climate. These community engagement sessions provided insights about residents' interests that informed the next stage of adaptation strategy prioritization.

In a second example, interviews performed by the Illinois–Indiana Sea Grant program with the city of Chicago identified climate information needs that GLISA helped provide, such as the influence of climate change on the frequency and intensity of ice storms and heavy, wet snow events. Such storms can produce widespread power outages. The realization that climate models project that changing temperatures will produce more heavy, wet snow events has already stimulated conversations within the city. For example, city officials have begun discussing contingency plans for community "warming centers" that can provide shelter even when electrical power lines are down.

The second path in the key chain model is exemplified by GLISA's relationship with the Toronto and Region Conservation Authority and the Nature Conservancy, where GLISA is taking on more of a networking function. In one example, in addition to GLISA providing informational support, the Toronto and Region Conservation Authority is looking at its collaboration with GLISA as an opportunity to link with other information-producing organizations like NOAA's Great Lakes Environmental Research Laboratory (GLERL). In the future, such connections could come to represent an additional link in the chain of tailoring climate information. Another example is the Nature Conservancy's leveraging GLISA's connections to other researchers to identify a pool of regional experts with whom they can engage to better understand and assess the potential impacts of climate change on the performance of agricultural best management practices. Rather than providing information, GLISA is providing connections to its own networks that help to support the Nature Conservancy's work. GLISA has also helped strengthen its connections with other small grant recipients like MSU Extension and has linked them to a researcher at Wayne State University who can provide methodological support for their expert elicitation effort.

Without a designated control group, it is hard to assess how the role of previous relationships that our partner organizations had with stakeholders might have accelerated the process of building trust and legitimacy in the context of users' decision environments. However, it is reasonable to expect that had GLISA started these interactions with stakeholders from scratch, the process of establishing trust and successful lines of communication would have been more costly in terms of time, human, and technical resources.

c. *Deepening customization: The linked chain approach*

In addition to the small grants project, GLISA engaged in relationships with two other organizations: the National Park Service (NPS) and the Great Lakes Adaptation Assessment for Cities (GLAA-C). For GLISA, these relationships represent the linked chain approach (Fig. 3).

The NPS initiated contact with GLISA, following from the NPS's productive engagement with RISA centers in other regions. Though the project focused narrowly on Isle Royale National Park, the engagement was managed by the NPS's Climate Change Response Program (for more information, see http://www.nature.nps.gov/climatechange/). The Climate Change Response Program performs boundary organization functions as it "works to foster communication, provide guidance, scientific information, and recommendations that support stewardship actions to preserve our natural and cultural heritage from the detrimental impacts of global climate change" (for more information see http://www.nps.gov/orgs/ccrp/index.htm). NPS's goal for the project was to create an adaptation plan for Isle Royale National Park focused on how climate change influences the decisions that park staff will make in managing the park's wolf–moose predator–prey ecosystem.

The NPS has a scenario-planning process that steers its development of adaptation plans (Weeks et al. 2011). Its initial engagement in this project included a small number of people from the Climate Change Response Program and GLISA (for a detailed description, see http://glisaclimate.org/project/isle-royale). Using its significant level of scientific resources, the NPS prepared descriptions of climate change based largely on previously published assessments and datasets (Parry et al. 2007; Solomon et al. 2007; Mitchell and Jones 2005). GLISA was first engaged to review this material and to tailor it to NPS users based on 1) more recent literature, 2) climate parameters of special importance to the park (e.g., lake ice), and 3) local effects on weather and climate. Through many conversations between GLISA climate scientists and NPS personnel, a "complete" climate change table was generated that teased out important climate parameters and included recent literature and local expertise. To this first table, others were added representing different scenarios (for a detailed description of the scenarios including the "least change scenario," see http://glisaclimate.org/wiki/isle-royale-least-change-climate-scenarios) that became the foundational material to a conference that included a complete range of discipline experts and managers, including GLISA personnel. Here, GLISA provided a narrative description of localized climate information, past, present, and future (http://glisaclimate.org/sites/default/files/20130114_Isle_Royale_Climate_Adaptation_Localization.pdf). Using the NPS scenario planning process, climate information was combined with other information, especially forest ecology, to develop a set of plausible scenarios of disruptive events that were then synthesized with management tensions between park priorities. The outcomes of this process were four divergent but plausible scenarios that synthesized ecological response to climate and climate-related factors. Participants in the meeting subsequently subjected each of these scenarios to four management responses.

When the scenarios were compared to initial expectations documented in the initial table of climate drivers and the incremental impact of climate change, two important issues emerged. First, the climate discussion evolved from incremental effects of temperature and precipitation change toward the role of high-variability processes such as the Arctic Oscillation, which is the largest statistical predictor of persistent extreme weather anomalies in the Northern Hemisphere (Carbone and Dow 2005). The focus on variability of extreme weather was indicative of the workshop participants' growing focus on adaptive management. Rather than viewing climate change as a straightforward progression of changes, participants considered the complex interaction of the dynamic climate system with park ecosystems. For participants, the result was a greater understanding of the necessity of developing strategies that accounted for more uncertain future conditions by cultivating greater ecosystem resiliency and planning for adaptive management via 3–5-yr assessments. Second, the focus of the discussion evolved from trying to preserve the past conditions on Isle Royale to how to achieve the best possible future and make sound resource investments for an ecosystem facing inevitable change. For example, because Isle Royale is a fragile transition zone between northern hardwood and boreal forest, some of its most significant inhabitants from an ecosystem perspective will be lost as climate change makes the area uninhabitable for boreal species. Better understanding of these processes is crucial to supporting NPS's planning for the future.

In this example, GLISA is one link in a longer chain formed by the NPS, its Climate Change Response Program, and the Isle Royale Park staff. The NPS and its Climate Change Response Program's facilitation role made interactions with Isle Royale much more efficient. Through repeated interactions, GLISA and NPS's Climate Change Response Program tailored climate information into a frame that would more easily fit Isle Royale's actual approach of making decisions. In addition, the NPS provided links to other sources of scientific expertise that helped interpret the implications of GLISA's climate projections for NPS staff. In the critical workshop session where all of these links came together, representatives from Isle Royale gave feedback to the representatives of GLISA and the NPS that ultimately resulted in Isle Royal representatives' current information needs being more directly met.

The linked chain approach is also well represented by GLISA's interaction with GLAA-C. GLISA's core involvement is helping GLAA-C respond to cities' requests for narrative descriptions of changes that have taken place in their own climate. GLISA climate scientists developed specific climatology products for the cities based on summaries of local temperature and precipitation observations. The climatologies also include seasonal and annual mean presentations of information as well as basic measures of extremes (for an example of the region's and cities' climatologies, see http://glisa.umich.edu/great_lakes_climate/climatologies.php and http://www.glisa.umich.edu/docs/WindsorON_Climatology.pdf). To support the Great Lakes cities' climate adaptation decisions, GLAA-C formed the Council of Sustainable Cities, composed of six cities in the U.S./Canada Great Lakes Basin. The council and GLAA-C meet every 6 months in person and more often through conference calls, reinforcing a closely interactive relationship. GLAA-C also engaged the participation of Headwaters Economics, an independent, nonprofit research organization, to tailor socioeconomic data to support the cities' adaptation decisions. With these efforts, GLAA-C leverages human and technical resources to bring together different sources of climate adaptation information for the cities (for more details see the project description at http://graham.umich.edu/glaac/).

GLAA-C has also organized specialized events (local workshops) in which all the information in support of adaptation (climate and nonclimate based) is discussed by different city officials and sectors projected to be negatively affected by climate change impacts. In these events, participants discuss how GLISA information can be tailored to fit city officials' decision processes (knowledge *fit*) as well as how it may interplay with other information that is important for adaptation (e.g., socioeconomic data, adaptation options) and/or other kinds of knowledge currently being used by city officials (knowledge *interplay*). As brokers of information, GLAA-C personnel organized meetings where different kinds of information were presented and discussed through visually attractive prepared materials that combined climate and nonclimate information (see http://graham.umich.edu/glaac/research), and created an environment for the communication of both scientists' and decision makers' challenges and expectations. While the long-term outcome and sustainability of the chain between GLISA, GLAA-C, other organizations such as Headwaters Economics, and the cities is uncertain, at this point the expectation is that this kind of iteration will accelerate the usability of climate (and nonclimate) information.

d. *Developing capacity: The networked chain approach*

GLISA's relationship with the NPS and GLAA-C is based on complementary roles that together enhance the fit and interplay of climate information and hence the usability of information to stakeholders' decision processes. The potential to extend usability via retailing information to other similar users in the region offers the promise of further strengthening regional knowledge networks both geographically (GLAA-C) and sectorially (the NPS) through networked chains (see Fig. 4).

The evolution of the GLISA model from a more traditional approach of brokering and bridging information directly to clients to growing diversification and customization through boundary chains suggests the possibility that the links that are created could become sustainable network ties in the future. Consistently providing the opportunity for GLISA boundary organization partners to interact both through required conference calls and annual meetings allows for the exchange of information and experiences. For example, when working on its outreach to farmers, the Toronto and Region Conservation Authority benefited from discussions it had with other GLISA grant recipients from MSU Extension about its own experiences with the agricultural community. In addition, discussions of weather phenomena between GLISA and other boundary organizations in the networked chain have exposed the network of stakeholders to new knowledge and impacts previously not considered. For instance, the Toronto and Region Conservation Authority is now interested in the ice storm and snow descriptions that GLISA initially developed for the Illinois–Indiana Sea Grant program with the city of Chicago. Sustained communication and interaction through a broader network of boundary organizations and stakeholders may not only increase usability among participants but it may also speed up the dissemination of climate information both within the network and potentially to other networks as well. However, exploring the characteristics and drivers of such a network may require a longer maturation time and further investigation of the processes initiated by GLISA.

5. Conclusions

As boundary organizations, RISAs have been notably successful in enhancing the production and use of climate information. However, they also face the challenges of high transaction costs and a limited range when engaging in highly interactive relationships with stakeholders, especially with the potential for increased demand for climate information in the future. Seeking to adapt and innovate and become more responsive to changing conditions and resources, RISAs have been trying different models of interaction to achieve their dual goals of producing/brokering relevant regional climate information and increasing its usability. In this article, we describe GLISA's efforts to share transaction costs and pool resources through a new model of stakeholder engagement, the boundary chains approach. We identify three main types of chains: the key chain approach, through which GLISA partners with a number of different boundary organizations to diversify its client base; the linked chain approach, in which GLISA is one of a number of organizations spanning the range between information production and use, and the networked chain approach, in which partnering organizations from different chains establish supportive relationships with one another. In each of these approaches, the goal is to minimize transaction costs and increase usability by building on each link's strengths to complement and leverage resources and experiences.

GLISA is using the key chain approach to leverage resources and capacities (especially trust and legitimacy) with six other boundary organizations. These boundary organizations have both long-term, established relationships with stakeholders and the ability to broker and bridge climate information produced by GLISA climate scientists (and others) with their stakeholders. Using the linked chain approach, GLISA is providing customized climate information while other organizations help to further tailor the information, drawing on their understanding of stakeholders' decision contexts to help improve information fit and interplay. Through the currently nascent networked chain approach, GLISA is playing a guiding role in cultivating relationships between partnering boundary organizations facing similar challenges. In all of these approaches, GLISA is seeking to increase the range of clients it can serve while preserving its ability to sustain close levels of interaction with each of them. Moreover, by creating links between complementary boundary organizations in a larger network, GLISA expects to strengthen individual links such that the network may be more sustainable in the long run.

The ongoing formation of such networks emphasizes the adaptive quality of "linked" approaches to connecting climate science with decision making. These approaches foster flexibility in two important ways: first, there is flexibility to add and subtract new contributors to suit changing requirements for each application as they arise and are resolved. Second, as illustrated in the cases described herein, flexibility is also enhanced in the supported organizations, as they have the opportunity to tailor the process itself to suit their emerging and evolving needs.

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Moving toward the Deliberate Coproduction of Climate Science Knowledge

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ABSTRACT

Coproduction of knowledge is believed to be an effective way to produce usable climate science knowledge through a process of collaboration between scientists and decision makers. While the general principles of coproduction—establishing long-term relationships between scientists and stakeholders, ensuring two-way communication between both groups, and keeping the focus on the production of usable science—are well understood, the mechanisms for achieving those goals have been discussed less. It is proposed here that a more deliberate approach to building the relationships and communication channels between scientists and stakeholders will yield better outcomes. The authors present five approaches to collaborative research that can be used to structure a coproduction process that each suit different types of research or management questions, decision-making contexts, and resources and skills available to contribute to the process of engagement. By using established collaborative research approaches scientists can be more effective in learning from stakeholders, can be more confident when engaging with stakeholders because there are guideposts to follow, and can assess both the process and outcomes of collaborative projects, which will help the whole community of stakeholder-engaged climate-scientists learn about coproduction of knowledge.

1. Introduction

As we come to grips with the impacts of climate change on our natural and cultural resources, our cities and towns, and our personal health and well-being, the production of "usable" climate knowledge—information that can help inform management, planning, and governance—has become a goal for many scientists, agencies, and governments. One promising way to develop usable climate knowledge is to coproduce it. Coproduction of knowledge is the process of producing usable, or actionable, science through collaboration between scientists and those who use science to make policy and management decisions. Coproduction involves collaborations between scientists and decision makers to frame research questions, decide how to answer the questions, and analyze the findings (Lemos and Morehouse 2005). Research on the outcomes of collaborations between scientists and decision makers has shown that when knowledge is coproduced it is more likely to be accepted and used by decision makers. By participating in its production, the information becomes more transparent to end users (Jasanoff and Wynne 1998); the process by which the information is produced is perceived to be more legitimate (Cash et al. 2006); the information is more likely to be at spatial and temporal scales useful to decision makers (Dilling and Lemos 2011); the knowledge is easier to integrate with existing information because it fits into the decision framework of the agency or organization (Carbone and Dow 2005; Lemos et al. 2012); and the end users gain a greater sense of ownership over the final product because they have contributed to it (Robinson and Tansey 2006). Because coproduction of knowledge takes time and resources to do well and is a process that is not well understood there are currently a limited numbers of scientists who undertake it (Cvitanovic et al. 2015; Shanley and López 2009), contributing to a gap between

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the number of people producing usable climate science and the demand from users for that information (Dilling and Lemos 2011; Lemos et al. 2014).

This paper aims to help close that gap by presenting several examples of modes of engagement and collaborative research approaches that can be used to structure a process of coproduction of climate science. Mode of engagement refers to the basic character of the interactions between scientists and decision makers. Research approaches mean a set of guidelines and activities designed to guide collaborative processes and data collection methods in order to achieve the overall research goals. We hope to lower the barriers to coproduction of knowledge by framing these approaches—action research (AR), transdisciplinarity, rapid assessment process (RAP), participatory integrated assessment (PIA), and boundary organizations—as tools to help guide and support researchers undertaking this challenging, yet rewarding, research. Several of these approaches have been used in climate science knowledge production (transdisciplinarity, PIA, and boundary organizations) and two (AR and RAP) are more generally associated with social science or development work. All of these approaches have been tested over time and in various contexts and been shown to be effective in engaging community members and decision makers in research processes.

The key elements in a successful coproduction process have been identified generally as building ongoing relationships between scientists and stakeholders, ensuring two-way communication between the groups, and maintaining a focus on the production of usable science (Dilling and Lemos 2011; Lemos and Morehouse 2005; National Research Council 2009). The factors required to support these activities are typically ensuring that the science team has the technical and disciplinary capabilities to answer the question; ensuring that both groups have the ability to facilitate the relationship; and ensuring that the science team has the resources (money, time, people) to complete the work in a timely and effective manner (Cvitanovic et al. 2015; Shanley and López 2009). However, confusion remains about exactly what should occur in a coproduction process to yield actionable science—what coproduction actually "looks like"—and why seemingly actionable science is not always used by decision makers. Although many factors may influence the use, or lack of use, of climate science in decision making, we propose that one factor inhibiting its use is that the knowledge is not genuinely being coproduced. Rather, researchers and decision makers may be interacting to some degree, but that interaction may be fairly superficial and may not be sufficient to result in coproduction of knowledge (Pregernig 2006). In other words, there has been too little attention given to planning for and execution of intensive and effective collaborative research activities that can lead to the coproduction of usable climate science.

Research on public participation in policy making has demonstrated that the ways in which participatory processes occur matter to the outcomes. More extensive engagement, such as through negotiation and mediation activities, tends to lead to higher-quality policy decisions, while cursory public or management input at meetings does not (Beierle 2002; Rowe and Frewer 2005). However, inexperience among researchers, insufficient resources, or a lack of clear guidance on best practices in collaborative knowledge production—or a combination of these and other factors—may hinder efforts to coproduce usable climate science. We argue that one way to improve the process of coproduction is to follow an established collaboration protocol, grounded in participatory research literature, because it can provide guidance on how to plan and manage collaborative activities, frameworks in which to examine stakeholders' decision contexts and concerns, and guidance on resources required to undertake collaborative research; it can also create better opportunities to evaluate the effectiveness of coproduced knowledge through comparative analysis. Using an established approach can help ensure that we "get the right participation and get the participation right" (Stern and Fireberg 1996). We present a small sample of approaches that can be applied to collaborative climate research. This is not an exhaustive list, but the approaches have been selected to present a range of possible ways to structure a coproduction process, depending on the research question, strengths of the research team, available resources, and the needs of the stakeholders.

