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 breadth 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 both as 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

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

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).

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.

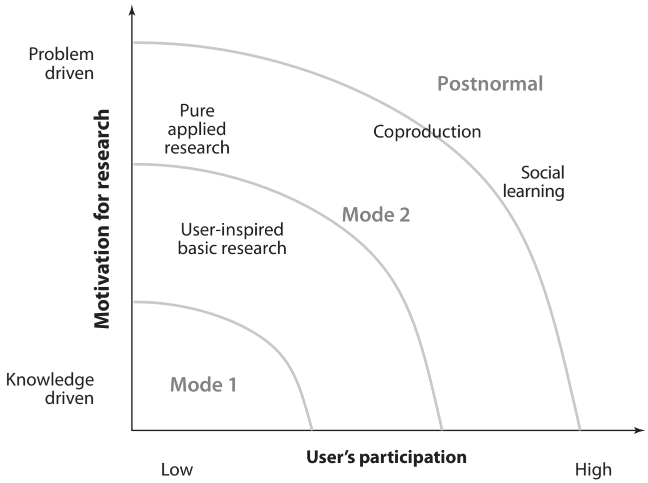

Figure 1

Evolution in the complexity of knowledge production and user participation. On the vertical axis, the complexity of knowledge production increases from low (where production is predominately focused on increasing our fundamental knowledge) to high (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 United States 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 may be 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 (102, 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 breadth 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 met 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 United Kingdom), 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 UNITED KINGDOM

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).

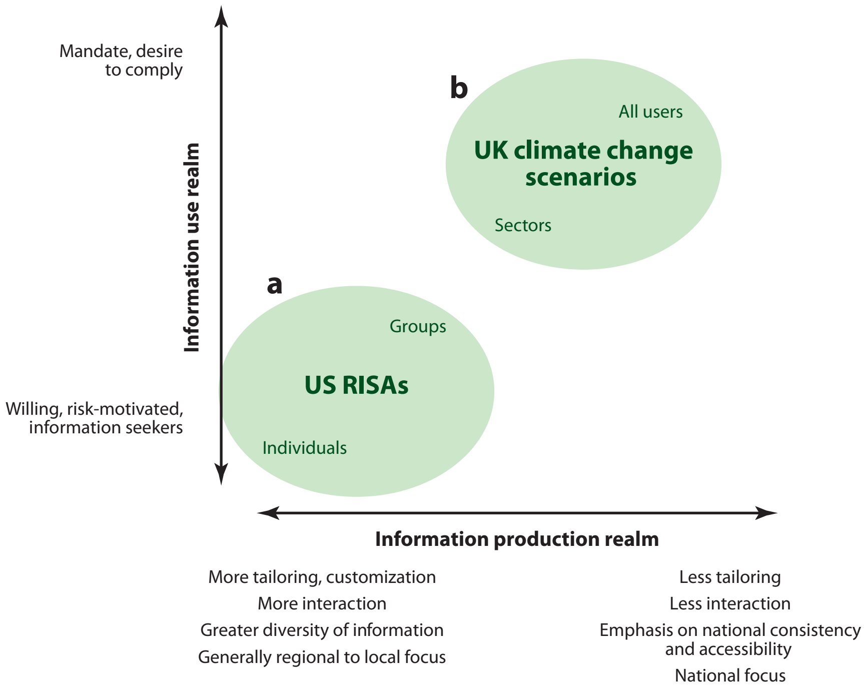

Figure 2

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 is 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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Annual Review of Environment and Resources

Volume 38, 2013

Contents

III. Management, Guidance, and Governance of Resources and Environment

IV. Integrative Themes

Indexes

Errata

An online log of corrections to *Annual Review of Environment and Resources* articles may be found at http://environ.annualreviews.org