Knowledge systems for sustainable development

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The challenge of meeting human development needs while protecting the earth's life support systems confronts scientists, technologists, policy makers, and communities from local to global levels. Many believe that science and technology (S&T) must play a more central role in sustainable development, yet little systematic scholarship exists on how to create institutions that effectively harness S&T for sustainability. This study suggests that efforts to mobilize S&T for sustainability are more likely to be effective when they manage boundaries between knowledge and action in ways that simultaneously enhance the salience, credibility, and legitimacy of the information they produce. Effective systems apply a variety of institutional mechanisms that facilitate communication, translation and mediation across boundaries.

A capacity for mobilizing and using science and technology (S&T) is increasingly recognized as an essential component of strategies for promoting sustainable development (1–3). Efforts to enhance such capacity over the past quarter century range from developing more efficient cook stoves for burning biomass, to nurturing an international system for agricultural research, to applying S&T to the challenges of stratospheric ozone depletion. In this pursuit, there have been few successes and many failures. Such a mixed experience contains lessons in how to improve the effectiveness of linking knowledge to action. Generally lacking, however, has been the systematic scholarship needed to extract those lessons for general use. As a result, society lacks a critical understanding regarding which kinds of programs, institutional arrangements, and, more generally, "knowledge systems" can most effectively harness S&T for sustainability.

Earlier work on the determinants of effective scientific advice in the environmental arena has established three points of departure for the work reported here. The first is based on historical analyses of environmental issues that trace their emergence from initial scientific discoveries to high-level policy agendas. This work suggests that the "effectiveness" of scientific inputs needs to be gauged in terms of impacts on how issues are defined and framed, and on which options for dealing with issues are considered, rather than only in terms of what actions are taken to address environmental problems. The same work shows that perspectives of a decade or more may be necessary to reliably evaluate the impact of science, technology and ideas on issue evolution (4–6).

Our second point of departure is based on evaluations of scientific advice in general, and environmental assessments in particular. It suggests that scientific information is likely to be effective in influencing the evolution of social responses to public issues to the extent that the information is perceived by relevant stakeholders to be not only *credible*, but also *salient* and *legitimate*. In the sense used here, *credibility* involves the scientific adequacy of the technical evidence and arguments. *Salience* deals with the relevance of the assessment to the needs of decision makers. *Legitimacy* reflects the perception that the production of information and technology has been respectful of stakeholders' divergent values and beliefs, unbiased in its conduct, and fair in its treatment of opposing views and interests. Our work shows these attributes are tightly coupled, such that efforts to enhance any one normally incur a cost to the others (7–9).

Finally, a wide range of studies have identified the importance to effective science advising of "boundary work" carried out at the interface between communities of experts and communities of decision makers. This work highlights the prevalence of different norms and expectations in the two communities regarding such crucial concepts as what constitutes reliable evidence, convincing argument, procedural fairness, and appropriate characterization of uncertainty. It points out the difficulty in effective communication between the communities that results from these differences, and stresses the importance for effective advising of explicit development of boundary-spanning institutions or procedures (10–12).

The work reported here integrates, applies, and extends these insights to the study of systems for harnessing science, technology, and, more generally, programs linking knowledge to action for sustainable development. In particular, we explore the extent to which variance in the effectiveness of such systems can be explained by the ways in which their provisions for boundary work at the interface of science and policy balance the tradeoffs among the credibility, salience, and legitimacy of the information they produce. Section 2 describes our case studies. Section 3 reports our initial findings on the functions performed by relatively effective systems for harnessing S&T to sustainability. Section 4 reports tentative conclusions regarding how performance of those functions is facilitated by explicit efforts to organize and manage the "boundaries" separating the knowledge and action communities. We close in Section 5 by discussing these results and their implications for both research and practice.