2. An evolution in thinking about the dialogue between science and policy: How did we get to the idea of coproduction?

In the decades following World War II, U.S. science policy was heavily influenced by Vannevar Bush's report titled "Science, the Endless Frontier" (Bush 1960). Bush articulated a vision for the contribution of scientific knowledge to society wherein "basic" research generated new knowledge and "applied" research found practical applications for that knowledge. This reasoning resulted in a linear model of science policy through which knowledge was generated in one domain (science) and then handed off to a recipient domain (society). The two sectors were intentionally isolated (Byerly and Pielke 1995; Pielke 1997; Stokes 1997) in order to insulate science from the value-laden world of applications.

By the early 1970s this linear model of science was critiqued as insufficient for dealing with complex, ''wicked'' problems that require scientific knowledge but also ''rely upon elusive political judgment for resolution'' (Rittel and Webber 1973, p. 160). Environmental issues, including climate change, are often cited as the epitome of wicked problems because they involve differing values that result in conflicts that cannot be solved by the simple application of scientific knowledge. As Ludwig (2001, p. 763) noted, ''[t]here are no experts on these problems, nor can there be.'' Instead, the new reasoning goes, we should establish and maintain a dialogue among the various interested parties, creating a process ''in which scientific expertise takes its place at the table with local and environmental concerns'' in order to achieve creative solutions to complicated problems (Funtowicz and Ravetz 1993).[1] When the need for more inclusive science production processes was recognized, the door was opened for a more integrated approach to addressing complex problems: intentionally bringing together science and other knowledge systems (Cornell et al. 2013).

Application of coproduction to climate science knowledge

In an attempt to understand the roles of science in society and society in science, Jasanoff and Wynne (1998) examined several developments in science and technology to demonstrate the ways in which those developments were the product of an ''interplay of scientific discovery and description with other political, economic, and social forces'' (p. 4). They noted that this process, which they called ''co-production'' of knowledge, did not represent a tainting of pure scientific discovery by external influences, but rather was a more accurate representation of the ways in which knowledge (particularly, knowledge useful for policy action) is simultaneously constructed and influenced by the society and culture in which it is developed. Lövbrand (2011) labeled this ''descriptive co-production'' because it described an existing phenomenon. Jasanoff and Wynne (1998) suggested that more generally accepted scientific explanations about the world, in particular about climate change, would emerge ''through inclusion rather than exclusion, through participation rather than mystification, and through transparency rather than black boxing'' (p. 77).

[1] The perception that scientific knowledge is being pushed aside in coproduction processes may also reduce some scientists' willingness to participate in these efforts. However, as Jasanoff and Wynne (1998) pointed out, the science/society dichotomy is false; the two have always intermingled and the more they do, the greater the opportunities to produce usable science.

The descriptive framework created by Jasanoff and Wynne was reframed as a model for improved science and policy development by, among others, Lemos and Morehouse (2005), Dilling and Lemos (2011), and Lemos et al. (2012). Lövbrand (2011) named this new model ''prescriptive co-production,'' calling it ''a normative framework for improved science–society relations'' (p. 226). An early example of this new model of coproduction was articulated by Lemos and Morehouse (2005) who identify iterativity in the scientist–stakeholder partnership as the key component in successful coproduction of climate knowledge. Iterativity depends on three components: 1) repeated interaction with stakeholders, including during problem definition, research, analysis, and testing results; 2) production of usable science, including making the science understandable, available, and accessible to users; and 3) interdisciplinarity, ensuring that the research integrates all the necessary disciplinary knowledge.

Later, Lemos et al. (2012) refined this prescriptive coproduction model to more narrowly focus on the issue of information usability. They noted that the usability of science depends on users' perception of their information need, how well new knowledge interplays with existing knowledge within the user group, and the level of interaction between knowledge producers and knowledge users. Other factors identified by Lemos et al. (2012) that improve the usability of climate science are two-way communication between the groups and establishment of an ongoing relationship between the groups, both of which increase the information users' perception of information salience, credibility, and legitimacy, and can address users' concerns about scientific uncertainty.

While the newer prescriptive models outline basic goals or tenets of how to conduct collaborative and usable research, the actual processes by which these activities are undertaken is not well documented. The ways in which collaboration is conducted, decision makers are identified, questions are articulated, and iterativity is achieved are important to the ultimate goal of the production of usable knowledge. Research on public participation in policy and decision making has demonstrated that the structure and implementation of participatory activities impacts the outcome of the collaboration (Beierle 2002; Rowe and Frewer 2005; Stern and Fireberg 1996). Good integration of decision makers' knowledge into science and the scientists' knowledge into policy or management requires a strong process, designed around specific collaborative goals, that is executed effectively. We describe this process as deliberate coproduction, which involves explicitly planning coproduction into research processes and applying the best practices in collaborative research to achieve usable science.

3. Modes and approaches to deliberately coproduce climate science knowledge

We present four overarching modes of engagement, as defined by Biggs (1989), that outline types of relationships between researchers and stakeholders: contractual, consultative, collaborative, and collegial. Different modes can accomplish different research objectives and each has different resource and project management requirements, according to Biggs (1989) (Table 1). Understanding first how different types of engagement can support different research objectives (i.e., which research questions require end-user perspectives to find a solution and which can rest on a linear-science model) and second how to plan the required engagement are both critical to the goal of developing usable climate science. Biggs' (1989) modes of engagement are somewhat oversimplified characterizations of the ways in which scientists and stakeholders work together. In reality, the lines between the modes are fuzzy, which allows for engagement activities and outcomes to apply to more than one mode.[2] Nonetheless, the simplified form helps distinguish some general principles for engagement.

We also present five approaches to collaborative research—AR, transdisciplinarity, RAP, PIA, and boundary organizations—that can help researchers and stakeholders work together to achieve the tenets of coproduction and produce the knowledge needed by the stakeholders. The context in which a collaborative effort takes place is critical in the selection of an approach. The type of research question determines the general mode of engagement required; then, the people involved, the resources available, the capacities of the scientists and stakeholders to engage in the process, and the political context in which the work takes place all influence the specific research approach best suited to the inquiry. These factors can change during a research project, and flexibility and willingness to correct course along the way is essential to the process of coproduction of knowledge (McNie 2007).

a. *Modes of engagement*

Mode of engagement refers to the basic character of the interactions between scientists and decision makers: Is the engagement egalitarian? Is the communication two-way? In which aspects of the research are the stakeholders involved? Who will make the final decisions about research methods and/or policy outcomes? Although Biggs (1989) wrote in the context of agricultural research, his modes of engagement are more broadly applicable because of the general principles he highlighted. He stressed that the modes are distinguished by ''differences in objectives and the organizational and managerial arrangements they require for implementation'' (Biggs 1989, p. 3), not by their ability to solve problems. Each can solve problems effectively when the mode is appropriate to the particular question, context, and resources available.

In the contractual mode, the research emphasis is on testing or verifying technology. Biggs' (1989) term ''contractual'' refers to contracts between scientists and farmers for the use of land, services, and resources to test experimental technology under real-world conditions. It does not refer to situations in which stakeholders contract with scientists to answer stakeholder-driven questions. We liken Biggs' contractual mode to standard academic research wholly conducted by scientists, albeit with the intension of developing real-world applications.

The consultative mode involves ''diagnosis, design, technology development, testing, verification, and diffusion'' in order to solve a problem pertinent to the community (Biggs 1989, p. 6). In this mode there is interaction between the scientists and stakeholders at specific stages of the research, such as initial problem definition, verification of results, and diffusion of findings. However, the interaction is not necessarily ongoing throughout the process. Stakeholder input may be facilitated or filtered through a social scientist or other research team member who may act as a science translator, somewhat reducing the opportunity for direct interaction and mutual learning between the science team and the stakeholders.

The collaborative mode involves continuous interaction between scientists and stakeholders, who are seen as partners in the research process (Biggs 1989). This mode focuses on questions that require stakeholder input, such as their local knowledge related to resource use, to answer the broader scientific question. Stakeholders are directly involved in the research and, unlike consultative mode, are more likely to speak for themselves in the process. In this mode, the stakeholders are brought into Western science processes, perhaps even receiving formal training as part of their involvement.

Biggs' fourth mode is ''collegial,'' which he defined as the formal research system actively strengthening the informal (stakeholder driven) research and knowledge development system. In other words, not only are researchers pursuing a standard scientific research project,

[2] We also recognize that the terms used by Biggs are not necessarily clear in the context in which we apply them. For example, Biggs applies the term ''collaborative mode'' to a specific type of engagement, while we use the term ''collaborative'' to mean engaged science research more broadly. However, we present Biggs' terms to provide the reader with the direct link to the history of research on stakeholder-driven research.

TABLE 1. Modes of stakeholder engagement, adapted from Biggs (1989, 3–4).

Mode	Objective	Origin of research question	Type of relationship	Stakeholder involvement	Stakeholder representation
Contractual	Test applicability of new technology or knowledge	Researchers	Unidirectional flow of information from researchers to stakeholders	Primarily as passive recipient of new knowledge or technology	Views and opinions of stakeholders are not emphasized
Consultative	Use research to solve real-world problems	Stakeholders or researchers	Researchers consult with stakeholders, diagnose the problem, and try to find a solution	At specific stages of research such as problem definition, research design, diffusion of findings.	Stakeholder views primarily filtered through third party (e.g., social scientists)
Collaborative	Learn from stakeholders to guide applied research	Stakeholders	Stakeholders and researchers are partners	Continuous with emphasis on specific activities, depending on joint diagnosis of the problem	Stakeholders themselves, local representatives, trained research team members
Collegial	Understand and strengthen local research and development capacity	Stakeholders	Researchers actively encourage local research and development capacity	Variable, but ongoing	Stakeholders themselves

they are also helping to increase the stakeholders' capacity to design and conduct their own research and solve problems. The collegial mode recognizes that the knowledge gained through local epistemologies is valuable and can support scientist-driven research.

While any of these modes can be used to effectively answer a stakeholder-driven question, we note that the engagement required to call a process coproduction of knowledge—to provide enough engagement for stakeholders to feel that the process has been legitimate [using Cash et al.'s (2006) definition]—is more likely to come from collaborative or collegial modes because these modes include the kind of long-term, two-way relationships that lead to coproduction of knowledge.

Once a researcher and stakeholder have determined the research question and general mode of engagement most suited to the question and context, the next step is to identify a specific research approach that will help them understand each other's concerns, languages, and collaboratively develop usable knowledge. For each general mode of engagement, there are a number of specific research approaches that can help to achieve these goals.

b. Approaches to collaboration

While Biggs' modes of engagement provide general guidance on how different levels of engagement support different research objectives, the approaches discussed below provide more detail about how to accomplish the necessary level of engagement. Each approach lays out specific activities and actions that researchers can take to reach both the research and collaboration goals of a given project (Table 2). The importance of process also leads us to stress the importance of interdisciplinary research teams, as suggested by Lemos and Morehouse (2005). In addition to all the scientific disciplines involved in producing climate knowledge, social scientists on the team can be instrumental in framing the collaborative approaches, interviewing stakeholders, elucidating the perspectives of stakeholders (Cvitanovic et al. 2014), and encouraging scientists to challenge their own assumptions and biases as they interact with stakeholders and the knowledge the stakeholders bring to the table.

1) ACTION RESEARCH

Action research (AR) is the approach that laid the foundation for collaborative research in the social sciences. As defined by Lewin (1946), AR is a qualitative research approach designed to both solve practical problems and further our generalizable knowledge of societal structures and processes. Lewin directed the method toward communities facing challenging social and economic situations for which no immediate solution was apparent. Lewin recognized that solutions must be meaningful within the context of the community and developed the AR approach to collaborate with community members to frame the inquiry, undertake the research, analyze the findings, and take action. "Together, the professional researcher and the stakeholders define

TABLE 2. Approaches to collaboration categorized by the mode(s) of engagement they fulfill.

Approach to deliberate coproduction	Mode(s)	Type of question	Role of research team	Resources required
Action research	Collegial	• Stakeholder defined • Effecting change for stakeholder • Social/environmental justice focus	• Facilitators, teachers, technical guidance • Support the research of the stakeholder community	• Sufficient time to spend in stakeholder community • Financial (or other) support for stakeholder participants
Transdisciplinarity	Collegial	• Technical question that also has complex political or social impacts	• Equal partners with stakeholders • Facilitators of the process	• Sufficient time to spend on participatory activities
Rapid assessment process	Consultative Collaborative	• Understanding how stakeholders frame an issue; what terms and knowledge systems they use to understand the issue	• Ethnographers—learning about stakeholders' context • Proposing solutions to address issue of concern.	• Social science research training • Travel funds to go to stakeholder community/organization
Participatory integrated assessment	Consultative Collaborative Collegial	• Scenario planning • Development of integrated models	• Facilitators of participatory processes • Provide technical input	• Sufficient time to spend on participatory activities • Sufficient funds to engage in participatory activities
Boundary organizations	Consultative Collaborative Collegial	• Any of the above	• Purveyors of salient, credible, legitimate science	• Sufficient time to spend on participatory activities • Sufficient funds support boundary organization work

the problems to be examined, cogenerate knowledge about them, learn and execute social research techniques, take actions, and interpret the results of actions based on what they have learned'' (Greenwood and Levin 2007, p. 3). The transparency of the AR approach is intended to ensure that stakeholders view the process and outcomes as legitimate and beneficial. While much AR focuses on social issues, some foundational work has occurred in the context of organizational studies (Greenwood et al. 1993; Whyte and Whyte 1991) (see case study below), which may be more pertinent to those working in the context of management agencies and policy making. The role of the academic researcher in AR may be better described as facilitator and teacher, providing technical guidance to community members while allowing for full community control of the information and resulting actions (Greenwood and Levin 2007).

A key tenet of AR is that once the problem has been diagnosed, action must be taken to change the situation and alleviate the problem (Greenwood and Levin 2007) and those actions should be assessed to determine their effectiveness. In the context of coproduction, this can mean taking policy or management action based on research findings then monitoring the outcomes. The interplay between action and reflection defines AR. The roots of AR are as a tool in effecting social change and, as such, it has been called ''openly ideological research'' (Lather 1986), which some researchers may find problematic because it implies a lack of objectivity. However, AR has been modified over the years for use in less political contexts although the ultimate goal of AR remains that stakeholders take action to address a problem. Researchers can modify their role to support research, reflection, and analysis necessary to this problem solving. Because AR requires that stakeholders drive the entire process from the framing of the problem to research, analysis, and decision making, it fits only the collegial mode of engagement.

Action research case study

In 1980, Xerox and its union workers launched an innovative experiment in participatory action research. The experiment grew out of recognition at Xerox that the market and manufacturing practices were shifting rapidly and that, to remain competitive, they would need to update their practices. Union and management representatives, as well as other employees, were trained as ''problem solving teams'' (PSTs) that identified problems within the organization and experimented with solutions. When Xerox considered outsourcing the manufacturing of wire harnesses found in some of their products, which was projected to save more than US$3 million dollars per year but would cost 150–180 union jobs, the union asked management for an opportunity to save their jobs by studying the wire harness assembly operation to identify potential cost savings. The employee PST was able to identify surplus costs and make recommendations about cutting them. In the end, the jobs stayed at Xerox and the company saved more than US$4.2 million per year (Pace and Argona 1991). Both management and the union saw this transparent process as legitimate and the outcomes as mutually beneficial.

2) Transdisciplinarity

Transdisciplinarity is a research approach that integrates multidisciplinary academic and practitioner knowledge through specific processes to produce a unified product (Jahn et al. 2012). The term has also been used as a broad theoretical concept to explain how knowledge can be produced and how to make science more interdisciplinary and democratic (Jahn et al. 2012). The goals of transdisciplinary research are to address complex, socially relevant problems (Hirsch Hadorn et al. 2006), reconcile social demand for and academic production of knowledge (Hoffmann-Riem et al. 2008), and build upon and use disciplinary knowledge (Klein 2004) while integrating disciplinary and "extra-scientific" knowledge (Jahn et al. 2012).

