HARVARD Kennedy School
JOHN F. KENNEDY SCHOOL OF GOVERNMENT

Crafting Usable Knowledge for Sustainable Development
Faculty Research Working Paper Series

William C. Clark
Harvard Kennedy School

Lorrae van Kerkhoff
Australian National University

Louis Lebel
Chiang Mai University

Gilberto Gallopin
Independent Scholar

Crafting usable knowledge for sustainable development

by

William C. Clark[a], Lorrae van Kerkhoff[b], Louis Lebel[c], and Gilberto Gallopin[d]

[a]Kennedy School of Government, Harvard University, 79 Kennedy St., Cambridge MA 02138, USA

[b]Fenner School of Environment and Society, ANU College of Medicine, Biology and Environment, The Australian National University, Canberra ACT 2600, Australia

[c]Unit for Social and Environmental Research (USER), Faculty of Social Sciences, Chiang Mai University, 239 Huay Kaew Rd, Chiang Mai, 50200, Thailand

[d]Independent Scholar, Tte. Gral. J.D. Peron, Buenos aires 1040, Argentina

Contents

Abstract

This paper distills core lessons about how researchers (scientists, engineers, planners, etc.) interested in promoting sustainable development can increase the likelihood of producing usable knowledge. We draw the lessons from both practical experience in diverse contexts around the world, and from scholarly advances in understanding the relationships between science and society. Many of these lessons will be familiar to those with experience in crafting knowledge to support action for sustainable development. But few are included in the formal training of researchers. As a result, when scientists and engineers first venture out of the lab or library with the goal of linking their knowledge to action, the outcome has often been ineffectiveness and disillusionment. We therefore articulate here a core set of lessons that we believe should become part of the basic training for researchers interested in crafting usable knowledge for sustainable development. These lessons entail at least four things researchers should *know*, and four things they should *do*. The "knowing" lessons involve understanding the *coproduction* relationships through which knowledge making and decision making shape one another in social-environmental systems. We highlight the lessons that emerge from examining those coproduction relationships through the 'ICAP' lens, viewing them from the perspectives of **I**nnovation systems, **C**omplex systems, **A**daptive systems, and **P**olitical systems. The "doing" lessons involve improving the *capacity* of the research community to put its understanding of such systems into practice. We highlight steps though which researchers can help build capacities for stakeholder collaboration, social learning, knowledge governance, and researcher training.

Keywords:

Sustainable development; knowledge systems; capacity; coproduction; innovation; complex system; adaptive system; political system; governance; collaboration; social learning; training; sustainability science; science-policy interface

Introduction

This paper seeks to promote better mobilization of knowledge for the pursuit of sustainable development. Our starting point is the original vision of sustainability[*] set forth by the World Commission on Environment and Development in 1987, and recently reaffirmed and refined by the UN General Assembly's formal adoption of *The 2030 Agenda for Sustainable Development*. Here we follow recent scholarship (1, 2) in encompassing the multiple UN goals under a broader conceptualization that sees sustainable development as the promotion of inclusive human well-being; this is to say, well-being that is shared equitably within and across generations, and is built on the enlightened and integrated stewardship of the planet's environmental, economic and social assets.

Great improvements have taken place in many people's well-being over recent generations. But contemporary development is not *sustainable* development. It leaves too many of today's people behind (3). And it achieves today's increasingly inequitable gains by degrading many of the essential assets on which the prospects for tomorrow's prosperity depend. Promoting a transition toward more sustainable development paths is an urgent task that will require unprecedented contributions from political leaders, business entrepreneurs, and civil society actors working together across scales. But it will also require mobilizing more and better knowledge of ways to secure and sustain inclusive improvements in human well-being. Much of the needed knowledge already exists, but new discoveries, inventions and practices are also needed.

What are the prospects for successful mobilization of knowledge to promote sustainable development? Much has clearly been accomplished. But too much potentially valuable knowledge produced by committed researchers languishes in libraries, unused by society; and too many of society's greatest needs for new knowledge remain relatively unexplored by researchers. A transition towards sustainability thus requires not just more knowledge, but more *usable* knowledge.

---

[*] We use "sustainability" and "sustainable development" interchangeably throughout this paper.