Case Studies in Knowledge Systems for Sustainability

The broad research program, of which the study represented here is a part, has relied on a wide range of cases for analysis. For research on the vulnerability of coupled human–environment systems, Turner *et al.* (13) report on in-depth analyses of the Yucatan peninsula in Mexico, the Yaqui Valley in Mexico, and the Arctic region. Members of the research team have also mined more than 30 cases derived from consultations in a series of eight international workshops in 2001–2002 sponsored by the Initiative on Science and Technology for Sustainability, the Third World Academy of Sciences, and the International Council for Science. Although relying on this diversity of cases as supporting evidence, this paper draws most heavily on several additional in-depth case studies conducted primarily by the authors of research, observation, assessment, and decision support systems

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Abbreviations: S&T, science and technology; R&D, research and development; CGIAR, Consultative Group on International Agricultural Research; ENSO, El Niño/Southern Oscillation; CIMMYT, Centro Internacional de Mejoramiento de Maiz y Trigo; PEAC, Pacific ENSO Applications Center.

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that address a range of sustainability issues. These studies include agricultural research and development (R&D) within the Consultative Group on International Agricultural Research (CGIAR) system; water management in the U.S. Great Plains; El Niño/Southern Oscillation (ENSO) forecasting in the Pacific region and southern Africa; transboundary air pollution in Europe; and fisheries management in the North Atlantic. These cases were chosen because they vary in both the institutional structures that link knowledge to action and in the effectiveness of such linkages. Together, the cases clarify the association of alternative organizational structures with instrumental success. The case studies use evidence from semistructured interviews, official and internal reports, gray literature, and formal surveys. We summarize these cases below, followed by a discussion of insights derived from them.

Enhancing Agricultural Productivity. The postwar international agricultural research system was developed to apply S&T to enhance agricultural productivity, with several related efforts coordinated under CGIAR sponsored by the Ford and Rockefeller Foundations since the early 1970s. These efforts are widely seen as responsible for the "green revolution," including major advances in crop production, increasing dependence of developing country farmers on multinational seed and fertilizer corporations, and concerns about lack of attention to the strengths of local agro–ecosystems (14, 33). Our research focused not on the international system as a whole, but on an emerging technology development effort at one of CGIAR's 16 international research centers, the Centro Internacional de Mejoramiento de Maiz y Trigo, the international maize and wheat improvement center (CIMMYT). Agronomists, economists and crop scientists at CIMMYT developed crop breeding and testing systems in the 1990s that involve a mix of farmer practices, indigenous knowledge of crops, and modern breeding methods (15). Such efforts, termed participatory plant breeding, seek to bridge the boundaries that hinder the integration of long-term knowledge accrued by farmers over many generations with the insights and methods developed by modern plant breeders (16). CIMMYT scientists work with farmers to test various models of integration to identify those that can most efficiently and effectively tap into the multiple knowledges of these various players in the development of useful technologies. This case demonstrates how a large system for research, innovation, and application evolves, including attempts to correct past shortcomings in the system (17).

Managing Aquifer Depletion. Producing enormous amounts of wheat, corn, cotton, and livestock, farmers and ranchers in the U.S. Great Plains depend on water drawn from the High Plains Aquifer. In the last 25 years, however, there have been increasing signs of over-pumping and resultant economic and social costs (18), as well as multiple attempts to solve this commons problem (19). The federal government provides resources for assessment through the U.S. Geological Survey and for conservation through the U.S. Department of Agriculture. Each state has different water laws and scientific and assessment institutions designed to analyze the aquifer. Furthermore, numerous jurisdictions at the county or multicounty level have varying degrees of autonomy and responsibility for addressing aquifer depletion. This inter- and intrastate variance produces a range of institutional structures that define the science–decision making system, from dense networks of linked scientific and management organizations to relatively autonomous local decision making with relatively few links to scientific organizations. We have explored how organizational structures support or block the construction of salient, credible, and legitimate information for a range of decision makers (12).