Jahn et al. (2012) proposed a conceptual model of transdisciplinary research, identifying three phases. Phase 1 is problem transformation, during which the societal problem is framed then related to scientific knowledge. The social and scientific problems are then linked to form a boundary object[3] and finally transformed from a boundary object into epistemic objects, or research questions. In phase 2, interdisciplinary integration, the disciplinary science teams interact with each other in several stages to produce new knowledge related to the research questions. Transdisciplinary integration occurs in phase 3 when the results of the knowledge production are assessed and products are assembled for both science and society. Mauser et al. (2013) developed a similar framework for the use of a transdisciplinary approach in sustainability research identifying the phases as codesign of the research (phase 1), coproduction of knowledge (phase 2), and codissemination of the results (phase 3). In both models, knowledge production is integrated and researchers and practitioners are engaged in each phase. The commitment to integrating science and other forms of knowledge in the transdisciplinary approach, and the sustained interactions it requires, makes transdisciplinarity an example of a research approach in the collegial mode of engagement. However, it differs from AR in that it brings the various participants together to accomplish specific tasks, while AR allows for a more immersive experience in which researchers interact with stakeholders within the stakeholders' social context, which may allow researchers to develop a deeper understanding of stakeholder needs and knowledge systems.

Transdisciplinarity case study

A transdisciplinary project was undertaken to address the issue of the level of active ingredients in pharmaceuticals for human use (active pharmaceutical ingredient, API) in water in Germany (Jahn et al. 2012). The project began by asking a group of stakeholders including medical and pharmaceutical professionals, public health professionals, and water managers to frame the issue as a societal problem. Next, subject matter experts provided a scientific framing of the issue and decisions about the focus of the project, which was to identify strategies to reduce API in waters but which were also sensitive to the conflicting values inherent in the issue. The project team worked with scientists and stakeholders to create a boundary object, which became the following statement: *The occurrence of APIs in communal water cycles is an undesirable side effect of the normal mode of operation in the health care system.* Research questions related to risk governance, risk perception, and risk communication were then developed based on the statement. After designing a process by which interdisciplinary integration could occur three project subgroups each developed a strategy to reduce APIs, which were then compiled into a formal document. Project outcomes included adoption of one of the reduction measures by a municipality. The strategic combination of scientists and industry stakeholders resulted in specific strategies to address an immediate environmental harm.

3) Rapid Assessment Process

Rapid assessment process, or RAP (Beebe 2001), is a structured approach to the use of qualitative research methods to identify the "most important elements of the local situation *from the perspective of the local participants*" (Beebe 2001, p. xvii; emphasis added) and the key terms and categories used by the participants so that

[3] Boundary objects are defined by Star and Greisemer (1989) as scientific objects or other materials that are meaningful to and can be understood by the various participants in a transdisciplinary (or other collaborative) research process.

problems can be solved in ways that fit within local knowledge frameworks. For example, Cvitanovic et al. (2014) found that natural resource managers do not necessarily consider scientific information to be more important than other knowledge, highlighting the importance of understanding how those managers frame the issues and which knowledge systems they rely on before attempting to develop usable knowledge for them. RAP was designed for use when there is an urgent need for intervention and/or when the resources (time, money, and people) are not available for long-term ethnographic research, in contrast to AR, which relies on long-term immersion in stakeholder communities.

RAP requires multiperson, multidisciplinary teams to enact its two main tenets: triangulation of data and iterative analysis. Teams should also include members of the local community whenever possible. Research teams should draw information from two groups of participants: a convenience sample to gain a broad overview of the issue and key informants selected for their particular knowledge of the situation. Multiperson data collection teams help researchers gain multiple perspectives on the situation and help them avoid missing key details during interviews and observations. Iterative data analysis requires the research team to spend significant amounts of time discussing among themselves what they heard and observed during fieldwork. Beebe (2001) stressed that at least one member of the research team should have training in social science research methods to ensure that inquiries are structured appropriately.

Using a RAP approach can be helpful for climate science research teams seeking to understand the management context in which climate science will be applied. By better understanding organizational functions, information flows within the agency, how decisions are made, and previous experiences with climate information, scientists may be better able to produce climate knowledge more readily usable by resource managers. RAP best represents either the consultative or collaborative modes because while it integrates stakeholder knowledge into the research process, the research team most often performs the analysis and interventions; the local community members or stakeholders are not necessarily part of these tasks. Researchers may find that they still need an approach with more opportunities for in-depth engagement in order to support knowledge coproduction. However, RAP can help lay a strong foundation for a relationship to be built between scientists and stakeholders.

RAP case study

Westphal and Hirsch (2010) used a RAP approach to better understand the attitudes and behaviors of Chicago residents toward climate change as part of the city's climate action planning process. They found that by deploying a team of researchers to work in a number of Chicago communities they were able to collect a large amount of data from residents in a short amount of time. They paid community members a stipend to help with research activities such as connecting researchers with key community organizations, facilitating focus groups, informing study design, and data analysis. The research team (including community members) used interviews, focus groups, participant observation, and other more novel methods such as drawing exercises to gather information from community members about climate change concerns. Westphal and Hirsch (2010) reported a key outcome of the RAP approach was that neighborhood concerns were placed at the center of discussions so that actions resulting from this project could balance local concerns and broader climate change concerns, reinforcing the sense that local voices had been heard.

4) PARTICIPATORY INTEGRATED ASSESSMENT

Participatory integrated assessment (PIA) is a multidisciplinary approach that seeks to develop policy- or decision-relevant knowledge about environmental problems through the integration of stakeholder knowledge into modeling and scenario-planning efforts (Salter et al. 2010; Toth and Hizsnyik 1998). PIA facilitates the integration of stakeholder knowledge and values into models and scenarios of climate change that can then be used to inform decision-making processes (Salter et al. 2010; van Asselt Marjolein and Rijkens-Klomp 2002). Stakeholders in PIA are can range from policy makers to the affected general public.

PIA frameworks rely on a set of primary disciplinary elements and primary integration tools (Toth and Hizsnyik 1998). Primary disciplinary elements are methods, theories, and models that address the issue of interest such as general circulation models, demographic models, opinion surveys, and participatory models (Toth and Hizsnyik 1998; van Asselt Marjolein and Rijkens-Klomp 2002). Primary integration tools can range from simple flow diagrams to complex network charts, or from plain checklists to impact matrices (Toth and Hizsnyik 1998). Participation mechanisms vary depending on the context and questions but can include workshops for larger, more public groups or focus groups for smaller, more targeted groups of stakeholders. PIA's focus on integrating a variety of forms of stakeholder knowledge with more standard scientific knowledge and its flexible approach in selecting participants means that it has the potential to be used in consultative, collaborative, or collegial modes. However, there are some limits on the ways in which stakeholder knowledge is likely to be used, due to the focus on technical models and scenarios, which could constrain the ways some stakeholders are able to participate.

Participatory integrated assessment case study

Climate Options for the Long Term (COOL) was a PIA project that was part of the development of long-term climate policy at the Dutch, European, and global scales (Berk et al. 2002). The project was designed as a series of workshops with the objectives of 1) exploring long-term targets for stabilizing greenhouse gas emissions; 2) exploring the most promising options for long-term international climate policy and their implications for the medium term; 3) enhancing the understanding between countries with different positions and interests in climate change; 4) broadening the understanding of scientific aspects of climate issues; and 5) developing common frameworks for analyzing and evaluating policy options (Berk et al. 2002). Utilizing a back-casting methodology, participants developed a potential future scenario based both on models and stakeholder input and reasoned backward to the present to identify policy goals consistent with achieving the future scenario (Salter et al. 2010). Workshop participants included policy makers from both developed and developing countries, stakeholders involved in international climate change policy negotiations, and climate scientists. Stakeholders were mainly involved in option assessment, goal setting, and strategy formulation (Kloprogge and van der Sluijs 2006). The project resulted in the development of strategies and policy goals for technological adaptations to meet an 80% reduction in greenhouse gas emissions for the Netherlands (Salter et al. 2010). Targeted stakeholder input helped the participants agree on a future scenario goal and created buy-in on strategies to achieve the mutual goal.

5) BOUNDARY ORGANIZATIONS

A boundary organization is a group or institution that takes on the challenging tasks of both working at and managing the science–policy boundary (Guston 2001). The role of a boundary organization is to facilitate the process of coproduction by allowing scientists and decision makers to maintain their independence and objectivity while also creating some permeability of the boundary to allow for coproduction of knowledge (Clark et al. 2011). To be successful in managing the boundary, these organizations take on four key functions (Cash et al. 2006):

1) Convening—the process of bringing parties together for face-to-face contact; this forms the foundation for relationships of trust and mutual respect.
2) Translation—either literally, as from one language to another, or figuratively, as from one side of the boundary to the other.
3) Collaboration—bringing the actors together in an effort to coproduce knowledge.
4) Mediation—representing and evaluating different interests so that mutual gains can be created and the process is perceived as fair and just.

These functions can appear in different mixes in different organizations (Cash et al. 2006). Boundary organizations act as ''an intermediary between the users and the scientists, and [are] fluent in both worlds'' (Dilling and Lemos 2011, p. 685). Knowledge brokers are individuals who fulfill many of the same functions as boundary organizations, acting as intermediaries between researchers and decision makers (Meyer 2010; Michaels 2009). They may work within boundary organizations or become members of the research team with the specific task of mediating the science–policy boundary.

There are several ways to approach creating or using a boundary organization in the process of knowledge coproduction. A research or policy team can create a new boundary organization to suit a particular project or purpose, which can ensure that information is customized for the intended user (Dilling and Lemos 2011). See the case study (below) for an example of a boundary organization created to facilitate one specific project. A second approach is to use an existing boundary organization to mediate a coproduction process. For example, the NOAA Regional Integrated Sciences and Assessments (RISA) program, established in 1995 with one organization to address a specific regional problem (Pulwarty et al. 2009), now consists of 10 programs, which have the capacity to work with new stakeholders and scientists on a range of projects. Science shops, a European model in which universities support small research groups whose goal is to democratize science by making scientists available to answer community groups' research questions either free of charge or at reduced rates (Fischer et al. 2004; Gnaiger and Martin 2001), are another type of existing boundary organization. Finally, an existing organization can take on the role of a boundary organization, although Dilling and Lemos (2011) caution that this can require large-scale mission change and is, therefore, not always practical.

Boundary organizations or knowledge brokers do not all work in the same way nor do individual boundary organizations work the same way on each project (Michaels 2009); they have training and experience that helps them select appropriate modes and approaches based on the specific questions and contexts of each individual project. Using a boundary organization, particularly one that is established, allows researchers to connect with experts who can help guide the collaborations and who may be able to use their existing connections to lay the foundation for a new collaboration between researchers and decision makers. Because the goal of a boundary organization is to facilitate collaboration between scientists and stakeholders, they regularly work within the consultative, collaborative, and collegial modes.

Boundary organizations case study

As part of a project to address the combined risks of sea level rise, population growth, and development of economic assets along the Dutch coast, the Dutch government appointed a committee on sustainable coastal development, which functioned as a boundary organization (Boezeman et al. 2013). The committee was made up of both scientists and politicians—members from both sides of the boundary. Within each of these domains, a number of disciplines were represented such as climate science, water engineering, agriculture, politicians, and business representatives, which kept either domain from being ''overhomogenised'' (Boezeman et al. 2013). The committee members and staff were also well connected outside of the group, which helped them to act as boundary agents with the broader Dutch community. The committee routinely sought opinions and ideas from regional stakeholders, which enabled them to gain the trust of the stakeholders and to refine their recommendations based on stakeholder experiences. Finally, the committee created a boundary object—in this case a report—which was used as a formative tool to vet and debate scientific and other policy-relevant information as well as translate technical information to reach multiple audiences. By working at the intersection of several boundaries (science/policy and general public/policy makers), the committee was able to craft recommendations for a ''worst-case'' sea level projection that went beyond the then-current IPCC sea level projections, reaching beyond the current scientific consensus to address, through policy, a potentially much more significant threat to the Dutch people.

4. Evaluating coproduction of climate science knowledge

A consistent refrain in the literature on coproduction of knowledge within the climate sciences is the need to assess the impact of the science as well as to understand why and under what conditions the science is or is not used as expected (Bellamy et al. 2001; Fazey et al. 2014). The complexities of evaluating impacts on natural resource management or attributing outcomes directly to any one particular action make it tempting to rely on more easily tracked metrics, such as number of peer-reviewed articles or other research outputs (Bell et al. 2011; Roux et al. 2010). While the scientific credibility afforded by peer review is important to ensure the quality of the science developed through coproduction, usability, which is the intended outcome of coproduction, must be evaluated in new ways more suitable to its unique role in both advancing science and societal outcomes (Bell et al. 2011; Fazey et al. 2014). As Fazey et al. (2014) noted, different types of knowledge exchange (modes of engagement in our terms) require different evaluative approaches. Since engagement and coproduction are processes, we note the importance of evaluation approaches that address process as well as outcomes. To evaluate process, one must understand how and why a particular collaborative approach and mode of engagement are intended to work, which is made easier by using an existing and tested collaborative research approach.

There have been some preliminary steps taken toward evaluating coproduction as a process as well as the desired outcome of that process: usable science. The National Research Council (NRC) developed a set of metrics to evaluate usable science and the processes used to produce it in the U.S. Climate Change Science Program (CCSP) (National Research Council 2005). The NRC metrics consist of process metrics, which include variables such as leadership, priority setting, and promotion of partnerships; input metrics such as sufficient intellectual and technological foundation to support the research and sufficient resources to complete the program; output metrics, which include peer-reviewed results that are also broadly accessible to users; outcome metrics such as improved scientific understanding and operational use of the results; and impact metrics, which measure long-term impacts such as an increase in the public understanding of climate issues. While the NRC metrics can be helpful in framing the kinds of questions that are necessary to assess the success of a coproduction of knowledge process, they fall short in terms of closely examining the process by which new knowledge is produced or coproduced. The process metrics focus on the presence or absence of various resources or activities (a leader with sufficient authority, development of a multiyear plan, a strategy for setting priorities and allocating resources, for example) but do not address how those resources are used or activities are undertaken.

Dilling and Lemos (2011) provided more detailed suggestions such as focusing on outcomes like the scientist–stakeholder relationship, the accessibility of the science knowledge produced, and progress on specific societal outcomes. As discussed above, Lemos et al. (2012) posited that the three key variables in the successful production of usable science are users' perception

TABLE 3. Example of metrics developed to assess scientist–stakeholder collaboration, adapted from Ferguson et al. (2015).

Outputs	Variable or indicator	Metric
Workshop research activities	• Interest among stakeholders • Learning and change in knowledge	• Attendance and feedback from postworkshop evaluations • Expressed feedback on learning impacts
Partnerships and collaborations	• Degree, type, and quality of partnership	• Lists of partners and stakeholders • Description of roles and involvement

of the information's fit to their needs, how well the new information fits within their existing knowledge frameworks (interplay), and the level and quality of interaction between science producers and science users. Kirchhoff et al. (2013) identified two-way communication and long-term relationships as keys to successful coproduction because they allow for trust building and accountability, which increases users' perceptions of information salience, credibility, and legitimacy.

Reed et al. (2014) distilled a set of five principles for effective knowledge exchange from a broad review of literature and expert interviews. They found that effective knowledge exchange requires that the process be designed into the research project, that stakeholders should be systematically selected to ensure accurate representation, that long-term relationships should be built on two-way communication and cogeneration of knowledge, that the focus should be on tangible, timely results, and that researchers should reflect on their work and refine their practice.

One example of an effort to apply these kinds of evaluation measures to a specific boundary organization comes from the Pacific RISA (Table 3). The program has identified indicators and metrics similar to those suggested in the literature above. They track partnerships and collaborations to gauge both the reach of their partnerships by counting how many stakeholders they work with and who they are missing in their collaborations as well as tracking the level and quality of those relations through qualitative descriptions of stakeholder roles and involvement.

5. Conclusions

The research on coproduction of knowledge has found that greater engagement between scientists and stakeholders tends to produce more usable science because engagement engenders trust in both the science and the science producers (Dilling and Lemos 2011; Lemos et al. 2012). The crucial next step in making coproduction of knowledge a more widely accepted and used approach to creating usable (and used) science is to refine our understanding, through empirical study, of what specific actions and activities most effectively produce the trusting, long-term relationships necessary to the coproduction of usable science. In other words, if we are more deliberate in how we coproduce knowledge and in how we assess the processes and outcomes involved, we can speed the process of learning and be more effective in coproducing climate science. We believe that by using established approaches, such as those described above, we stand a better chance of creating processes in which we can effectively establish working partnerships between scientists and stakeholders. Using and evaluating existing approaches may also help us develop new approaches, through iterative testing, that prove particularly effective in the climate science community.

The approaches discussed here provide frameworks to help both scientists and decision makers better understand the needs of and challenges facing their partners. It is crucial, however, that attention be given to how the approaches are undertaken. Researchers interested in coproduction of knowledge or other forms of collaborative research should reflect upon the questions being raised by decision makers, the context in which those questions arise, and the resources available to answer the questions. The answers to these questions will determine which mode of engagement and research approach will be most effective in any given project.

In much the same way that descriptive coproduction notes the interplay between science and society, deliberate coproduction should be an interplay between social science and physical or natural science. Social science can help structure and guide the ways in which the physical or natural science is deployed in search of policy or resource management answers. The social science practice of researcher reflection can also be considered an integral part of coproduction of knowledge, encouraging researchers to reflect upon their experiences, their challenges, and their successes. Lessons learned from one project can then be consciously applied to another coproduction process.