A great deal has been learned in recent years about the nature and production of usable knowledge (4, 5). This is reflected not only in a growing body of case studies on relationships between science and society, but also in flourishing fields of relevant theory building, replete with the requisite jargon and impenetrable insider debates. We have sought to make both empirical and theoretical contributions to this emerging body of scholarship through our own work, and to apply it in advancing sustainable development on the ground. In pursuing those applications, however, we have found that the very success of science and society studies as a field of fundamental scholarship has tended to make its practical implications increasingly inaccessible to many of the researchers who might use it in their struggles to produce more usable knowledge. Our goal in this paper is therefore not to enrich fundamental understanding of science–society relationships but rather to distill some of what we believe to be the field's most important practical implications for sustainability-related research. In particular, we present here our response to two pragmatic questions: i) What should researchers *know* about the nature of usable knowledge and the barriers and opportunities for producing it? ii) What should they *do* in order to translate what they *know* into action?

What should researchers *know* about usable knowledge?

Researchers interested in sustainable development generally acknowledge that they are seeking to understand the dynamics of coupled "social-environmental systems" (SESs)[†] in which the "social" (human populations, economies, technologies, institutions, etc.) interacts with the "environmental" (climate, ecosystems, biogeochemical cycles, etc.) at multiple scales (6-8). Less widely appreciated is that knowledge making and decision making in such systems are continually reshaping one another in what have been called relationships of "coproduction"(9, 10). Consider, for example, how the growing scientific evidence for transboundary movement of pollutants in the 1980s helped to launch whole new forms of international environmental treaties. At the same time, however, that drive for global rules undermined attention to the

---

[†] We use this term to encompass work describing itself as focused on socio-ecological systems, social-ecological systems and coupled human–environment systems.

local knowledge that was necessary to implement the global rules effectively in particular contexts. Another example is how hydropower researchers' decisions to focus on improving large dams and turbines rather than small-scale, in-stream generators resonated with a preference by governments for centralized planning and decision making rather than the empowerment of local communities. Such coproduction relationships have profound implications for researchers striving to craft usable knowledge for sustainable development. We have found that those implications can be illuminated by viewing coproduction in SES's through the 'ICAP' lens: seeing them as **I**nnovation systems, **C**omplex systems, **A**daptive systems, and **P**olitical systems (Figure 1).

Innovation systems

This first ICAP perspective highlights that researchers' new discoveries, inventions or insights become usable knowledge only through integration within larger innovation systems. A copious literature on such systems addresses the factors shaping how new knowledge is "conceived, developed, codified, and deployed" (11, 12). For our purposes, it implies that to produce usable knowledge for sustainable development, researchers need to: i) listen to the potential users who they hope will act upon their discoveries, adjusting their agendas to reflect those users' needs rather than the enthusiasms of academia or funders; ii) integrate their work on discovery and invention with complementary innovation processes involving adjustment to fit local contexts, field testing, scale-up, and retirement; and iii) realize that new knowledge is more likely to become useable knowledge when it is shaped to "fit" within, and thus draw utility from, the system of existing ideas, technologies, and governing institutions. Sustainable development also needs radical new knowledge that challenges existing ideas, technologies and practices. But such potentially transformative knowledge will still need to find connections into existing innovation systems, and will thus depend on actor coalitions pushing the system to adopt and use it (13, 14).

The importance of seeing the challenge of crafting usable knowledge in terms of whole innovation systems rather than discovery or invention alone is illustrated by the history of the first green revolution in agriculture (henceforth 'GR1', ca. 1966-1985) (15). GR1 was launched

with the goal of inventing and making publically available high yielding crop varieties that could alleviate the risk of hunger in the developing world. Its basic strategy was to do the inventing by mobilizing scientific talent from around the world in newly formed global research centers, and then relying on public and private sector actors at the national level to do the essential work of adaptation to local conditions, field testing and dissemination. By many measures, GR1 was a success. On the other hand, because the initial selection of crops on which to focus was strongly influenced by what crops had already been studied in the developed world (rather than by the needs of farmers in the developing world) many important crops – especially for Africa – were neglected. Even for those crops that were selected, the research emphasis was on developing varieties that would result in higher yields under "favorable conditions" of ample water from rain or irrigationplus access to fertilizers and pesticides. Places that could not meet such conditions failed to benefit from them. Since the mid-2000s, these multiple shortcomings have been the focus for a second "evergreen" revolution, one more focused on the needs of the least well off farmers, more attentive to environmental and health effects of new crop varieties and practices, and more committed to nurturing local capacity for fitting new varieties to specific social-environmental contexts (16). That revolution in innovation systems for food production is ongoing with some clear success. But the ultimate outcome is still in doubt.