Using El Niño Forecasts. Climatic anomalies of 1982/1983 and 1992/1993 focused attention on the economic and social impacts of ENSO events. Major scientific efforts in the U.S. and elsewhere studied and sought to predict El Niño events. Different regional systems were established to undertake research and assessment of ENSO events and develop and apply tools to aid decision makers (20). Our research compared the Pacific ENSO Applications Center (PEAC) and the southern African ENSO forecasting system, both set up by the National Oceanographic and Atmospheric Administration (NOAA) and designed to link international, regional, national, and subnational organizations. A central challenge facing these systems is to make global climate models usable at local levels, and integrate climate sciences with hydrology, agronomy, and fisheries sciences. Boundaries among scales of organization and among disciplines are critical in this domain. Although both forecasting systems strive to produce timely and useful information to a range of decision makers, the organizational structures vary significantly, allowing identification of those system features that promote effective use of predictive information (21, 22).

Managing Ocean Fisheries. Stock assessment science and the establishment of maximum sustainable yields in fisheries management appear to present a direct link between knowledge and action: estimate a fish stock population and extrapolate the maximum number of fish that can be harvested in a given year without jeopardizing the stock's ability to sustain itself. When coastal states extended their management jurisdictions through 200-mile exclusive economic zones (EEZs) in the late 1970s and early 1980s, there was considerable optimism that a new cadre of fisheries scientists, armed with sophisticated models, could facilitate sustainable fisheries policies within EEZs, if not outside them. Two decades later, most EEZs still experience significant overfishing (23). We have compared variation in how regional management organizations, comprised of member states that fish in the region such as the North Atlantic Fisheries Organization and the North East Atlantic Fisheries Commission, use scientific advice produced by the International Council for the Exploration of the Seas and in how North Atlantic states manage domestic fisheries stock assessment processes. The assessment efforts vary in how embedded they are in management agencies and how regulatory agencies relate to different interest groups. This variance helps explain how characteristics of these regimes influence political, economic, and natural resource outcomes (24).

Negotiating Reductions of Transboundary Air Pollution. The ascendance of acid rain on the political agenda in the 1970s and 1980s challenged European nations to manage a problem characterized by transboundary pollution flows, heterogeneous impacts, multiple interests, and high uncertainty (5). International negotiations produced the Convention on Long-Range Transboundary Air Pollution (LRTAP) in 1979 and, under the auspices of this treaty, several innovative approaches were developed to assess the problem, evaluate options, and support negotiations (17, 25, 26). Ultimately, a system was developed that engaged independent institutions such as the International Institute for Applied Systems Analysis (IIASA) in "boundary spanning" roles between scientists and negotiators. The success of LRTAP in reducing transboundary air pollution is largely due to an assessment and decision support system that has enabled adaptive and flexible use of science in decision making (27).

What Effective Systems Do

The cases explored here suggest that efforts to mobilize S&T for sustainability are more likely to be effective when they manage boundaries between knowledge and action in ways that simultaneously enhance the salience, credibility, and legitimacy of the information they produce. We characterize the three functions that contributed most to such ''boundary management'' as ''communication,'' ''translation,'' and ''mediation.''

Communication. Active, iterative, and inclusive communication between experts and decision makers proves crucial to systems that mobilize knowledge that is seen as salient, credible, and legitimate in the world of action (11).

We found effectiveness suffered when communication was largely one-way, whether this involved experts assuming they knew what questions decision makers would see as salient or decision makers assuming that questions relevant to them were ones experts could credibly answer. The ability to mobilize knowledge for action was also reduced when communication was infrequent or occurred only at the outset of an assessment. In such cases, experts often ended up addressing yesterday's problems (producing nonsalient information) or decision makers ended up with yesterday's knowledge (receiving noncredible information). Finally, effectiveness declined when stakeholders from either the expert or decision making communities saw themselves as excluded from relevant dialogues regarding knowledge mobilization. Excluded parties often questioned the legitimacy of the information that emerged from the ensuing conversations, regardless of the information's salience or credibility.