More research focused on the outcomes of collaborative knowledge production can also help move the field forward. Case studies describing how particular projects were structured, detailing both challenges and successes, and describing whether or how new climate science has been integrated into management decision making can help future researchers and stakeholders better understand the dynamics of collaboration and set reasonable goals for the use of new knowledge. Broader investigations of collaborative approaches using common evaluative frameworks will allow us to be rigorous in the ways we identify the specific elements that contribute most directly to coproduction of knowledge and usable science.

The context in which scientists and stakeholder collaborate, the questions being asked, the approach taken to build the partnership, and the specific actions and activities used to further the collaboration will all impact the outcome of the production of usable science. By being deliberate about our approaches to collaboration and reflecting upon on our practices we can advance the practice of knowledge coproduction, better integrate science and decision making, and address some of the most urgent environmental challenges of our time.

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The Geopolitics of Climate Knowledge Mobilization: Transdisciplinary Research at the Science–Policy Interface(s) in the Americas

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Abstract

Climate change and sustainability science have become more international in scope and transdisciplinary in nature, in response to growing expectations that scientific knowledge directly informs collective action and transformation. In this article, we move past idealized models of the science–policy interface to examine the social processes and geopolitical dynamics of knowledge mobilization. We argue that sociotechnical imaginaries of transdisciplinary research, deployed in parallel to "universal"

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regimes of evidence-based decision-making from the global North, conceal how international collaborations of scientists and societal actors actually experience knowledge mobilization, its systemic barriers, and its paths to policy action. Through ethnographic study of a transdisciplinary research program in the Americas, coupled with in-depth analysis of Colombia, we reveal divergences in how participants envision and experience knowledge mobilization and identify persistent disparities that diminish the capacity of researchers to influence decision-making and fit climate knowledge within broader neoliberal development paradigms. Results of the study point to a plurality of science–policy interface(s), each shaped by national socio-technical imaginaries, development priorities, and local social orders. We conclude that a geopolitical approach to transdisciplinary science is necessary to understand how climate and sustainability knowledge circulates unevenly in a world marked by persistent inequality and dominance.

Keywords

epistemic geographies, knowledge coproduction, international science programs, science–policy interface, sociotechnical imaginaries, scale, sustainability science, Colombia

Throughout the Americas, science has evolved toward new modes of transdisciplinary knowledge production, aimed at mobilizing climate, health, and sustainability knowledge to inform policy and catalyze societal transformation at multiple scales (de Almeida Filho 2005; Lahsen et al. 2013; Liverman 2009; Max-Neef 2005; Romero-Lankao et al. 2013). Transdisciplinary knowledge regimes reflect implicit logics of accountability and imaginaries of social impact that shape program design, collaboration, and the very conditions for knowledge mobilization and future engagements between science and society (Felt et al. 2016; van der Hel 2016). Such "zones of engagement" are further complicated in developing countries, where Northern technologies and ideals of progress—such as the linear model of the "science–policy interface" in which "value-free" science is adopted and applied by earnest policy advisors (Jasanoff 2004; Pielke 2007)—are used as benchmarks to facilitate national economic development, scientific infrastructure, and human capacity-building (Lahsen 2009; Lahsen and Nobre 2007; Nunes, Rajão, and Soares-Filho 2016; Rajão and Duque 2014).

In this article, we advance a "geopolitical" approach to conceptualizing knowledge mobilization in transdisciplinary climate and sustainability research, particularly as the process of moving knowledge into use confronts different spatial and social orders. Climate change geopolitics are not limited to nation-states sparring over international treaties but also include the epistemic geographies of climate and environmental knowledge—such as how space, place, and power are part of the coproduction of knowledge and social order (Mahony and Hulme 2016). Our geopolitical framework elicits the performative and place-based aspects of scientific knowledge—or ways of representing the world—that emerge from local social orders and shape conditions of knowledge production and mobilization (Dalby 2013). Feminist approaches to geopolitics, for example, locate broader political struggles over territory, authority, and hegemony in "mundane" and overlooked social practices and sites—in bodies, within collaborations, and in the everyday spaces and social relations that configure authoritative knowledge (Massaro and Williams 2013). Transdisciplinary science is perhaps the least understood and most contentious regime of climate and environmental knowledge production, as it explicitly incorporates "use-driven" imaginaries of public purpose, development pathways, and desirable futures.

Similarly, in this article, we demonstrate why the sociotechnical imaginaries of transdisciplinary sustainability science must grapple with its lived geopolitical realities at multiple scales. We move past idealized models of the science–policy interface to examine the social processes and geopolitical dynamics of knowledge mobilization. To do this, we first illustrate how universalized and "global" visions of knowledge mobilization are reproduced in the programmatic design and expectations of use-driven research, drawing on a case study of the Fulbright NEXUS, a transdisciplinary research program based in the Americas. Second, we show how NEXUS participants experience and reconcile a plurality of science–policy interface(s), each shaped by national sociotechnical imaginaries, development priorities, and local social orders. We argue that sociotechnical imaginaries of transdisciplinary research, deployed in parallel to global regimes of evidence-based decision-making from the global North, conceal how international collaborations of scientists and societal actors actually experience knowledge mobilization, its systemic barriers, and paths to policy action.

Sociotechnical Framings of the Science–Policy Interface

Transdisciplinary research is defined as a mode of knowledge coproduction that involves societal actors in the design, execution, application, and mobilization of knowledge into policy—features that distinguish it from interdisciplinary and multidisciplinary types of scientific collaboration (Groß and Stauffacher 2014; Klenk et al. 2015; Mauser et al. 2013). Transdisciplinary knowledge regimes transform the very practices of science—who is included, how discoveries are made—with the hopeful promise of "democratizing" science–society interactions and legitimizing outcomes and applications (Felt et al. 2016). This model has been upheld as one possible way to "close the gap" between climate knowledge and action (O'Brien 2013).

While there is no single prescription for better integration of science into decision-making (Bai et al. 2016), there is equally poor understanding of how transdisciplinary experiments morph into policy and practice, particularly as use-driven and "actionable" science becomes intertwined with implicit norms—or "sociotechnical imaginaries"—of public purpose, desirable futures, and national development (Felt et al. 2016; Jasanoff and Kim 2009; Jasanoff 2015). Science–society ideologies, for example, tend to universalize how knowledge translation and application occurs in all places, despite very real place-based differences in development conditions, decision-making, and sociopolitical contexts (Jasanoff and Wynne 1998; Lahsen 2009). Climate change science is especially prone to this dynamic, given its spatial framing at regional and global scales on the one hand and its need to compose policy-relevant and locally specific outcomes on the other (Wynne 2010). For programs such as Future Earth, funders promote transdisciplinary models of research as a way to accelerate and improve the "linear" model of knowledge mobilization—where academic experts make discoveries and hand off results to decision makers (Bai et al. 2016; Leemans 2016).

Transdisciplinary knowledge regimes have a distinct epistemic history based in the global North. Scholars in critical policy studies have tracked the rise of evidence-based policy-making (EBPM): the idealized, rationalistic, and nonpolitical perspective that has gained international hegemony among regimes of evidence (Holmes et al. 2016). Government agencies in Europe and North America have implemented EBPM as a response to demands for increased efficiency and transparency in public policy-making and to "close the gap" between knowledge production and utilization. Originally, EBPM developed within the health-care sector by using systematic review of clinical trials as the benchmark for "decision-ready" evidence (Hodgkinson 2012). Proponents argue that EBPM demystifies the decision-making process by adopting clear protocols for policy based on the most relevant and rigorous knowledge base—"the best available science"—with the promise of reducing the number of policy failures. Critical policy scholars, meanwhile, question the rationalistic assumptions underlying EBPM. They point to the social construction of evidence, the politics involved in adjudicating the relevance and rigor of different types of knowledge (e.g., quantitative vs. qualitative scientific research, expert judgment, and practical knowledge), and the risks associated with the exclusion of certain types of knowledge such as the interpretive social sciences.

Identifying the "sociotechnical imaginaries" of transdisciplinary science is one way to better understand its tacit ordering rules, epistemic geographies, and potential misalignments. Sheila Jasanoff (2015, 19) and Sang-Hyun Kim define sociotechnical imaginaries as "collectively held and performed visions of desirable futures (or of resistance against the undesirable) that are animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology." Key to the concept is its definition as collective social practice and performance, which ties sociotechnical imaginaries "more closely [to] instrumental political action—in other words, to policy as well as politics" (Jasanoff 2015, 20). The concept was first developed to describe the coproduction of science and social order at the site of the nation-state, a cradle of policy actions and future-oriented development (Jasanoff and Kim 2009). For example, the goals and practices of a national transdisciplinary research program in Austria were mutually constitutive with national identity ("being Austrian"), local visions of "sustainability," and place-based visions of who should be included in the research (Felt et al. 2016).

While national programs are important sites for investigation, this article seeks to expand analysis of geopolitical dynamics at multiple sites and scales. Such critical work is already underway in STS. For example, Lahsen (2002, 2009) explains how rifts between scientists and policy makers, in debates over global carbon cycle research in Brazil, are rooted in localized notions of national sovereignty, territorial hegemony, and political control. Brazilian decision makers, she found, portrayed "international science" as a mechanism through which rich countries maintained geopolitical advantage and influence over Amazonian territory and resources (Lahsen 2002, 4). Resulting policy interpretations diverged sharply from the scientific consensus, which considered the Amazon a key site in "global" environmental dynamics (Lahsen 2009). Participating Brazilian scientists, meanwhile, reported a "North American bias" in program design and execution and described feelings of being used as a "token scientist" rather than an equal participant (Lahsen 2002, 2009). As one participant explained, "this issue of what I call colonialism in science, it exists. It is *very* strong. And nobody talks about it. On either side. Who profits and who suffers" (Lahsen 2002, 19-20).

Transdisciplinary research is caught within a dominant regime of evidence, idealized as a model of "input–output," "delivery-uptake," and "supply-demand," which assumes a nonpolitical science–policy interface, on the one hand, and on the other obscures how such a sociotechnical imaginary can displace alternative pathways of knowledge mobilization. Our article examines the ways that transdisciplinary knowledge mobilizes and coproduces the science–policy interface in different geographic contexts that span the development gradient of the Americas. We anticipate that a geopolitical exploration will reveal a plurality of science–policy interface(s) including the power imbalances between knowledge systems attempting to steer global environmental change science and decision-making. To explore these dynamics, we delve into the NEXUS case.

The Fulbright NEXUS

Perspectives and experiences from the Americas are profoundly instructive for advancing critical STS theories of international science and interdisciplinary collaboration (Anderson 2002; Harding 2016; Rajão, Duque, and De'Rahual 2014; Vessuri 1987). Key programmatic precedents in the region, such as the Inter-American Institute for Global Change Research, have established a two-decade legacy of South–North collaboration and interdisciplinary, policy-driven research in climate change, and sustainability sciences (Liverman 2009).

Fulbright NEXUS is a transdisciplinary research program, jointly sponsored by the US State Department and Brazilian Ministry of Education, designed to address climate change, energy, and health challenges in the Western Hemisphere. The NEXUS case is notable for two reasons. First, its geographic diversity invites a plurality of science–policy imaginaries, transdisciplinary configurations, and "performances" in knowledge mobilization. To date, most critical studies of transdisciplinary science have focused on national programs based in North America and Western Europe (Felt et al. 2016; Groß and Stauffacher 2014; Mattor et al. 2014; Turnhout, Hisschemöller, and Eijsackers 2008) or the "global" approach taken by Future Earth (Lahsen 2016; van der Hel 2016). NEXUS assembled researchers and societal actors from all corners of the Americas including its wealthiest and poorest countries. Through its regional focus and stakeholder-driven design, the program serves as a template to elicit diverse imaginaries and social practices that are central to theorize knowledge mobilization.

Second, NEXUS was designed as a "cultural exchange" unlike most transdisciplinary programs that focus strictly on science-generating activities. As NEXUS scholars ourselves, we experienced this cultural exchange firsthand: during six-week visits to the country where our research was conducted, by engaging with project stakeholders with different capacities of decision-making, and through reflection on such experiences with other scholars during weeklong NEXUS meetings. The program worked as an open-ended, experimental container, assembling scholars and stakeholders and tasking them to conduct policy-relevant research, all while facilitating diverse opportunities for research teams to immerse themselves in different cultures and to confront different norms, practices, and local social orders (Klenk and Meehan 2017). Such encounters inevitably shaped the trajectory of our argument. In bringing together people from across the Americas, the NEXUS program sought to cultivate *hybrid* researchers—socially engaged policy informants.

Method and Material

We adopted an ethnographic and interpretive approach to data collection and analysis. As NEXUS scholars, we were immersed in our case study, which enabled participant observation, reflective engagement, and grounded insight into the program's implementation. The article draws on our experiences and two other bodies of materials: (1) semistructured interviews with NEXUS scholars and program staff and (2) program concept papers and project outputs such as diagrams, websites, presentations, articles, and notes.

We invited sixty-three participants from three NEXUS cohorts implemented by the Fulbright program (in 2011, 2012, and 2014) and interviewed thirty scholars (48 percent response rate) and six program staff (86 percent response rate) for a total of thirty-six interviews. Participants have advanced degrees in science, engineering, design, architecture, public health, social science, and the humanities. Most NEXUS scholars work as university academics, though several have current (or previous) positions in government agencies, international research institutes, civil society organizations, and private firms. Women represent 43 percent of total NEXUS scholars, a proportion mirrored by our recruited interview participants (43 percent women, 57 percent men). Among the thirty interviewed scholars, twelve are based in Canada and the United States, with the remaining eighteen located in Latin America and the Caribbean.

We were mindful that our position as NEXUS "insiders" might present challenges in the study: would interviewees interpret the study as directed by program staff? Would interviewees be reticent to speak openly about the nature of their collaborations? The first two authors of this article conducted the interviews and did not experience any awkward conversations. To the contrary, NEXUS participants were eager to tell their stories. At the same time, we cannot account for the sentiments of those who chose not to participate. While the views presented here are not exhaustively representative of the program, we do not seek such quantifiable data. Our objective is to elicit an ethnographic explanation of transdisciplinary research and knowledge mobilization from the perspective of science as human practice embedded in particular social orders.

In analysis, we coded and interpreted data to elicit the key imaginaries, discourses, and practices in knowledge integration and mobilization, relying on a mix of grounded theory and extensive review of transdisciplinary science (Klenk and Meehan 2015). To protect informant confidentiality while conveying important details about participants, we balance the use of participant pseudonyms (presented as numbers in brackets) with details that disclose location, nationality, and gender.

Transdisciplinary Knowledge Politics

In this section, we examine transdisciplinary knowledge mobilization at three important sites of coproduction: at the scales of global circulation, the nation-state, and individual participants. Following Escobar (2008), we understand scale not as a vertical hierarchy of nested models but as immanent, emergent, and embodied "sites" of spatial and social relations. NEXUS participants experienced geopolitical dynamics at all three "scales" to varying degrees. We first examine how universalized and "global" visions of knowledge mobilization are reproduced in the programmatic design and expectations of NEXUS, even though participants encountered a plurality of the science–policy interface(s) and systemic barriers that shaped pathways for knowledge mobilization.

Second, we explore the "national" sociotechnical imaginaries of transdisciplinarity as a mechanism of national economic development, exemplified by the case of Colombia. This dynamic selectively limits what kinds of knowledge can even be mobilized across the science–policy interface. NEXUS participants working in Colombia find themselves, on the one hand, riding the crest of a popular scientific paradigm, and on the other, caught in sieve that favors—in their words—knowledge that creates more market-ready "D" (development) than basic "R" (research).

Finally, we explore the geopolitics of knowledge mobilization at the site of the individual. As Fulbright grant recipients, NEXUS scientists and stakeholders were expected to stand in as national subjects—literally, as cultural ambassadors of their country—and to partake in knowledge and cultural exchange activities throughout the hemisphere. Participants had to confront and negotiate broader systems of cultural and socioeconomic difference within teams, which was elevated by even starker differences between the capacities of decision makers and scientists. Friction was inescapable; but as we point to in the concluding section, the NEXUS program also tested new pathways of productive collaboration and action.

Global Regimes of Knowledge Mobilization

Transdisciplinary and international models of scientific collaboration, informed by a logic and desire for evidence-based policy, served as the blueprint for the funding, organization, and desired impact of the Fulbright NEXUS program. NEXUS was initially created in 2010 during a meeting of staff from the US State Department (Bureau of Educational and Cultural Affairs) and Fulbright Commission directors from Latin America. Staff met to craft a "new model for Fulbright research" based on collaborative, problem-oriented, regional research—"the idea came to life in that meeting." Unlike other Fulbright programs, the NEXUS emphasized team-based transdisciplinary research. The first cohort (2011 to 2012) featured scholars doing mostly independent research with their own selected stakeholders. The second cohort (2012 to 2013) continued to fund individual projects and also implemented requirements for small group research with other NEXUS scholars and stakeholders. By the third cohort (2014 to 2016), Fulbright staff increased grant length to two years and jettisoned independent projects in favor of only team-based research with stakeholders.