Innovation systems analysis has shown that efforts to craft usable knowledge have been constrained by models of researcher-driven, one-directional "technology transfer." Reformers have called for and implemented more collaborative, iterative and interactive models of innovation that acknowledge the importance of coproduction relationships between knowledge and decision-making. The systemic perspective emphasizes that success or failure in crafting usable knowledge is not only shaped by ultimate users and decision makers working more effectively together, but also by a host of other actors needed to perform the multiple tasks of a well-functioning innovation system: funders, entrepreneurs, field evaluators, etc.

Complex systems

Our second ICAP perspective suggests that researchers seeking to produce usable knowledge for sustainable development should know that the SESs they seek to influence are profoundly *complex systems*. The study of such systems has generated a substantial literature

about how collective behaviors of a relevant "whole" (sand dunes, a human body, an SES) emerge not only from the properties of its component parts, but, more importantly, from the interactions among its component parts and between those parts and their surroundings (17). This literature suggests that to produce usable knowledge for sustainable development, researchers should know that: i) you can't just do one thing (i.e. your discoveries, inventions and interventions will have multiple impacts at multiple scales, not just the one you intended); ii) those impacts will almost always be context dependent, rendering quixotic quests for "panaceas" that can be applied universally (18); and iii) many of those impacts may involve abrupt or irreversible changes to the system, limiting the efficacy of traditional trial and error approaches.

A striking example of the challenges posed for efforts to craft usable knowledge by the complex system characteristics of SESs is provided by recent efforts to promote biofuels as a sustainable alternative to fossil fuels (19-21). The basic concept, backed by early experience in Brazil, made biofuels seem to many a perfect case for moving knowledge into action for sustainability: the plants would capture sunlight and carbon dioxide, and turn it into fuels that could be burned with little or no net release of greenhouse gases. However, while net emissions of greenhouse gases from the use of sugar cane biofuels produced in Brazil were indeed, substantially lower than those of the fossil fuels they replaced, emissions of biofuels produced from heavily fertilized corn in the USA turned out to be higher (i.e. no panaceas). Worse, the biggest impact of promoting corn-based biofuels turned out not to be on greenhouse gas emissions at all, but rather on food prices. The shift of crop land from producing food to producing fuel, mainly in the US, combined with droughts and policy errors, resulted in spiking food prices around the world that in turn, exacerbated political unrest (i.e. multiple impacts). The US biofuel blunder turned out to be difficult to reverse because the system of government subsidies put in place to stimulate adoption developed a strong political constituency of its own to keep the program in place (i.e. irreversibility). Comparable examples abound.

Because SESs are complex systems it is important to identify the key variables that determine the potential for sustainability of development: armed with such knowledge, the

researcher has from the beginning a "watch list" of possible impacts across the entire SES that can counter tendencies to focus prematurely on a narrow range of planned or expected outcomes. Current progress in sustainability science provides a theoretical foundation for this work, suggesting that any scoping effort should identify key variables relevant to the specific SES of interest from each of 5 major clusters of capital assets: natural capital, human capital, manufactured capital, social capital, and knowledge capital (22). The scoping effort should also seek to identify potential trends in key boundary conditions (environmental *and* social) that are beyond the control of the SES of interest, but could significantly affect the potential utility of new knowledge there.

Researchers need to realize that exogenous conditions (e.g. climate change, political unrest) may overwhelm local SES dynamics, such that the search for useable knowledge to change those dynamics becomes unrealistic. Finally, researchers should appreciate that even with effective scoping efforts, the non-linear characteristics of SESs guarantee that the knowledge produced by research will have impacts researchers didn't intend. It follows that in the face of the complexity of the systems we seek to understand and manage for sustainability, the ultimate requirement for researchers seeking to produce usable knowledge may simply be humility (23).