The ENSO case illustrates these points. PEAC created salient information through close engagement with local managers and decision makers. Regular meetings, workshops, and other communication not only educated water managers, farmers, emergency management officials and the fishing industry about ENSO, but allowed PEAC to learn what information managers need and to adjust questions and answers accordingly. This dialogue produced locally specific forecasts that mobilized expert knowledge about ENSO events in ways that helped local decision makers (e.g., how river flow will change or how rainfall patterns will deviate from the norm on one side versus another side of an island). By promoting communication that bridges the boundary between producers and users of forecasts, PEAC has increased the credibility and legitimacy of the information produced. PEAC's products gained credibility by using data from local resource managers whom local decision makers trust. PEAC's forecasts gained legitimacy by using a process that was transparent, inclusive, and served the interests of the major stakeholders. In contrast, stakeholders who were excluded from the dialogue rejected its information products. This pattern occurred with farmers in southern Africa targeted by ENSO forecasts, modelers from state agencies involved in Texas water management, inshore fishers of the North Atlantic fisheries, and farmers treated merely as implementers of ''scientific'' breeding programs. Failures in these cases can be traced to lack of communication and resultant difficulties in producing salient information or technology. Although information in these cases also lacked legitimacy and credibility, the salience shortfall was the most pronounced.

Translation. Linking knowledge to action requires open channels of communication between experts and decision makers but also requires that participants in the resulting conversation understand each other. Mutual understanding between experts and decision makers is often hindered by jargon, language, experiences, and presumptions about what constitutes persuasive argument. Systems mobilize knowledge for action by translations that facilitate mutual comprehension in the face of such differences.

Our cases illustrate how difficult it can be to not only translate events or phenomena (e.g., what maps of sea-surface temperature say about climate variability), but to bridge the gap between experts' and decision makers' views of what information is credible. Fishers' observations that fish seemed relatively plentiful led them to distrust scientists' models and analyses that suggested stocks were on the verge of collapse. Farmers wanted firm evidence of impending drought, whereas experts could provide only probabilistic forecasts. The problem runs deeper than disagreements about the facts to failures to understand the other side's knowledge claims or criteria of credibility.

CIMMYT illustrates attempts at successful translation. CIMMYT has made new research findings on crop breeding useful to farmers and converted the tacit knowledge of traditional farmers into information useful to crop breeders. CIMMYT's current work seeks to avoid problems evident in more conventional ''scientific'' plant breeding programs of the green revolution. In such programs, scientists sometimes did not engage farmers in their studies for fear of forgoing conventional statistical designs required to make field trials and experiments credible to their peers. Instead, researchers focused on laboratory and greenhouse work later ''transferred'' to the field. This approach maintained credibility with scientists but sometimes lost it with farmers. Although often successfully transferred from the breeding program to the field, crops developed through such processes sometimes did not work in local environments, did not have the qualities desired by farmers (e.g., taste and storage capacity), and did not fit with existing management regimes. ''User'' preferences and place-based knowledge were not effectively translated to scientific plant breeders. The technology (crops) produced was not relevant to the needs of the user. Likewise, farmers, not consulted during R&D, saw both the process and its products as illegitimate. CIMMYT (and, other select parts of CGIAR) are beginning to experiment with new models of participatory research to integrate experimental and tacit knowledge in breeding programs that will be credible to both communities, while maintaining adequate levels of salience and legitimacy to all concerned (15).

Mediation. Translation can facilitate information flow between experts and decision makers when, as is often the case, they are divided primarily by different languages, usages, and histories. But the tradeoffs among salience, credibility, and legitimacy are fundamental. Conflicts among efforts to attain them cannot always, or even often, be resolved merely by improving understanding. Mobilizing S&T for sustainability often requires active mediation of those conflicts (10, 28).

Mediation appears to be most important in facilitating the legitimacy of efforts to mobilize S&T for sustainability while retaining adequate levels of salience and credibility to multiple actors. Mediation worked in our cases by enhancing the legitimacy of the process through increasing transparency, bringing all perspectives to the table, providing rules of conduct, and establishing criteria for decision making.