Climate change policies quickly became one of the central planks of the program, "especially as President Obama started to talk a lot more about climate change in public." While countries in Latin America, such as Mexico, were already leaders in developing national climate policies, the climate-friendly rhetoric of the Obama administration was key to unlocking programmatic possibilities for the NEXUS. "When we opened the first cohort competition," recalls a staff member, "we had a large share of people who proposed programs related to climate change." Topics emerged organically and included diverse aspects of climate change including projects about climate science (modeling and prediction), mitigation (low-carbon energy development), adaptation (farmer responses to market shocks and extreme weather events), and societal transformation (hazard communication). By the second cohort, "a decision was made to move to climate change more fully because people in my office were working on it and thought it was important. We've been given new guidance from above."

From the start, the regional focus of NEXUS (the "Western Hemisphere") reflects the spatial vision of the US State Department—"you know, the world regions that we're structured around here at State"—and how the Department structures its internal offices and bureaus including the units that house the NEXUS program. It is important to note that the "Western Hemisphere" is a constructed spatial imaginary and social order. Regional bureaus were initially developed in the 1870s and mirrored colonial divisions of the world, early struggles of nation formation, and intense economic competition. In 1910, the State Department formally established the Western Hemisphere bureau, a portfolio of thirty-nine countries (including Canada, Latin America, and the Caribbean), with the goal of sustaining regional hegemonic power within a globalizing world order (Moore 2016). This geospatial order was not lost on NEXUS participants. Most participants identified NEXUS as an "American" (read: USA) program, despite its hemispheric template and cofunding with Brazil. For the Chilean participant below, NEXUS represents the norms, standards, and expectations of US scientific institutions, a point she makes by using the interviewer as a prime example:

Participant 28:	Where are you from, Katie?
Interviewer (Katie):	I'm from the United States.
P28:	Yeah, therefore you are different because you have the background of the people from Fulbright, you know what I mean. But we are from South America and things are quite different here.

Programmatic antecedents such as the Fulbright New Century Scholars program (2001 to 2010) were "global" in mandate and scope, yet NEXUS adopted a regional model. Staff hoped that a shared region would facilitate collaboration and improve outcomes of knowledge mobilization:

> I think the general idea was like, if you bring a group of people together from the same region that are working towards the same goal and on the same issues, [then] we have an effective program model.

Funding also reflected regional power dynamics. The Brazilian Ministry of Education, at the "apex of their glory" in terms of science funding in 2014, partnered with the State Department to jointly sponsor the third NEXUS cohort. "It didn't hurt that at the time Brazil was involved with strategic partnership dialogues," explains a staff member, "and at the Summit of the Americas, there [was] renewed focus on US relations with its Latin American and Canadian neighbors." Consequently, the third cohort featured a more prominent number of Brazilian scholars, direct involvement by the Brazilian Fulbright Commission in meetings, and guest appearances by prominent Brazilian global change scientists, diplomats, and ministry representatives.

From the very beginning, NEXUS was designed to "reach across" the science–policy interface—to foster "that culture of young researchers trying to inform [policy] with their work" that, according to program staff, is less valued in university settings and academic culture. The NEXUS vision was underpinned by a strong belief, held by staff and participants alike, that stakeholder involvement resulted in improved knowledge mobilization and policy outcomes:

> The idea was fantastic, I think, linking knowledge in general but linking scientific research with the process of elaborating policy, [that's] wonderful. It's a very basic premise: you believe that policy will be better if it is informed by science and technology. That is what NEXUS was trying to do, is [to] connect policy with science research.

Scholars shared a similar view that research should "leave the lab" and interact with society:

> Let's get a little bit philosophical. NEXUS is what we should have been doing for a long time. People in universities throughout the world, we tend to focus a lot on what the professors around us tell us what should be done. You don't get many chances to see a guy who arrives late at a meeting because he had trouble with a camel in South Sudan. You need to look outside the fences around your university. Research has to impact someone and it can't be done just by staying in the lab.

At the beginning of each cohort, NEXUS participants were trained—or, as one participant jokingly described, "brainwashed"—on the benefits of mobilizing knowledge into practice.

> We spent so much time both at the initial meeting and I think also the Mexico meeting talking about how scientific research could be translated to policy. Like, how to have an impact. That science should have an impact on people—not only science for science, science for knowledge. But science to create benefit for people.

While NEXUS included scholars from Canada and the United States, its target audience was, in practice, policy makers in the "developing countries" of the Western Hemisphere. With few exceptions, nearly all of the individual and group research projects took place in Latin America and the Caribbean. No groups worked collectively on climate change knowledge mobilization in Canada or the United States—a great irony, given these countries' role as major generators of greenhouse gases and the urgent need for science–policy transformation regarding climate change in the United States. While NEXUS advanced the model of transdisciplinary sustainability research beyond efforts at "national" or "global" levels, it also reproduced the dominant patterns that characterize international scientific collaborations, where scientific theory and funding dollars radiate from the North to be "applied" in the environmental and social contexts of the South (Lahsen 2002; Nobre, Lahsen, and Ometto 2008; Vessuri 1986, 1990).

In sum, the NEXUS program promoted a distinct sociotechnical imaginary of knowledge mobilization: one in which the region was the desirable geographic unit of scientific partnership; the inclusion of extrascientific actors would yield improved policy outcomes; and problems of climate change, health, and environmental sustainability naturally lent themselves to transdisciplinary inquiry and application. In what follows, we document how the experiences of participants diverged from the transdisciplinary ideal; participants encountered a plurality of science–policy interfaces including entrenched national priorities and political economic imperatives.

Neoliberal Development and Knowledge Mobilization in Colombia

Scientific discovery and knowledge production have a long geopolitical history in the Americas, through their use as instruments of colonial territorial expansion, sovereignty claims, and resource control and development (Hecht 2013; Lahsen 2002; Vessuri 1986, 1987). Against the backdrop of regional trends of scientific isolation and state disinvestment in research during the 1980s (Vessuri 1990), in the past two decades, Colombia has increasingly promoted and institutionalized transdisciplinary science. The Colombian government justifies investments in transdisciplinary initiatives, scientific infrastructure, and human and institutional capacity as a means to foster economic growth and international competitiveness, ensure efficient and sustainable use of natural resources, and resolve social problems of violence, poverty, and inequality (Bortagaray and Gras 2014, 273; Crespi and Dutrénit 2014). Not surprisingly, this mandate is a tall order for a country newly emerging from a six-decade, tumultuous civil war.

Colciencias (the Administrative Department of Science, Technology, and Innovation) was established in 1968 as the financial fund and national coordinating body for scientific and technological development in Colombia. Since the 1980s, the agency has incrementally reformed its policies and institutional structure to incentivize and reward transdisciplinary-style knowledge mobilization. Milestones include the development of the National Innovation System (in 1995), the adoption of international standards for research (in 2000), the development of national STI plans (in 1998, 2006, and 2010), and the passage of law 1286 (in 2009) that elevated Colciencias to the equivalent of a ministry and stabilized its budgetary independence (Bortagaray and Gras 2014). By the year 2000, Colciencias had developed clear policies and funding mechanisms to reward science for the productive sector (Bortagaray and Gras 2014; Pérez-Rincón 2014).

NEXUS participants working in Colombia inevitably encountered its national imaginary of "useful" science. Reflecting on the shift, a Colombian NEXUS participant explained the trade-offs involved when societal actors—namely, elected representatives in the government—are in positions to shape the expectations and conditions of knowledge mobilization:

> Politicians really want results. They just don't want academic, blue sky research, they want something applied so that they can show to others and keep them happy, so they can be elected for the following year. Most of the research that is being done in Colombia is somewhat applied research. The problem with this is the blue sky fundamental research is not receiving much funding now.

With politicians at the helm, the participant continued, science risks losing its "objective" status, as academics become mere "consultants" for market innovation and political will. "Applied research poses the risk of becoming a consultancy," he said, "just something a company can do—something being shown as research but it's just developing. Not much R but mostly D. Especially due to the politics involved."

Knowledge mobilization for big "D" development is certainly on the Colombian scientific agenda, especially without the presence of the guerrillas and organized opposition. With the formal launch of Colombia's accession process to the Organization for Economic Cooperation and Development and the signature and ratification of the peace agreement, there exists new institutional pressure to develop natural resources—mining, oil, and industrial agriculture—that are evident in "sustainable development" instruments like the Green Economy Mission, launched in 2015 by the Colombian National Department of Planning. "Colombia has promoted the neo-extractivist path [to development]," writes Pérez-Rincón (2014, 82), "through the design and implementation of a series of policies crafted by decision-makers and an international context that promotes it." The road map to the green economy includes STI activities and policies that call for more efficient use of natural resources and improved economic development but fail to recognize the roots of ongoing land use and water conflicts across the country and the extractivist mode of environmental governance (Perez-Rincón 2014).

With the passage of *Scientific Colombia*, the latest national STI policy plan (for 2015 to 2025), the Colombian government institutionalized a vision of transdisciplinary science that fosters international networks, innovation in the productive sector, and market-ready technologies. Specifically, the plan gives funding to Colombian universities that partner with at least one private sector firm and one of the top 500 world universities, as rated by the Academic Ranking of World Universities. The stated purpose of this reform is to increase global competitiveness and productivity that contribute to development of the country. Large amounts of money are promised to research initiatives that include nanotechnology or biotechnology, as well as proposals that include patents, products, and efforts to strengthen the productive sector.

New STI policies in Colombia are, in part, justified as a means to improve human rights, social development, and the sustainable use of natural resources (Bortagaray and Gras 2014). Despite such promise, in practice, transdisciplinary knowledge mobilization has to navigate real structural barriers in Colombia: regional poverty and power asymmetries, the historical legacy of violence and conflict, and "market-ready" imperatives to compete internationally. High oil prices allowed investment in regional scientific infrastructure for many years, but the process began to resemble institutions characterized by productive sector outcomes, rather than by goals to advance basic knowledge (see also Vessuri 1990). Funding is flush, this NEXUS participant explained, but the close involvement of government implies trade-offs:

Participant 6:	The Colombian government decided to dedicate 10 percent of royalties from oil and coal and mining to R&D. And this money was given to the departments, which are like states in Colombia. They [the states] would define the areas of interest they want to invest in. This had an interesting outcome, a negative one. The problem was that too much politics was involved. Projects doesn't get [approved] if the Colombian government doesn't want, if the government doesn't like it. Even though before it [a project] gets accepted, it needs to get accepted by Colciencias, like a similar [approval] process. Even though in some departments, it definitely went to corruption, unfortunately. So for example: a million dollar project for a document—a 30-page document.
Interviewer:	Wow.
P6:	Yeah, exactly.

Crucially, this story reveals more about transdisciplinary knowledge regimes than just "corruption" and poor management. Colombia's shift toward transdisciplinarity introduces a deliberate "politicization" of science that disrupts closely held scientific norms of objectivity and value-free knowledge, as the NEXUS participant notes. Given the Colombian government's aim to develop competitively on the global stage, knowledge regimes are at the mercy of government economic priorities, which are clearly neo-extractivist in character (Pérez-Rincón 2014), and reflect a trend toward the commercialization of academic outputs and knowledge production (Vessuri and Bueno 2016).

We use these stories to illustrate that national sociotechnical imaginaries selectively limit what types of knowledge can even be mobilized across the science–policy interface. Geopolitical dynamics matter here. In the case of Colombia, the neo-extractivist model of development selects for profit-yielding and export-oriented transdisciplinary projects—a depressing reality for climate change, health, and sustainability researchers studying, say, vulnerability and adaptation. Yet, as our informants suggest, national imaginaries, science–society relations, and the conditions for knowledge mobilization shift across place. A personal NEXUS anecdote, set in the United States, provides a brief illustration. In May 2016, we traveled to Washington, DC, and presented research briefs to policy organizations and decision makers. During a conversation with a member of the US House of Representatives who serves on the House Committee for Science and Technology Policy, we asked what types of climate change research or information are most useful in her job. She responded that S&TP committee members, under leadership of climate skeptics, are prevented from using the phrases "climate change" and "global warming" in internal meetings, documents, or legislation. In the United States, climate-related research cannot even get through the front door of legislative bodies.

These examples are geopolitical in the sense that they reveal a plurality of science–policy interfaces produced by local social orders and global hegemonic ideas and practices. Such testimonies also expose the real-life constraints of decision makers, who operate in worlds that refute any "rationalist" and depoliticized characterizations. For scientists attempting to meaningfully link climate knowledge with policy action and societal transformation—the core thrust of NEXUS and cognate programs like Future Earth—such conditions shape the very pathways of knowledge mobilization including which types of knowledge are even deemed acceptable, valuable, or translatable into policy and how such experiments will succeed in "developed" countries like the United States, where knowledge mobilization is just as (geo)political as everywhere else.

Embodied Geopolitics of Knowledge Mobilization

NEXUS participants routinely confronted and struggled with the geopolitical dynamics of knowledge mobilization in embodied ways, reconciling global and national discourses with experiences at the scale of individuals. Language provides an illustrative example. Participants described deferring to scholars with English fluency, frustrated by the dual challenges of merging academic and national languages. Knowledge production in English served to expedite its dissemination for a "global" audience of academics, yet undermined its potential for use in the language of the stakeholders—whom this research is intended to transform. Not all participants felt comfortable with this practice, even if they complied. Feelings of anxiety and guilt, expressed by this US participant, accompanied the acceptance of hegemonic Anglo-American academic norms and standards that are imported through language:

> I must admit, in international collaborations, something that I always feel a little, I don't know, a little reluctant is that the other person who ended up leading a lot was another American. I always feel like this part of it is the language issue, being able to write easily in English. It's always an advantage in these kinds of things, knowing the formula writing of articles. It would

> have been nice to have more leadership from the region [Latin America and the Caribbean] but that's the way it came out.

Not only did using the English language provides a license to import knowledge traditions, epistemic beliefs, and norms of research practice—marginalizing scholarship in local languages—it also served to reproduce socioeconomic and class divisions.

For example, many of the Latin American participants spoke fluent English, were trained abroad (in the United States, Canadian, or European universities), and held extensive networks and collaborators in the United States. Class divisions, coupled with nationalist stereotypes, influenced how research problems and cases were imagined, selected, and understood, as this US participant explains:

> The other thing is there are cultural differences. Like, we ended up doing our project on Nicaragua. And a lot of the people from Latin America in the group were from Argentina, Chile, Colombia. And they were from the upper classes and they had no interest in Nicaragua, none whatsoever. Especially because it is a very leftist country, and they felt like we had an agenda as American academics. I don't think that people in the group really spoke up about their preferences or what they wanted to do, they were just kind of like "we have to do it because it's not our first choice, we're going to do the bare minimum sort of thing" . . . No one really spoke up, I think because they just felt like [the leaders] had everything under control and maybe the tendency to defer to Americans because it was an American program, and of course there's all these power dynamics.

Unlike most transdisciplinary programs, where national or class differences are muted or subsumed, NEXUS scientists and stakeholders were expected to stand in as national subjects—literally, as cultural ambassadors of their country—and to partake in cultural exchange activities throughout the hemisphere, culminating in a final "policy impact" meeting in Washington, DC. Participating scientists, no matter how open to international collaboration, had to negotiate broader systems of cultural and socioeconomic difference that shape individual capacities to actually mobilize knowledge into policy, especially with local stakeholders thrown in the mix.

NEXUS participants used several metaphors to describe knowledge mobilization. While some invoked positive and idealized associations ("fantastic," "wonderful," and the "sweet spot"), others utilized metaphors that described the science–policy interface in terms of a chasm, a "middle point," or a "wall." Mobilizing knowledge required navigating differences in work standards, cultural expectations, institutional mandates, and reward structures that created very different operating conditions for scientists versus stakeholders.

> Sometimes [policy makers] need to make the decision really fast and they can't wait to run the whole model, like weeks or even months. They need to make a decision right now! It's really hard because you want to be as rigorous as possible, but sometimes maybe having some information can help the decision making, it doesn't have to be perfect. You need to decide where to stop.

Perhaps the biggest rift emerged when NEXUS scholars worked with politicians or political appointees in government—a necessity for investigators who needed research permission, access to sensitive or large-scale data, or who desired proximity to individuals who are "close to power." "If you're not really next to the politicians that is very difficult no matter how good project you do," a participant explained, "From my experience as a Chilean, if you don't have somebody supporting you there from a good level that could influence decision-making and policy, that's difficult." Yet, as this Argentine explains, political appointees come and go, thus requiring scientists to locate more "permanent" but perhaps less influential public employees:

> Participant 7: There are [knowledgeable] people but they are lost in the structure. It's not like a developed country, you know. It's very different because perhaps in your countries only the head changes, but here no.
>
> Interviewer: Did you notice differences with colleagues from different countries?
>
> P7: No, that was another interesting issue. We all had the same problem. Our group had people from Argentina, in my case and another colleague from Argentina but isn't working with the public sector, and there was the guy from Uruguay and another person from Colombia. And we all had the same issues with stakeholders. I think that it is still true that in developing countries, the interface between academia and the public sector is more difficult.