Adaptive systems

Our third ICAP perspective suggests that researchers seeking to manage coproduction relationships in SESs should also know that they are intervening in highly *adaptive systems*. The relevant literature often subsumes the "adaptive" character of SESs in more general discussions of their behavior as "complex adaptive systems" (24, 25). But systems can be complex without being adaptive. The key features that make even simple systems adaptive involve the added processes of variation and selection. For our purposes here, the ubiquity of such processes in SESs means that researchers hoping to produce usable knowledge for sustainable development, should know that: i) novelty is always bubbling up in SESs through natural processes and, increasingly, through human choices, discoveries and inventions mediated by governance arrangements and market-based processes; ii) local conditions, both social and environmental,

determine where and which novelty withers away, and where some of it prospers and spreads (though such conditions often reflect the intersection of multiple higher order conditions in a particular place); iii) the SES dynamics that shape the future will therefore seldom be the same as the ones that have shaped the past.

Humanity's encounter with malaria provides a good example of the challenges for crafting usable knowledge that are posed by the adaptive character of coproduction relationships within SESs (26, 27). Malaria is an ancient and deadly disease of humans, caused by parasites that are transmitted via mosquito bites. Throughout history, people have adapted to malaria through evolution of immunity and development of acquired resistance. Such biological adaptations, however, are restricted to people living in places where malaria incidences have historically been high. Newcomers to malarial areas (whether soldiers, traders, tourists or newborns) lack some or all of the biological adaptations, and therefore have historically sickened or died at high rates. Research to protect such biologically vulnerable populations was initially focused on helping a relatively few soldiers and tourists from the rich world, rather than the much more numerously affected children of the poor world. Still, it eventually produced usable knowledge on how to keep mosquitoes and people apart (e.g. with bed nets), and how to kill some of the parasites (with medicines) and mosquitoes (with insecticides). While successful, however, these new discoveries stimulated new adaptations by both pests (that evolved resistance to the poisons and medicines as well as new feeding habits to mitigate the efficacy of nets), and people (who have appropriated bed nets for a remarkable range of alternative uses). The result is that what was once usable knowledge no longer does the job, necessitating new efforts to craft knowledge that will be usable (however transiently) for the perpetually changing challenge of malaria control in particular locations around the world. Such continually adapting systems are more the norm than the exception in the SESs we seek to manage in pursuit of sustainable development.

Because SESs are adaptive systems, researchers seeking to craft usable knowledge for sustainability need to see their tasks less in terms of optimality and control, and more in terms of flexibility and adaptive management. In other words, researchers should take a significant role in helping society to see its SES interventions reflexively, emphasizing the tentativeness

and transience of any new understanding of how the system works. Actions taken in hopes of guiding the system towards sustainability therefore need to be treated as experiments (28). Practically speaking, this means devoting more attention to the design of relevant indicators and monitoring systems, and ways to make use of such knowledge. At a structural level, it means protecting novelty (conservation) and fostering it (innovation). It also means designing SESs that are "safe-to-fail" (as opposed to futilely striving for "fail-safe"), thus allowing them to survive long enough to learn from the blunders and surprises that the future will inevitably entail.

Political systems

Our final ICAP perspective suggests that researchers seeking to manage coproduction relationships in SESs should take to heart the old adage that "knowledge is power." The creation and deployment of knowledge is therefore likely to be contested by stakeholders in the *political systems* that are a central component of SESs as various groups engage in their perennial struggle for "who gets what." The relationships between knowledge and power are central to the growing literature on coproduction (29, 30). For our purposes, that literature implies that to produce usable knowledge for sustainable development, researchers should know that: i) they are likely to be perceived as "taking sides" through the knowledge they produce no matter what they do, especially when their research grapples with the full complexity of SESs; ii) the incentives they face in their choice of which questions to pursue are likely to disproportionately reflect the priorities of some interested parties and not others; and iii) how they treat the knowledge of local stakeholders will either empower those stakeholders by validating their knowledge, or disempower them by conveying that such knowledge is of little value.

Decades of largely ineffective political negotiation over crafting global climate change agreements show both the contested nature of the science, as well as the interactions between science and politics. Taking the scientific understanding of climate change as a global earth system process into the political realm as a call for a global agreement, has had profound ramifications for the complexity and challenges of taking steps to reduce carbon emissions (31).