In our U.S. water study, local district managers and county extension agents helped mediate between farmers and hydrological modelers. Such mediation resulted in a process that was deemed legitimate by most actors – different interests and perspectives had standing in the scientific endeavor. They also made information products salient to users while assuring scientists had control of, and used, peer review to maintain the credibility of their research. Likewise, in our ENSO case, PEAC's mediation between climatologists and managers in structuring forecasts resulted in producing information that was both more salient and more credible, in the context of a highly legitimate process. Managers received timely information about issues that mattered to them (e.g., when a drought might start) presented in a usable form, and researchers built more robust climate models by integrating large-scale with locally collected data. Even though users and researchers had generally shared interests, PEAC's mediation helped reveal which interests were shared while finding ways to address those that were not, in order to enhance legitimacy.

Mediation activities helped to make the boundary between experts and decision makers selectively porous, open to certain purposes (e.g., getting user research needs to researchers) but closed to others (e.g., keeping politics out of the scientific process). When mediation fails it can create a too rigid boundary, as when aquifer assessments by Texas' state science agencies were so effectively segregated from local decision makers that they retained scientific credibility but lacked salience with local decision makers. But failed mediation can also create a too porous boundary, as when Canadian fish stock assessments had their scientific credibility called into question because they were seen as excessively vulnerable to the influence of interested decision makers.

How Effective Systems Are Organized

Our research suggests that the "boundary management" functions summarized above—communication, translation, and mediation—can be performed effectively through various organizational arrangements and procedures. These functions can be institutionalized in "boundary organizations," organizations mandated to act as intermediaries between the arenas of science and policy (11). As originally conceived, boundary organizations have at least three features: (*i*) they involve specialized roles within the organization for managing the boundary; (*ii*) they have clear lines of responsibility and accountability to distinct social arenas on opposite sides of the boundary; and (*iii*) they provide a forum in which information can be coproduced by actors from different sides of the boundary through the use of "boundary objects" (11). Whether formalized in organizations specifically designed to act as intermediaries, or present in organizations with broader roles and responsibilities, three institutional features stand out as characteristic of systems that effectively harness S&T for sustainability.

Treating Boundary Management Seriously. Our central finding is that, all else being equal, those systems that made a serious commitment to managing boundaries between expertise and decision making more effectively linked knowledge to action than those that did not. Such systems invested in communication, translation, and/or mediation and, thereby, more effectively balanced salience, credibility, and legitimacy in the information they produced. Consider the following illustration.

In the ENSO case, the key boundary organization is PEAC, a hub that connected NOAA climate scientists, the National Weather Service, university scientists, managers of water, emergency services, and agriculture and private firms. PEAC effectively coordinated the production of an array of forecasting tools that linked global climate models to local hydrologic, coastal, and agricultural conditions. In contrast, southern Africa had no single counterpart to PEAC. Several different organizations, such as the Drought Monitoring Center, Agritex (an agricultural extension service), and the Southern African Development Community, undertook some boundary work, but the lack of coordination meant many communication, translation, and mediation functions were not addressed, leading to less effective efforts to produce and use ENSO forecasting tools.

Dual Accountability. Although taking systematic boundary work seriously was important, several specific structures and strategies emerged as important to performing that work effectively. One of the most important of these involved the accountability of boundary managers.

Institutionalizing accountability of boundary managers to key actors on both sides of the knowledge/action boundary was crucial to building effective information flows. Such dual accountability arrangements forced boundary managers to address the interests, concerns, and perspectives of actors on both sides of the boundary. For example, the Nebraskan County Agricultural Extension (CAE) offices managed the boundary between water managers and researchers (e.g., hydrologists, agronomists, and geologists) as they engaged in iterated, long-term, joint model building. This produced salient, credible and legitimate models of the aquifer that were widely used in decision making at multiple levels. In this case, county extension agents were dually accountable: they worked under contracts with the local management district that could be cancelled, but also had to answer to the academic departments and universities with which they were affiliated. On the other hand, in states where CAE offices were not subject to dual accountability, the boundary between local decision makers and experts remained relatively impermeable with little trust between parties and little coordination of assessment or action. The absence of an organization accountable to both state experts and local actors resulted in a lack of effective boundary work and less effective responses to aquifer depletion.