Metaphors of conduits, champions, and direct lines of entry into policymaking refer to an idealized model of the science–policy interface, in which researchers expect to produce usable knowledge only if they are connected to the "right" level of decision-making. As the NEXUS stories explain, to achieve the transdisciplinary mandate—to establish a close working relationship with "influential" policy actors—participants must navigate differing organizational, institutional, political–economic, and knowledge seeking practices, especially between scientists and stakeholders.

A geopolitical approach to knowledge mobilization implies that the path linking research with policy is neither linear nor singular; scientists must navigate highly localized landscapes of development priorities, institutional capacity, territorial claims, socioeconomic differences, and power asymmetries at multiple scales. In the case of NEXUS, science–policy interface(s) are fundamentally plural. While stakeholders are assumed to be vectors of knowledge and catalyzers of action, in practice they may resist "evidence-based" decision-making if such knowledge does not fit organizational priorities, political economic imperatives, or if they are positioned at the "wrong" level of government to effect change.

The extent to which programs like NEXUS open up alternative paths to dealing with the future of climate and development depends, in part, on how research is imagined and designed to inform decision-making at different scales and whether societal actors are empowered to shape research in a way that may challenge global framings of climate issues, governance, and solutions. Local decision makers may not be attractive to researchers, if they lack power to suitably effect change; conversely, without their input, it seems unlikely that research will contribute to the crafting of locally appropriate climate responses. The NEXUS case reveals how sociotechnical imaginaries reflect variegated constructions of space and social order—a fact that current models of transdisciplinary sustainability science, in their ambition to produce universal knowledge, fail to reckon with.

Conclusion

Transdisciplinary research holds great promise for transforming climate and sustainability knowledge into policy action. At the same time, dominant models of transdisciplinary interactions privilege a depoliticized version of knowledge mobilization, stripped of its geographic specificities, differential capacities, and diverse paths to policy action. In this article, we moved past idealized models of knowledge mobilization—the "linear" model that relies on the "best evidence" available—to advance a geopolitical approach to transdisciplinary knowledge regimes, which seeks to characterize how scientific knowledge is coproduced and circulates at multiple scales in "a world of persistent inequality and dominance" (Jasanoff 2015, 22). Through analysis of the Fulbright NEXUS program, we sought to identify persistent disparities and divergences that diminish the capacity of researchers to influence decision-making and fit climate and sustainability knowledge within broader neoliberal development paradigms. In line with feminist understandings of "geopolitics" in everyday life, NEXUS participants experienced plural imaginaries and misalignments in the production of "useful" knowledge, national development agendas that differentially equipped mobilization pathways and capacities, and resistance to imposed rationalistic models of a singular science–policy interface. With the growth of transdisciplinary research schemes as a mechanism of market-ready innovation and development, as we show in Colombia, there is even greater need for critical understandings of how scientific knowledge regimes operate in practice to empower marginalized communities and developing countries (Nobre, Lahsen, and Ometto 2008). Our study provides a useful starting point.

Reflecting on our own experiences of the NEXUS collaboration, we briefly conclude with two potential lessons for future transdisciplinary efforts. First, climate and sustainability science should learn from experiments such as the "Latin American School" of social medicine and public health, with its long-standing history of stakeholder design, applied practice, and direct action for human welfare and social justice, often in contexts of extreme socioeconomic and environmental inequality (Méndez 2015). In Colombia, the field of public health has yielded successful examples of knowledge coproduction, scientific innovations, and policy applications. For example, scientists and practitioners have identified and synthesized the determinants of health from different schools of thought, a process that requires the coordination of multiple organizations, disciplines, policy tools, and ethical considerations that go beyond the identification of biophysical risk factors (Méndez 2015). Researchers in Latin American social medicine conceptualize the health–disease–action process with an emphasis on translating results into a coherent and just social response (see Iriart et al. 2002)—supporting what de Sousa Santos (2007) calls "epistemologies of the South" by lending visibility and credibility to the cognitive practices of those who have been historically exploited and oppressed by extractive colonialism and global capitalism.

Second, we have found that rather than seek to locate the "best" recipe or "right" stakeholder or "perfect" team, transdisciplinary knowledge creation and mobilization should be viewed as intimately entangled, relational, and dynamic convergences of multiple social and political orders—an "adventure in relevance" rather than a prescribed course of action (Klenk and Meehan 2017). Engaging with a local decision maker requires negotiating a web of decision makers at higher levels and differing capacities, as well as with national sociotechnical imaginaries—including desired futures, public policies, and international political economies. The Fulbright NEXUS was an innovative experiment in this regard: its design and organization allowed transdisciplinary knowledge to develop as a *cultural* exchange and not simply as the "best" answer to a wicked problem. Rather than provide a recipe, our experiences suggest that knowledge mobilization should be understood as a process of negotiation, entanglement, and testing potential scenarios and paths of action (Callon, Lascousmes, and Barthe 2011; Klenk and Meehan 2015). Moving along these paths is the task at hand for transdisciplinarity. There is no silver bullet; transdisciplinary sustainability research must grapple with its epistemic geographies and lived geopolitical realities to truly change the intellectual climate.

Authors' Note

Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the aforementioned government agencies.

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Developing Evaluation Indicators to Improve the Process of Coproducing Usable Climate Science

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ABSTRACT

Resource managers and decision-makers are increasingly tasked with integrating climate change science into their decisions about resource management and policy development. This often requires climate scientists, resource managers, and decision-makers to work collaboratively throughout the research processes, an approach to knowledge development that is often called ''coproduction of knowledge.'' The goal of this paper is to synthesize the social science theory of coproduction of knowledge, the metrics currently used to evaluate usable or actionable science in several federal agencies, and insights from experienced climate researchers and program managers to develop a set of 45 indicators supporting an evaluation framework for coproduced usable climate science. Here the proposed indicators and results from two case studies that were used to test the indicators are presented, as well as lessons about the process of evaluating the coproduction of knowledge and collaboratively producing climate knowledge.

1. Introduction

As the impacts of human-influenced climate change are increasingly recognized in the United States and around the world, the need for climate science and information that can be readily used in decision-making contexts for climate change adaptation and mitigation has grown rapidly (Melillo et al. 2014). As many researchers have acknowledged, however, simply producing more information does little to solve the problem (Clark et al. 2016). Information that will inform decision-making must apply directly to the problem at hand, be at spatial and temporal scales that match the problem, and be scientifically sound (Lemos et al. 2012; McNie et al. 2007). To address this need, some researchers have increasingly focused on approaches that involve the end users of research in a collaborative or ''coproduced'' research process.

Previous research has shown that taking a collaborative approach to knowledge development is more likely to result in science that is used by decision-makers (Jasanoff 2004; Jasanoff and Wynne 1998; Lemos and Morehouse 2005; van Kerkhoff and Lebel 2015) than science produced using the ''loading dock'' model of delivery in which the engagement with users is one way: from researcher to user (Carbone and Dow 2005; Cash et al. 2006; Jasanoff and Wynne 1998; Lemos et al. 2012). Social science research on science production has indicated that collaboratively produced science tends to be more easily accepted and applied by decision-makers because they better understand the process by which it was developed and feel a greater sense of knowledge ownership (Jasanoff and Wynne 1998), and the information is more likely to fit their needs (Lemos and Morehouse 2005; Lemos et al. 2012).This more collaborative approach to knowledge development has been termed coproduction of knowledge (Jasanoff and Wynne 1998), stakeholder-driven science, user-driven science (Dilling and Lemos 2011; McNie 2007), actionable science (ACCCNRS 2015), knowledge exchange (Cvitanovic et al. 2015), and transdisciplinary research (Jahn et al. 2012). While acknowledging these varied

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terms, we most often use coproduction of knowledge in this paper to refer to highly collaborative, user-driven research approaches.

Evaluating these types of programs and projects requires innovative approaches, as more traditional metrics of research success are often insufficient to assess the processes and outcomes of coproduced climate science, which differ from the more output-focused metric of traditional academic research (Bell et al. 2011; Evely et al. 2010; Fazey et al. 2014; Ferguson et al. 2016; Moser 2009; National Research Council 2005). Standard tools for evaluating scientific research are often inadequate to capture decision and policy impacts; they largely rely on scientific impacts of the research (Bell et al. 2011) that address scientific credibility (Cash et al. 2003) but fail to address its saliency to decision-makers or the legitimacy of the process of developing the knowledge (i.e., the extent to which stakeholders were involved in knowledge development; Cash et al. 2003; Evely et al. 2010; Fazey et al. 2014). New evaluative frameworks can help to identify, for example, which research approaches best support genuine collaboration between scientists and stakeholders, when a project has been successful in producing a collaborative product, and to what extent programs are successful in supporting such efforts.

While significant research has identified key principles that support this kind of collaborative effort (Lemos and Morehouse 2005; McNie 2013; Reed et al. 2014), those studying the field of coproduction continue to struggle with a lack of empirical evidence to support the principles (Hegger and Dieperink 2014), provide greater detail about how to apply the principles (Reed et al. 2014; van Kerkhoff and Lebel 2015), evaluate the processes and outcomes from collaborative research (Bellamy et al. 2001; Fazey et al. 2014; Meadow et al. 2015), and go beyond a set of best practices to effectively measure these key principles and their importance in the coproduction process.

In this paper we present our work on developing and testing an evaluative framework for coproduced climate science. In this research, we identified the key principles in coproducing knowledge from the existing literature, examined how usable climate research is currently evaluated, and interviewed experienced climate science integrators to gain insight from their direct experiences coproducing such knowledge. We synthesized information from these sources to develop an evaluative framework that consists of 45 indicators grouped into context; process; and output, outcome, and impact indicators. We also present lessons about the process of collaboratively producing climate knowledge based on findings from our evaluative framework. We then reflect upon lessons learned about the process of evaluating the coproduction of knowledge.

2. Literature review

In this section, we discuss three related areas of literature: coproduction of knowledge, information use in decision-making, and evaluating coproduced climate research. This body of peer-reviewed knowledge has focused on the benefits and challenges of coproduction approaches, as well as identifying future steps and unanswered questions, including a greater awareness of the role of researchers in informing adaptation process (Lacey et al. 2015) and the challenges of doing this type of research within an academic context (Brugger et al. 2015). Within the context of developing evaluation frameworks, understanding how information is used in an organization for decision-making (or barriers to its use) is relevant to interpreting and measuring the impacts and outcomes of information use (Choo et al. 2008; Rich and Oh 2000; Taylor 1991). Evaluation research focused on understanding the value of coproduced climate research contributes to developing best practices for coproduced climate research; increasing capacity to conduct coproduced climate research; and providing insights into when coproduced strategies or approaches are a good fit with the project, stakeholders, and researchers involved.

a. *Coproduction of knowledge: Process and principles*

The process of coproducing science knowledge holds challenges and benefits for both researchers and decision-makers. Decision-makers often must grapple with new scientific fields in which they have little training as well as with the inherent uncertainty of science knowledge, while simultaneously trying to protect and conserve the natural resources and human communities to which they have responsibilities (Brugger et al. 2015). As Lacey et al. (2015) and Ford et al. (2016) note, researchers also bear responsibility for understanding the implications of research focused on adaptation, that is, what the direct effects of adapting (or not) to climate change will be for the communities in question. For the purposes of this review, we define coproduction of knowledge as the process of collaboration between researchers and decision-makers to develop new or refined climate science with the intention of making that science usable by decision-makers (Meadow et al. 2015).

Early work on collaborations between scientists and decision-makers identified strategies that are linked to more successful outcomes (i.e., increased use of science in policy or decision-making). Lemos and Morehouse (2005) outlined the following list of activities within the research process in which stakeholders should, ideally, participate in order to improve the usability of climate science: defining the problem, formulating the question, selecting methods, conducting research, analyzing findings, developing knowledge, testing and evaluating results, and disseminating findings. More recent consideration has specifically identified strategies for coproduction approaches. Hegger and Dieperink (2014) and Hegger et al. (2012) propose a set of seven ''success conditions'' for coproduction of knowledge, including who is included in the process, whether they achieve a shared understanding of problems and goals, how project responsibilities are shared, and whether specific resources such as boundary objects and certain competencies are present. Van Kerkhoff and Lebel (2015), Wyborn (2015), and Schuttenberg and Guth (2015) all discuss the importance of coproductive capacities in setting the stage for coproduction of knowledge to take place. These capacities are as follows: material (resources available), cognitive (process of generating knowledge), social (capacity to produce effective and equitable governance), and normative (the underlying values inspiring actors to work toward a common goal). These are each mediated through the existing socioecological system in which the process takes place (Schuttenberg and Guth 2015). While all the capacities contribute to the level of influence of coproduced knowledge (Schuttenberg and Guth 2015), the capacities differ in various contexts, and therefore, different interventions to promote coproduction of knowledge are likely to be necessary in different contexts (van Kerkhoff and Lebel 2015).

Other analyses of scientist–stakeholder collaboration have focused on the role of communication and relationships in development of credible, salient, and legitimate information (Buizer et al. 2016; Jacobs et al. 2005; Lemos and Morehouse 2005; Wyborn 2015). Research also has highlighted certain elements in the relationship between climate science producers and users that seem to have particularly strong influences on ultimate use of information: two-way communication, building trust, being accountable for the findings, and the importance of building long-term relationships in order to be successful (Brugger et al. 2015; Kirchhoff et al. 2013). These long-term relationships also may contribute to the development of information-sharing networks that encourage the development of both weak and strong ties that influence how research is promulgated and its impacts amplified (Granovetter 1983). Ferguson et al. (2014) developed a set of guiding heuristics that emphasize the role of relationships and open communication to improve the process and outcomes of collaborative science research, including the following: 1) the importance of setting mutually agreed upon ground rules, 2) the responsibility of the researcher to learn about institutional governance and norms, and 3) the importance of demonstrating mutual respect throughout the collaboration.

Like Ferguson et al. (2014), Reed et al. (2014) synthesized literature and data from a series of interviews with researchers and stakeholders involved in knowledge exchange research for environmental management and proposed the following five principles for knowledge exchange: 1) design knowledge exchange into the project, 2) represent the diversity of stakeholders and systematically identify all stakeholders, 3) engage through two-way dialogue and long-term relationships, 4) generate impact by delivering tangible outputs, and 5) reflect upon and sustain connections with stakeholders. The list of questions and guidance provided by the cited authors are comprehensive but do not directly address the need to measure responses—such as how much participants' perceptions changed, characterizing the specifics of communication, or measuring the intensity or length of relationships—in order to understand how a particular variable impacts the ultimate use or nonuse of information in decision support.

b. *Information use in decision-making*

Beyond coproduction of knowledge as a concept, other scientists have been exploring ways in which information is or is not used in organizational decision-making. Their research can inform the ways in which we frame the outcomes and impacts of coproduction processes by helping us understand how and under what conditions information is adopted by organizations. Patton (1978, 1982), Mark et al. (2006), and Alkin et al. (2006) have considered how to make the information generated by program evaluations more useful by program decision-makers. There are clear analogies between the struggle evaluators face and those faced by climate scientists hoping to develop actionable science. For example, Patton (1982) noted that ''evaluators found that methodological rigor did not guarantee that findings would be used,'' an experience similar to many researchers we interviewed for this project (see also Brugger et al. 2015).

Taylor (1991) identified eight different types of information use that provide a spectrum of ways to think about how information can inform decision-making, ranging from organizations or an individual perceiving itself to be better informed about an issue (enlightenment) through a tangible application of information to solve a problem or learn a new skill (instrumental).

Oh (1996) further refined these information use types into three categories (with more detailed subcategories): 1) conceptual information use, where an organization/individual perceives itself/himself/herself to be better informed about an issue or has changed opinion about the issue; 2) justification, where information is used to justify a predetermined decision; and 3) instrumental, where information is directly used to inform a new decision. Choo (2006) presents three different conceptual models for how organizations use information, each driven by the reason they were seeking information: sense-making in response to a change in their environment, knowledge creating to develop new capabilities or innovations, and decision-making to select alternatives and take a goal-directed action.

c. *Evaluating coproduced climate research*

The challenge for those undertaking coproduction processes at either project or program levels is to link the principles and frameworks to ‘‘tangible (measurable) project goals or outcomes’’ (van Kerkhoff and Lebel 2015) and to understand how our capacities to coproduce knowledge contribute to its impacts on resource management and governance (Hegger and Dieperink 2014). New studies are employing empirical assessment of collaborative science research to propose ways to understand the processes involved and evaluate outcomes (Bell et al. 2011; Fazey et al. 2014; Ford et al. 2013; Hegger and Dieperink 2015; Walter et al. 2007). Even the idea of assessing the impact of research on decision-making is new within many academic disciplines, where reward structures rely primarily on the number of peer-reviewed publications (Bell et al. 2011; Roux et al. 2010).