Commentators have pointed out that having global impacts does not necessarily equate to demanding global accords, especially when most of the world's emissions are produced by a small number of countries. Sub-global agencies were long disempowered as agents of for mitigating climate change, because the political discourse dictated that local action should not be supported until there was a global accord. Furthermore, political contestations over responsibilities and actions brought the science into the political domain, with widely publicized challenges to the authority of the Intergovernmental Panel on Climate Change (IPCC). The small but vocal band of critics hasn't hesitated to accuse scientists who have built successful academic careers in climate research of pushing the climate agenda to further their own status and careers. Due to the inescapable political dimensions of the system in which researchers operate, debates over the 'truth' or otherwise of these claims, or indeed of the science itself, have been irrelevant to the main political claim of those few resisting action — that science should not hold any special position in political systems.

Researchers seeking to craft usable knowledge need to accept the political character of their work, and be aware that it may impinge on power structures conditioning the opportunities of various actors. This means thinking through whose interests and agendas are likely to be supported, and whose threatened, by the problems we choose to address or ignore. This may mean forsaking research that academic colleagues would judge to be at the cutting edge of the field, in favor of more practical work. It also means paying attention to the broader context, for example, where research projects generate positive outcomes (for instance, gender equity or minority empowerment) at a local level that are resented or counteracted by those further up the political hierarchy who are threatened by those outcomes. Above all, researchers need to recognize that they must earn the trust of potential users who they are inviting to risk their futures on the new ideas, interventions and devices that we push their way. Such trust does, of course, require that our work be perceived as *credible* by users – that they see our new discoveries and insights as likely to be true, and our new technologies likely to perform as claimed. But new knowledge must also be seen by users as *salient* (relevant) to their needs, rather than simply stuff that we ourselves are enthusiastic about. Finally, it must be seen to be *legitimate* – to have been created in ways that have potential for empowering users to shape

their own futures (32, 33). How new knowledge can be crafted so that it will be perceived by users to meet these salience-credibility-legitimacy criteria, and thus be trusted enough to be used, is addressed in the next section of this paper.

What should researchers *do* about usable knowledge?

Understanding what makes knowledge usable for sustainable development is of limited value, unless we also have the *capacity* to transform such understanding into practice. "Capacity," as we use the term here, includes the capability to act and the competence to do so effectively (34). We argue that to support the crafting of usable knowledge for sustainable development, researchers can and should help build capacities for stakeholder collaboration, social learning, knowledge governance, and researcher training (Figure 1).

Stakeholder Collaboration

Efforts to craft usable knowledge must build a capacity for collaboration with a wide and inclusive range of stakeholders in sustainable development. There are at least two reasons for this.

First, collaboration is needed because researchers can't craft usable knowledge on their own. Because our efforts involve dealing with *complex systems*, we need to collaborate with other experts – researchers and practitioners – who understand parts of the SES that we do not. Because our efforts to craft usable knowledge locate us in *political systems*, we need to collaborate with the intended users to craft a shared understanding of what sorts of knowledge, produced how, will be salient, credible and legitimate for them. Because our discoveries, insights and inventions are only part of the larger *innovation system* through which usable knowledge is created, we need to collaborate with evaluators and entrepreneurs who can help to grow our research findings into action at larger scales. Finally, because we know these are also *adaptive systems*, we need to collaborate with people committed to long term monitoring and management who can help us design, assemble and utilize feedback on how the SES responds to interventions.

12

A second reason to build capacity for collaboration is that researchers *shouldn't* craft usable knowledge on their own. Understanding research as a social and political process, not just a process of discovery, highlights the moral and ethical dimensions of working with the people whose lives are affected by sustainability decisions. Building and utilizing a capacity for collaboration is therefore both an important means for advancing inclusive development, and an antidote to the elitism that expert-led development so often – and so inappropriately – entails. Researchers need to be aware, however, that the inclusion created through collaboration is never complete. Understanding the implications of knowledge for those who are 'in' and those who are 'out,' always remains an important aspect of collaborative research design.

How can researchers help build the capacity for collaboration that is needed to support the crafting of usable knowledge? First, is to recognize that stakeholders are diverse, and thus meeting the needs of particular groups requires tailored, often distinct, approaches to communication, engagement and building competencies within each group (35). Second, the opportunities and barriers to collaboration among stakeholders are context specific, emphasizing the importance of also tailoring strategies to particular situationsincluding histories of conflict or cooperation (36).   Third, and ubiquitous, are challenges of competing "cultures" (sets of assumptions, norms, incentives and expectations) that can divide potential collaborators (37).