Use of Boundary Objects. A third strategy for harnessing S&T for sustainability involved joint production, by experts and decision makers, of models, scenarios, and assessment reports. Such "boundary objects" are collaborative efforts/outputs that "are both adaptable to different viewpoints and robust enough to maintain identity across them" (ref. 29, p. 387). Such collaboration creates a process more likely to produce salient information because it engages end-users early in defining data needs. It can increase credibility by bringing multiple types of expertise to the table, and it can enhance legitimacy by providing multiple stakeholders with more, and more transparent, access to the information production process.

European management of acid rain provides a clear example of the use of such boundary objects to link science and policy. During the early 1980s, countries used their own experts to bolster their negotiating position and, not infrequently, to question the expertise of others. No widely accepted scientific assessment of the problem existed and no political agreement on action could be reached. Over the next decade, however, the International Institute of Applied Systems Analysis (IIASA) worked with relevant experts and policy makers to construct and apply the Regional Air Pollution INformation and Simulation (RAINS) model. The modeling effort linked researchers from various disciplines (producing a more credible model of acid deposition and impacts) with the multinational delegates negotiating emission reduction protocols (producing information more salient to the policy debate). The RAINS model became a boundary object that facilitated discussion among parties with multiple interests regarding differences in perspective, methodology, preferences, values, and desired outcomes. The iterated process of its construction, revision, and application created communication between model producers and model users that assured its information outputs were salient to negotiators, credible to scientists of all nations, and legitimate in not favoring the interests of any particular country.

Discussion

This paper has developed a framework for understanding the effectiveness of systems that link knowledge to action for sustainability. Here we seek to explore the implications of that framework for research and practice. Science, technology, and knowledge certainly can and sometimes do make substantial, indeed essential, contributions to sustainability across a wide range of places and problems (30). Unless that contribution can be dramatically increased, however, it seems unlikely that the transition to sustainability will be either fast or far enough to prevent significant degradation of human life and the earth system (31).

Individual efforts in research, innovation, monitoring, and assessment clearly can contribute to sustainability. But the full utility of such independent contributions depends on developing integrated knowledge systems, a lesson already learned in the agriculture, defense, and health sectors, but generally neglected elsewhere. In general, such systems function as mechanisms systematically to motivate and harness relevant R&D work in support of problem-solving and decision-making activities (14, 32–34). For R&D to address the challenges posed by sustainability, our work confirms the great need to strengthen the ‘‘demand’’ side of the dialogue between experts and decision makers involved in action programs for sustainability (30). Another acute need emphasized by our work is for the creation of bridges across spatial scales, so that the location-specific needs and knowledge central to sustainability can be linked with relevant national and international level R&D (35–37).

How such knowledge systems for sustainability can best be structured remains a question for scholarly research, practical experimentation, and comparative learning. Some of the most common models, e.g., that of the postwar international agricultural research system, may fit only when end users are not in acute economic or political competition with one another and when a strong scientific base exists (32). These conditions hold reasonably well for many problems of sustainable development and for many of the cases we examined. But they may not apply to other areas equally central to sustainability, e.g., the potentially competitive world of energy and biotechnology or the poorly understood problem of conserving ecosystem services. More seriously, the agriculture and health experiences give little guidance on the crucial but illusive question of how the private sector, potentially both a user and a source of relevant knowledge, can be better integrated into knowledge systems for sustainability (38). Such integration of private and public sectors is a special case of the general problem of the provision of public goods, an area of scholarship that provides useful models for addressing the challenges of free-ridership, aligning incentives, and the distribution of authority, but has relatively little to say on how public and private information systems can be better structured (39–41). Finally, a potentially fruitful area of research lies in how to integrate institutional analyses of knowledge systems with emerging frameworks of vulnerability that acknowledge the centrality of coupled human–environment systems, and we are beginning to identify important institutional dimensions of the components of resilience and vulnerability (13).