Writing from the perspective of a resource manager, Jacobs (2002) proposed ‘‘measures of success’’ for collaborations between scientists and decision-makers, such as answering the following questions: Did participants modify behavior in response to information? Did participants initiate subsequent contacts? Did the stakeholders claim or accept partial ownership of final products? Was the process representative of all interests? Were the outcomes implementable in a reasonable time frame?

Bell et al. (2011) reviewed projects designed to produce environmental science results for policy and found a diversity of evaluative approaches, as well as some common challenges including the following: attributing management outcomes to any particular piece of information, timing the evaluation appropriately to observe any impacts, determining the reliability of the information, and assessing the resource-intensive nature of impact evaluation. Fazey et al. (2014) reviewed 135 studies of knowledge-exchange evaluations from a variety of fields to develop a set of principles for evaluating this type of work. These studies encouraged researchers to 1) build evaluation into the knowledge-exchange project, 2) be explicit about why a knowledge exchange approach is necessary to yield desired outcomes, and 3) evaluate diverse outcomes (not just the expected ones).

Focusing on the process of engagement between scientists and stakeholders, Walter et al. (2007) constructed an explanatory model to evaluate a transdisciplinary project. Through statistical analysis, they found that the outcomes of network building, distribution of knowledge, and transformation of knowledge were significantly correlated to the predictor variable ‘‘involvement’’ as measured by the number of engagement activities that took place during the project. Beierle (2002) examined 239 public processes focused on environmental management decisions. He categorized the participatory processes into four groups: public meetings or hearings, advisory committees not using consensus, advisory committees using consensus, and negotiations and mediations. He used the following four evaluative questions as criteria to determine the extent to which public participation led to higher-quality decisions: Are decisions more cost effective than the likely alternatives? Do decisions increase joint gains? Do participants contribute innovative ideas, useful analysis, or new information? Do participants have access to scientific information? He found that more intensive participatory processes tended to produce higher-quality decisions.

Blackstock et al. (2007) developed an evaluative framework for participatory research in sustainability science. Their framework examined the role of process (champion or leader, communication, conflict resolution, influence on the process, and representation), context (political, social, cultural, historical, and environmental), and outcomes (accountability, capacity building, emergent knowledge, recognized impacts, social learning, and transparency). A key finding from their test of the model was that impacts often take a long time to emerge, and simply evaluating at the end of a project is insufficient. Armitage et al. (2011) identified five following dimensions of coproduction of knowledge within marine mammal comanagement frameworks in the Arctic and empirical examples of each: knowledge gathering, knowledge sharing, knowledge integration, knowledge interpretation, and knowledge application. They note that each of these dimensions contains complex processes within them. At a program level, McNie (2013) proposed that evaluations consider whether end users’ understanding of climate science has improved, whether policies and decisions can be linked to the collaborative knowledge production effort, changes in resource allocation, and the number and breadth of stakeholder networks created by the project.

3. Methods

In this section, we describe our methods for developing an evaluative framework for the coproduction of usable climate science. Through a process of program theory-driven evaluation (Donaldson and Lipsey 2006), we synthesized the following to create the framework: 1) literature on the theory and practice of coproduction of knowledge, 2) the metrics currently used to evaluate usable science in several federal agencies and nongovernmental organizations, and 3) insights from the lived experiences of those engaged in this work. We combined insights from these sources to create a set of indicators of successful coproduction of knowledge, then used two case studies to both test the indicator framework and glean lessons about the practice of coproducing climate science.

a. *Literature search and review*

We focused our literature search (see literature review) on research concentrating on evaluation or assessment of collaborative research, coproduction of knowledge, or societal impacts of science—using a process analogous to snowball sampling (Given 2008) by using the search tool ''Web of Knowledge'' to identify journal articles and books cited by or within several key works in the field (e.g., Lemos and Morehouse 2005; Dilling and Lemos 2011; Bellamy et al. 2001; Reed 2008; Fazey et al. 2014; Walter et al. 2007; Cvitanovic et al. 2015; Feldman and Ingram 2009; McNie 2007) that helped us trace the similarities and differences in proposed metrics and indicators as ideas evolved through the literature. We also used keyword searches on several terms (i.e., evaluation, assessing science, participatory methods, coproduction, collaborative research, usability of science, observation theory, program theory, and utilization theory). In addition, we examined existing performance metrics for programs and organizations that conduct collaborative, decision-focused research. These sources included federal programs such as the National Research Council's (2007) evaluation of the U.S. Climate Change Science Program; the U.S. Department of the Interior (DOI) and the U.S. Geological Survey's strategic plans and budget justifications (U.S. Geological Survey 2014; U.S. Department of the Interior 2014); the annual reporting tool developed by the NOAA Regional Integrated Sciences and Assessments (RISA) program; recommendations developed by the Advisory Committee on Climate Change and Natural Resource Science (ACCCNRS 2015) to evaluate the DOI Climate Science Centers (CSCs); an evaluation of stakeholder involvement in the U.S. National Climate Assessment (Moser 2005); evaluations of other programs focused on coproduction of climate science, including Jorgensen et al. (2014) and Ferguson et al. (2016); and performance metrics used by nongovernmental organizations such as the Bill and Melinda Gates Foundation (2016) and the International Development Research Centre (IDRC; Earl et al. 2001) that specifically consider the process of collaboration within their evaluations.

b. *Interviews with climate researchers, program managers, and climate program leaders*

Through 19 in-depth interviews, we drew on the experiences of climate science integrators, program managers whose programs fund stakeholder-engaged climate research, and leadership within two federal programs focused on production of decision-relevant climate research (NOAA's RISA program and the DOI CSCs). Because this work focused on research being conducted within the DOI CSCs, we included leadership within this organization to understand how they conceptualized successful projects and what they considered to be effective steps toward success. We also included leadership within the RISA program because of its long history of experimentation with collaborations between climate scientists and decision-makers (Ferguson et al. 2016; Pulwarty et al. 2009). We interviewed a convenience sample of other experienced climate science integrators (Brugger et al. 2015). We acknowledge this is a limited sample, so we used the interview data only to triangulate data from the literature and performance metrics. The interviews were semistructured and typically lasted approximately 60 min. The focus of the questions for the researchers was how they learned to conduct ''engaged research,'' the incentives and challenges involved in this kind of research, how they self-assessed and monitored their own successes and failures, and their recommendations for indicators of success and evaluative metrics for this kind of work. Our interviews with program managers and leaders more specifically focused on their recommendations for indicators and metrics and how they might use such metrics in their programs. The interviews were recorded then transcribed and coded in Dedoose, an online qualitative coding software.

c. *Coding and indicator development*

We coded all the indicators or metrics from the three sources (literature, existing performance metrics, and those recommended by climate science integrators and program leaders) using the five following categories common to evaluation frameworks (see, e.g., Earl et al. 2001; W. K. Kellogg Foundation 2004): context (including inputs to the project and external factors that influence the project), process, outputs, outcomes, and impacts. We then compared the suggested indicators (from different sources) to identify common themes across sources and any gaps, such as whether indicators suggested by experienced ''integrators'' have been identified in the literature or put into practice in existing performance metrics. We recoded all the compiled metrics by specific themes within each category and then summarized the themes into one coherent ''indicator'' statement.

Context factors relate to the preexisting conditions that may influence researchers' and stakeholders' ability to engage in the coproduction of science and ultimately use the information. We organized these context factors into input and external indicators. Input indicators assess capacity, including the skill set of the research team, team composition, resource allocation (both time and material resources), and stakeholder involvement. External indicators are those conditions that can affect the outcome of a project but are outside of either the research team's or stakeholder's control. These include factors such as employee turnover, scientific uncertainty, or a catalyzing event.

Process indicators are actions and activities such as inclusion of stakeholders in the proposal writing process, collaborative development of research questions and research design, and ongoing communication between researchers and stakeholders throughout the lifespan of the project.

We divided project results into three categories (i.e., outputs, outcomes, and impacts) to capture the nature of information use as a spectrum of activities, not a fixed end point (Taylor 1991; Oh 1996). We defined output indicators as tangible outputs from research, such as workshop reports or peer-reviewed publications. Outcome indicators are less tangible and more conceptual results. These include the perception that project goals have been achieved and end users' perception of the credibility, saliency, and legitimacy of the final outputs and process. Impact indicators generally represent instrumental uses of science information, such as directly informing management decisions, policy actions, or adaptation decisions. The resulting indicators are listed in Table 1.

With support of the DOI's Southwest Climate Science Center (SW CSC) and its affiliated researchers, we tested our indicator framework in two case studies funded by the SW CSC. Our methods for analyzing the case studies were similar to Meagher et al. (2008), who conducted a retrospective analysis of the impacts of social science research on policy and practice. We developed the evaluative framework (described above) and then collected data using multiple methods including semistructured interviews, document analysis (project proposals, interim, and final reports, and project outputs), and experimented with use of observational data collection by developing several tools to gather data, such as detailed record sheets to count and categorize interactions at project-related meetings. We conducted 13 interviews with the principal investigator and coinvestigators in each project as well as key representatives of the stakeholder agencies involved in each project (as identified in the project proposals and by the research team). Interviews were recorded, transcribed, and coded using our indicators. We attended and observed four project-related meetings to gain more perspective on the relationships and collaborative partnerships developing between researchers and decision-makers. Although we took ethnographic field notes at each meeting and piloted several tools to assess equitable participation in the meetings, data from observations are not included in these assessments as the piloted tools were not consistent throughout data collection. We are continuing to refine our observation processes to ensure the validity and reliability of the methods.

In the following section, we report on our experience applying the evaluative framework to the case studies as well as lessons learned about both the practice of coproducing knowledge and the practice of evaluating the coproduction of knowledge. Indicators specifically referenced are in parentheses and refer to Table 1.

4. Results

a. Case study 1

Case study 1 involved academic researchers from several institutions working with a tribal community. The project objectives focused on understanding how the community might be affected by climate change, particularly their water resources, as well as development of a climate change adaptation plan and adaptive strategies. We started evaluating case study 1 during the final half of the project, meaning that some of the evaluation was retrospective, while other elements were concurrent with project activities. During the course of 18 months, we conducted interviews with four researchers and three stakeholders involved with the project. These were recorded, transcribed, and coded using our indicators. We observed an in-person meeting between the researchers and key stakeholders and a community-wide final project meeting (see discussion in section 5 about not including observation data at this time). In addition, we reviewed the original proposal, final reports, and other outputs from the project.

1) CASE STUDY 1: CONTEXT

Using our evaluation indicators, we identified the project inputs and external factors that influenced the project. Based on the project proposal, we mapped the project objectives against the research team expertise and in interviews specifically asked about the expertise on the project and how the research team members interacted with each other (I.3). Overall, the team expertise mapped well to the project objectives (i.e., hydrologists and water quality experts; I.1). The team included researchers with expertise in social science and collaborative research methods (I.9) as well as hydrologists and other physical scientists in the relevant fields. We also attempted to assess how researcher time was allocated to this project based on salaries included in the proposal (I.2). This is an imperfect metric because researchers may have dedicated additional unpaid time to the project, but we applied it as best as possible because of the importance of allocating adequate time to collaborative research (National Research Council 2007; Greenwood and Levin 2007).

We also were interested in tracking relationships, both those that existed previously and relationships formed or strengthened during the project (I.11). In this case study, two researchers had worked with the stakeholders for three years previously, and this project developed from that initial work. During the course of the project, employee turnover at the stakeholder agency led to the loss of those connections (E.1), but there were indications that the foundational relationships helped the new stakeholder representatives engage with the project and gain a sense of trust in the team. The stakeholder representatives supported the project by providing in-kind technical support, consultants in local knowledge, and serving as meeting hosts (I.4).

Decision-makers' motivations for seeking new information often influence later use of that information (Oh 1996). We found a range of motivations among these decision-makers from seeking general knowledge to having specific questions about climate impacts. One stakeholder representative expressed a general interest in learning about climate change and the process of adaptation planning, while another had more specific questions related to a traditional food source that has cultural significance for the community (I.5).

2) CASE STUDY 1: PROCESS

We identified project activities that involved the researchers communicating and collaborating with the stakeholders (e.g., workshops, trainings, meetings, phone calls, and conference presentations). In interviews with the stakeholders, they noted that the researchers had provided information proactively and often (P.2). When asked to rate their desired level of involvement against their perceived actual involvement, however, most wanted to have a greater level of involvement than what they felt they actually had (P.4). They cited lack of time or other resources, personnel turnover, and a perception that they were not invited to participate in the research process as barriers to greater collaboration. Both stakeholders and researchers commented on the limited time available for in-person meetings and lack of resources available to fund travel to the stakeholder community (P.5).

3) CASE STUDY 1: OUTPUTS, OUTCOMES, AND IMPACTS

This project produced a number of peer-reviewed articles (OP.1) and other materials (OP.6). However, the stakeholders reported that the adaptation recommendations produced by the research team were too general to be immediately useful for management action (OC.4). They did report that the recommendations would be useful in spurring additional community discussion and supporting future funding requests (IM.7, OC.4), which could lead to future management decisions. This possible delay in application of the research results is reflected in Oh's (1996) explanation of the process decision-makers often go through from intake of new knowledge to ultimate application of the knowledge only after a period of time in which they become more familiar and comfortable with the new information.

b. *Case study 2*

Case study 2 was a project led by USGS researchers and academic scientists from several institutions along the U.S. West Coast who were focused on understanding climate change effects on shore-based ecosystems. Although the research team was working at several sites, we concentrated on one site, largely because of resource constraints (see section 5 for additional information on site selection). We conducted semistructured interviews with three researchers and four representatives from the management agencies involved in the project. These were recorded, transcribed, and coded using the indicators. We attended and observed one stakeholder workshop held by the research team (see discussion in section 5 about not including observation data at this time). While many of the findings were similar to case study 1, there also were several new findings of interest that helped us refine our indicators and evaluation process.

TABLE 1. Proposed indicators for evaluating coproduced climate science.

Components	Indicators
Inputs	I.1. Necessary scientific disciplines are included on research team (research capacity maps to research question). I.2. Significant research time is devoted to project (% of FTE yr^{-1} allocated to the project) I.3. Research team works collaboratively among themselves. I.4. Target agency indicated commitment through contribution of services, funds, time, and a specific point person. I.5. Target agency representatives on the project can articulate a need for this research (i.e., they have a problem they want to solve through this research project). I.6. Target agency representative perceives a path to use/application of the research findings (i.e., does manager see barriers to implementation?) I.7. Proposal includes a clear plan for communication, engagement, and/or collaboration between research and management team I.8. Total funding for project compared to total amount allocated for engagement/collaboration activities (if discernable). I.9. Research team has training or experience in collaborative research approaches. I.10. Research team's motivations for participating in the project (i.e., their goal is actionable science). I.11. Research team and agency representative have preexisting working relationship.
Process	P.1. Point at which host/target agency enters or participated in the project: vision, problem definition, research question articulation, research design, data collection, data analysis, knowledge/meaning making, testing results, dissemination of knowledge, evaluation of project. P.2. Frequency and medium of communication between research and management teams. P.3. Participants perceive they had equitable opportunities to participate in project meetings, workshops, etc. (observe interactions when possible). P.4. Target agency representative is satisfied with the level of engagement. P.5. Researchers are satisfied with the level of engagement. P.6. Challenges within project are resolved in mutually agreeable ways. P.7. Researchers are aware of whether/how information was used or not used by agency.
Outputs	OP.1. Number of peer-reviewed articles. OP.2. Number of technical reports/gray literature. OP.3. Workshops or meetings to disseminate findings. OP.4. Final report is delivered directly to agency representative(s) or made easily accessible via another format. OP.5. Findings are delivered in a timely manner (meet agency's decision calendar or timeline). OP.6. Other outputs (media reports, websites, other products created by the project).
Outcomes	OC.1. Project goals have been achieved (both objective assessment by evaluator and researcher and agency representative perceptions with regard to completion of goals). OC.2. Participants perceive science as credible. OC.3. Findings/outputs meet the standard the agency applies to "usable" information for action. OC.4. Agency participants perceive the science as salient to their needs/problems. OC.5. Participants perceive that the process of producing the science was legitimate (i.e., all participants had opportunities to contribute). OC.6. Mutual interest in longer-term collaboration (i.e., both teams express interest in working together again).
Impacts	IM.1. "Enlightenment" use of information (agency representative perceives self to be better informed about an issue). IM.2. "Problem Understanding" use of information (more specific than Enlightenment, better comprehension of particular problems). IM.3. "Instrumental" use of information (agency representative finds out what to do and how to do something; gained new skills). IM.4. "Factual" use of information (provision of precise data, for example). IM.5. "Confirmational" use of information (previous information was verified). IM.6. "Projective" use of information (agency gained better understanding of possible future scenarios). IM.7. "Motivational" use of information (encouraged someone to keep going (or not) on search for information). IM.8. "Personal or Political" use of information (helped a person gain control of a situation or avoid a bad situation). IM.9. Findings from study are explicitly used in agency planning, resource allocation, or policy decision. IM.10. Findings contribute to successful climate change adaptation action.