If we do not yet have a general, well tested model of knowledge systems for sustainability, we have identified several likely characteristics of such systems. For example, the work reported here has extended to knowledge systems for sustainability earlier findings from the narrower realms of science advising and assessment that knowledge is more likely to be influential to the extent that it, and the process that produced it, is perceived to be salient and legitimate as well as credible by relevant stakeholders (8, 42). Achieving adequate levels of all three criteria simultaneously is a central challenge facing knowledge systems for sustainability. In part, the difficulties match those in other domains: tight tradeoffs among the three criteria mean that most efforts to enhance one succeed at the expense of the others, undermining the information's overall influence. Such difficulties are aggravated by the multiple actors involved in knowledge mobilization and utilization for sustainability issues. With each actor likely to enter the debate under different concepts of what makes information salient, credible, and legitimate, effective knowledge systems must promote communication and translation across actors as much as R&D or management *per se*. Moreover, because different actors often want different outcomes from applying S&T to sustainability problems, effective knowledge systems must also serve as venues for negotiation and mediation. These are not tasks conventionally associated with research, leading many scientists, not surprisingly, to see participating in knowledge systems for sustainability as at best uncomfortable and at worst inconsistent with real scholarship. Reciprocally, many managers and decision makers see participating in such systems as at best an expensive time investment with uncertain returns and at worst a risk to their perceived autonomy and independence (43).

These kinds of tensions are revealed and accentuated in the emerging models of sustainability research exemplified in the framework for vulnerability analysis presented in a companion article in this issue (44). With its focus on multiple, interacting perturbations and stressors, attention to coupled human–environment systems, and place-based analysis in the context of large scale change, this framework demands a recasting of the interactions between scholar and practitioner. Such recasting exposes the myriad boundaries between multiple actors and the tensions inherent in constructing useful analyses in contested and complex arenas.

The most effective approaches we found for resolving such tensions within knowledge systems for sustainability are reminiscent of the boundary organizations identified by scholars of science studies: organizations that play an intermediary role between the science and policy arenas (8, 12, 45). The boundary organizations we encountered developed rules, procedures, and norms of accountability that shaped perceptions of salience, credibility, and legitimacy of the information and effectively balanced tradeoffs among them. By providing insights about these intermediate variables (salience, credibility, and legitimacy), this work offers an important link between the boundary organizations literature and the broader institutional literature on how rules, norms, and procedures of information institutions influence actors (6, 46). Our work also emphasizes that such organizations need be neither formal nor unique. It is the performance of boundary management *functions* that matters. We found that many effective knowledge systems are characterized by multiple boundary organizations, or multiple organizations that perform specific functions in managing boundaries of complex systems. Moreover, in many cases single individuals played key ‘‘boundary spanning’’ functions, independent of their particular organizational affiliations. A higher-order obstacle to designing knowledge systems for sustainability is thus to learn how to harness the boundary-spanning potential of multiple individuals and organizations in ways that can most effectively bolster salience, credibility, legitimacy, and the tradeoffs among them.

We close with the observation that building more effective knowledge systems for sustainability takes time and patience. Strategies to promote such systems require a sufficiently long-term perspective that takes account of the generally slow impact of ideas on practice, the need to learn from field experience, and the time scales involved in enhancing human and institutional capital necessary for doing all these things. A decade or more thus seems the minimal period over which efforts to harness S&T for sustainability should be planned, implemented, and evaluated. The ‘‘new contract’’ for science and engineering that is being called for in many sustainability discussions thus needs to be seen as a truly radical contract, not just for individual studies or projects, but for whole professional careers (30, 47, 48).

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