TABLE 1. (*Continued*)

Components	Indicators
External factors	E.1. Turnover in agency staff. E.2. In-house (agency) technical capacity to manage new information. E.3. Political will for action/change within agency. E.4. Financial capability for change/action within agency. E.5. Catalyzing event affected perceived need/lack or need for information.

1) CASE STUDY 2: CONTEXT

One strong indicator in this project was the existing relationship between several of the researchers and representatives from stakeholder agencies (I.11). The researchers knew a majority of the research site contacts through previous work, and a lead researcher had particular familiarity with the agency that had jurisdiction over many of the sites, lending her both credibility and a greater level of trust; stakeholders felt " [she] knows our business and she understands [what we do] . . . that's huge." In addition, several of the researchers, although working for different agencies, were located in the same building, allowing for greater collaboration between team members. Several researchers and stakeholders cited this as a key factor in the success of the project.

As in case study 1, stakeholders in this project varied in their desire for specific information versus more general information (I.5). Stakeholders who were located at the specific study site were seeking information relevant to their management of the area, while stakeholders from the broader region—who have responsibility for management at a regional scale—were interested in more general knowledge to use in regional-level planning efforts.

2) CASE STUDY 2: PROCESS

Despite different reasons for seeking new information, the various stakeholders involved in this project expressed a desire for involvement and, in some cases, increased communication between the study site managers and the researchers (P.2). In particular, site managers expressed a desire for more upfront engagement in the project (P.4). Because of the design of the project, this site was included after the scientific research questions and research design had been established (P.1). Local managers expressed concern that site-specific limitations would impact data accuracy (OC.2). This reinforced the importance, in designing research intended to be used by decision-makers, of ensuring that intended end users are engaged in development of the research questions and design (P.1).

3) CASE STUDY 2: OUTPUTS, OUTCOMES, AND IMPACTS

Like case study 1, case study 2 produced a number of peer-reviewed articles (OP.1) and technical reports (OP.2). We found in case study 2 that the project also had outcomes beyond those outlined in the original research proposal, such as contributing to development of what appears to be a nascent "knowledge-to-action network" with resource managers in the region. For example, project researchers we interviewed indicated that they received requests from resource managers at other sites asking to be included in the project. This suggests that the project is reaching beyond the original individual researcher networks and that end users are disseminating information and outcomes within their own networks (an indicator of perceived credibility—OC.2).

One of the indicators we were not able to calculate and compare to case study 1 was the level of funding used specifically for stakeholder engagement (I.8). In this project, much of the travel expense related to data acquisition, and participants reported that these contributed to relationship building. However, a lack of clearly defined categories in the project budget (i.e., nothing specifically tagged as "engagement" or "collaboration") limited our ability to calculate how much of the researchers' time was allocated to engagement activities. While we feel the indicator is relevant, we need to identify how to alter our data collection approach to better capture this information in the future.

5. Discussion

a. *Lessons about evaluating coproduction from employing the objectives and indicators framework*

Through this study, we learned several important lessons about *evaluating* collaboratively produced climate science. Although it was not feasible because of timing differences between this project and the case study projects, we were reminded of the importance of integrating evaluation into the main project as early as possible. One impact of not engaging with the study participants sooner was that we failed to gain the trust of some resource managers, who declined to participate in this evaluation effort, contributing to our inability to include a second site in case study 2. Gaining trust is a key tenet of all social science research (Somekh and Lewin 2004), and we regret that our late introduction into one project meant we were unable to do so. We must note, however, the overwhelmingly positive reception we received from other study participants. They welcomed our questions and were pleased to discuss their experiences and perceptions of the process of producing actionable science because they saw it as an effort to strengthen coproduced climate science research in the future.

As Fazey et al. (2014) note, we needed to broaden our evaluation of outcomes, particularly in terms of looking for unexpected outcomes. For example, most current evaluations of project impacts focus on stakeholders, but as several climate science integrator interviewees noted, we also need to examine how this process impacts researchers. These interviewees were more likely to note the importance of tracking the impacts of participating in a coproduction process on their *own, future scientific processes*, a finding similar to Hegger and Dieperink (2015). One interviewee explained that working with a decision-maker, who may not be familiar with the science, "forces you to think out loud. There are a lot of unstated assumptions even in good research and the coproduction process makes you say things aloud."

Another unexpected outcome was the nascent development of networks through connections made by case study 2. Development of such networks has the potential to create changes in the model of how stakeholder-driven research is conducted. Instead of a traditional loading dock model where research is disseminated largely through peer-reviewed journals, the research is made more credible and salient by peer-to-peer recommendation within and across agency and sector-based networks in an information-sharing network. While this might seem difficult to evaluate, our experience in case study 2 suggests that it is achievable, dependent on the duration of the project and timing of the evaluation process.

Additionally, there are indications that the categorizations of *stakeholder* or decision-maker are too coarse to effectively encompass the differences in stakeholder capabilities and the roles they can assume in a coproduction process. Through interviews and observation, we noted that stakeholders and decision-makers bring a range of knowledge, interests, and capabilities to a collaborative process that influence how, when, and what kinds of information they ultimately use. In case study 2, we noted significant differences in motivations for participating (i.e., what the stakeholder expected to get from the process) between the regional-scale managers and site managers, even when they represented the same agency. Stakeholders also vary in terms of their technical background and capacity. Their abilities and interest in contributing to various research tasks (such as problem definition, research design, analysis, and dissemination) vary depending on their existing capacity and that of their organization. Finally, stakeholders vary in terms of their roles in the decision-making agency or community; for example, whether the individual acts as a node in a social network or as a knowledge broker in a community of practice will influence the extent to which information is shared across a wider network of people. Understanding the role of stakeholders in coproduction processes and assessing the outcomes and outputs of coproduced research will require indicators that capture the complexity inherent in stakeholders and information end users and the interplay between user types and collaborative processes.

b. *Findings concerning coproduction of knowledge*

A clear finding from our two cases was that stakeholders became frustrated with the research process and outcomes/impacts when they were not included in development of research questions and research design. While this is not a novel finding (Lemos and Morehouse 2005), both case studies pointed to factors that contributed to this frustration. In case study 1, the current stakeholder representatives were brought into the project later in the process because of staff turnover, so they were not involved in the original conceptualization of the project. Although supportive of the project, even at the end they felt unsure of the original intent or what they should have expected in terms of results. This situation points to the importance of the stakeholder agency making a firm commitment to sustained and regular participation in coproduction processes. In the second case study, the specific site managers were not involved in initial project development because they were added to a preexisting project, largely because of the constraints of the funding mechanism, in which the research design had been set, although the research team attempted to integrate site-specific questions when possible. In this case, the site managers perceived that the research design did not accommodate site-specific constraints. There was a fine balance between collecting comparable data from multiple sites and providing specific, usable information about any one individual site that was not fully achieved in this particular case.

6. Next steps

To further explore implications of heterogeneity among stakeholders, even those within the same agency, future research efforts could focus more attention on how and under what conditions information is used within organizations. This exploration of organizations' information use environments (Choo 2006) will help identification of whether agency practices can help or hinder adoption of new climate information, with or without a ''successful'' coproduction process.

Additionally, future research efforts should continue to test and refine use of observational data by experimenting with tools and methods in this evaluation process. An extension of this research could also include looking into exploring the role that researcher attitudes toward collaborative research approaches play in whether a coproduction process is successful and whether it results in instrumental information use within the agencies of interest.

7. Conclusions

We began this research by identifying the key principles in coproducing knowledge from the existing literature: building ongoing relationships between scientists and stakeholders, ensuring two-way communication between groups, and maintaining a focus on production of usable science. We examined how usable climate research is currently evaluated by federal agencies. Through interviews with experienced climate science integrators, we explored which activities, actions, and conditions they believe most influence the process and outcomes of knowledge coproduction. We combined information from all three sources to develop an evaluative framework that consists of 45 indicators grouped into context; process; and output, outcome, and impact indicators. We tested the indicators using two case studies, which allowed us to identify several lessons about evaluating coproduction from employing the objectives and indicators framework (including evaluation early in the project, evaluation from the perspective of the researcher as well as the stakeholder, impacts of external factors on projects, and identifying conceptual uses of information and measures) and coproducing climate science knowledge (more nuanced understanding of stakeholder roles and the importance of involving stakeholders early in the research design). We will refine these indicators and heed the call for more empirical research in this field (Bellamy et al. 2001; Cvitanovic et al. 2015; Fazey et al. 2014). We plan to continue to test and refine the indicators and develop metrics through additional case studies representing a diversity of resource management sectors and types of research teams. The end goal is creation of an evaluation-based framework relevant for a diversity of climate science programs, projects, and researchers.

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To co-produce or not to co-produce

Researchers, stakeholders and funding organizations have embraced co-production of knowledge to solve sustainability problems. Research focusing on the practice of co-production can help us understand what works in what contexts and how to avoid potentially undesirable outcomes.

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In the sustainability and climate change arenas, scientists, stakeholders and funders increasingly believe that collaborating to co-produce knowledge will increase its use in policy, decision-making and practice[1]. In the last decade, co-production how-to guides, webpages, handbooks and peer-reviewed articles have proliferated, and many funding solicitations now include requirements for scientist–stakeholder engagement and co-production. For many, this represents much needed change in the culture of science — a small step toward relinquishing the old and powerful myth that any and all science inherently meets society's goals.

In this Comment, we discuss knowledge co-production as a focus of research and as a rapidly spreading practice among scientists, stakeholders and funders seeking to increase the role of science in solving society's most pressing problems. We use the term stakeholder to describe individuals invested in and affected by problems and with whom researchers interact to co-produce knowledge. These include policymakers and decision-makers, public officials, practitioners, community members, resource managers and individuals whose livelihoods are informed by environmental science knowledge. We write as a group of researchers, stakeholders, funders and co-production practitioners operating at the intersection of knowledge production and use — a space that happily is becoming larger and more crowded. We believe in advancing co-production as an important approach to increasing the impact of science, but we also believe that doing so requires recognizing its limitations and grappling with problems that arise as the practice of co-production becomes more broadly taken up and institutionalized.

The science of science use

Over the past twenty years scholarship on co-production has increased rapidly. In particular, scholars of science production and use discuss how to conceptualize and operationalize co-production. To some, co-production means how social orders and power relationships emerge from the interactions among science, society and nature — referred to as the descriptive view[2]. To others, it is the deliberate choice of researchers and stakeholders to co-produce knowledge because the process promotes inclusion of different perspectives and increases knowledge use in decision-making — the normative view[2]. However, the debate about what co-production actually means is less relevant to those scientists, stakeholders and funders seeking to co-produce knowledge to have societal impact. Rather, we argue that the scholarship focusing on both the descriptive and normative views provides insights into, and evidence of, how co-production works in practice. This is important because the emergence of co-production as the 'gold standard' of engaged science has generated its own brand of support and tension. While co-production has become a panacea to overcome barriers of knowledge use, such as lack of credibility, legitimacy and relevance to decision-making, there is considerably less understanding of the opportunity costs of co-production relative to how much knowledge is effectively used and with what impact — positive or negative.

Why co-production

In the process of co-production, stakeholders and researchers often have complementary and overlapping knowledge and skills that are essential for problem-solving. In principle, stakeholders know their decision context, what information they have used in the past and what information might support decisions in the future. Researchers draw on different methods, disciplines and knowledge to produce information to meet stakeholders' needs.

The evidence that co-production increases the likelihood that knowledge will be used in decision-making is compelling[3–6]. A large social experiment in Germany found that fishery managers both retained new information better and were more likely to enact pro-environmental measures when scientists engaged with the managers in two-way information exchange rather than merely lecturing them[4]. In Benin, a carefully designed, inclusive co-production process between researchers and farmers to improve the physiological quality of oil palm seedlings achieved not only that, but also expanded the farmers' social networks[5]. However, as growing numbers of scientists and potential users organize to meet, iterate and spread the word about co-production, fewer have questioned the merits of co-production[7–11] (Box 1). Moreover, the costs of co-producing are potentially high, requiring more time, money, facilitation expertise and personal commitment from participants than more conventional modes of knowledge production[6]. Co-production often takes a long time to come to fruition and many sustainability problems cannot afford the wait[3]. The constant request for participation in co-production may lead to fatigue among stakeholders repeatedly sought out as co-production partners[12]. Similarly, close interaction may be taxing or intimidating for both scientists and stakeholders, who may feel they do not have the training, personal inclination, understanding of each other's contexts or organizational support to participate in co-production.

Reducing costs and assessing impacts

Much of the current focus on co-production rests on a broad-based perception that all co-production will lead to positive outcomes despite some evidence suggesting that this is not always the case. The idea that co-production will help to solve complex problems has generated an entire industry

Box 1 | Promise or peril of co-production

As an iterative process, co-production can lead to unanticipated consequences. For instance, because of the time necessary to build trusting relationships, scientists may choose to interact only with the same groups and focus on the same scope of action, privileging familiarity over the uncertainty of new partners or issues[9]. And as co-production is mainstreamed as a desirable or even a required part of the scientific process, it has increasingly been used as an indicator of performance for scientists as well as stakeholders. For example, some research and funding organizations have begun to evaluate scientists on the number of stakeholders and organizations with whom they interact and by how much funding they have for stakeholder-driven research[14]. Although many see this as a welcome and needed change in the way science is evaluated, some scientists feel that being evaluated on the grounds of the societal impact of their research and on their level of engagement with non-academics can devalue fundamental research and reduce opportunities for those who prefer to focus on basic research[15].

of services in which co-production risks becoming an end in and of itself rather than the means for substantive, more-effective engagement and knowledge use in decision-making.

Some research has shown that there are different ways to decrease the various costs of co-production for participants, such as funding to enable interaction between scientists and stakeholders, and time to sustain those interactions and to build trust and legitimacy. One way to decrease costs is to create boundary organizations, or organizations that broker and bridge the production of scientific knowledge and its use, often through co-production. For example, in the United States, the Great Lakes Integrated Science and Assessments (GLISA, a National Oceanic and Atmospheric Administration-funded boundary organization) has engaged with the Great Lakes Cities Adaptation Network (GLCAN, a network of city officials), to co-produce customized climate vulnerability assessments for each city in the GLCAN network. These assessments can, for example, help cities identify vulnerable communities and develop hazard mitigation and resilience plans in support of adaptation. In this chain, GLISA and GLCAN act as intermediaries between climate scientists and the cities by organizing interaction and customizing climate information to specific uses. In the process, GLISA and GLCAN decrease the costs of co-production for scientists and stakeholders, especially during the long period required to build trust and legitimacy as GLCAN had already developed trust with city officials and GLISA had a network of climate scientists from whom to draw expertise[6].

Assessments of the long-term effectiveness and impact of co-production in terms of knowledge use and societal outcomes have been rare to date. An emerging literature focusing on how to design and evaluate co-production suggests that there are different principles and indicators that can be applied to customize co-production processes[13]. Understanding what does and does not work in different contexts can critically inform different ways to reduce costs and scale up varied approaches to co-production.

Where to go next

Funding organizations, scientists and stakeholders must grapple with the question of how to institutionalize and facilitate the use of co-production as an effective approach while dodging potential pitfalls. We need a stronger understanding of how to foster the kind of knowledge production and use that yields sustainability outcomes, and we can only achieve that through deeper integration of research and practice. To this end, the scholarship of how co-production works can be of use; yet somewhat ironically, the practice and scholarship of co-production are often divorced.

We must support not only the current generation of scientists and stakeholders, but also the next generation, which will perhaps face even greater challenges to practice co-production as it becomes more mainstreamed and is used as an indicator for research funding and for evaluating career performance. Some best practices — such as co-creating the process with all participants, being inclusive and respectful of diverse perspectives and knowledges, paying attention to equity among participants and non-participants and being aware of the different incentives and capacities among stakeholder and scientists — are already widely disseminated. Other practices are less widespread; for example, it is critical to understand how and why co-production works under certain circumstances, and to avoid highly prescriptive approaches that mostly focus on the process rather than on achieving desired sustainability outcomes.

As Box 1 shows, explicitly considering the diversity of interests and views within co-production can be challenging. To avoid pitfalls, we can work to carefully design outcome-oriented evaluations that focus not only on the process, but also on understanding what drives desired impact. One way to help integrate the practice and scholarship of co-production is to improve collection and reporting on the process of co-production itself in the many case studies of environmental knowledge production and use being prepared and disseminated. Tracking what stakeholders are doing on the ground, with what results, would go a long way towards fostering better decisions related to when and how to co-produce and what strategies can be scaled up to increase impact. Carefully assessing whether, and under what conditions, co-production is the best way to achieve those goals is a must; not all co-production leads to inclusion, use, or desirable use and not all knowledge needs to be co-produced.

In this Comment, we do not question co-production as a viable and desirable mechanism to increase the use of scientific knowledge in decision-making. But we appeal to scientists, co-production practitioners, stakeholders and funders of co-production to reflect on the existing scholarship to better understand where and how to invest in and support co-production, so that it leads to sustainability outcomes. In this way, we may avoid co-production becoming an end in itself, glossing over the very values and goals that often inspire scientists and stakeholders to engage with one another. ❐

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