Bridging such cultural divides often benefits from "boundary work" (38, 39). Boundary work is essentially what its name implies: engagement at the interface among potential collaborators to address practical, political, and cultural mismatches in their notions of usable knowledge. It can be as simple as promoting communication among potential collaborators who have no history of talking with one another., Or more complex, involving translation of mutually incomprehensible concepts or even mediation of substantive differences (32). Boundary work can be carried out informally by committed and respected individuals, or formally by dedicated organizations (e.g. an agricultural extension service). The common feature of effective boundary workers is that, they gain the trust of potential collaborators by working to promote the crafting of shared knowledge that is usable by all. The capacity for

effective boundary work in a particular context can be difficult to build and hard to maintain. Since boundary workers are often looked upon by the stakeholders they seek to bring together as neither classic researchers nor active users, their work is often undervalued. Researchers can contribute to capacity building for stakeholder collaboration by understanding the need for, and role of, boundary workers, publically valuing their contributions, and helping to protect them when their independence is threatened.

Social Learning

Researchers seeking to craft usable knowledge for sustainable development also need to build capacity for continuous, contextualized social learning. There are many definitions of social learning (40) (41). Here we focus on learning that takes place beyond the level of the individual, across teams, organizations and institutions. In such *social* learning , lessons, innovation and change at higher levels of organization can be greater than the sum of individualexperiences. This may often require substantial adjustments in present research capacities, oriented as they are to the goals of knowing rather than learning (42).

The need for building learning capacities follows directly from the characteristics of SESs discussed earlier. Because such systems are complex, they will surprise us. Because they are adaptive, the rules that govern their behavior are constantly changing in unpredictable ways. Because they are heterogeneous, those changes in rules will take different forms in different places. The prospects for accurately predicting the long term consequences of new ideas, policies or technologies, are therefore limited (43, 44). We have no realistic choice but to treat the introduction of new knowledge as experiments that present us with opportunities to learn. In the previous section we argued that researchers need to engage in collaboration with a range of stakeholders; social learning is an important part of what those collaborations should do. Researchers can help build improved capacity for social learning in at least four key ways:

i) Starting with individual researchers, fostering social learning requires an orientation to research that favors learning over knowing. Seemingly simple, this implies a shift from prevailing mental models of research as often individualistic, competitive and based on a search for science-based knowledge creation, to an understanding of research as interactive,

cooperative and based on bringing multiple knowledges and expertise together. Social learning aims to create multi-dimensional, evolving understandings of complex issues.

ii) Next is the organizational challenge to design research arenas as "safe spaces" that reward rather than punish the recognition of error and failure. At their best, independent universities, think tanks, and the press have provided some of the most important safe spaces critical to social learning (45, 46). Researchers need to work to assure that the potential of such organizations to create safe spaces for social learning are realized in practice.

iii) A third key area of capacity building for social learning is methodological, where research designs and methods facilitate the first two points—methods for dialogue and knowledge sharing, alongside research designs that are iterative and allow for adaptation of the research as it progresses (47). Methodological innovations support learning within research projects, but also across the academic community as experience and expertise in co-production builds.

iv) Finally, social learning that builds expertise in co-production should also critically examine contemporary scientific institutions that favor single-issue, log-frame approaches to research while excluding diverse knowledges and iterative process. Extending the social learning community to include research funders and development agencies creates opportunities to reconsider markers of research quality and indicators of success. Building a dialogue with those responsible for evaluating research can start to address the structural constraints that hinder more widespread application of methods that better link research-based knowledge with action.

An emerging opportunity for social learning can be seen in current discussion and debates around the measurement of the UN Sustainable Development Goals, with their renewed emphasis on data and monitoring (48) . The so-called 'data revolution' required by the SDGs is creating exciting new opportunities for rapidly expanding the global data pool, both through facilitating 'formal' monitoring systems via innovations in technologies, and through crowdsourcing. But there is a large difference between designing elaborate monitoring systems and connecting these data to actual decision-making. Research-based processes that foster collaboration, create safe spaces for experimentation, develop iterative methodologies and

engage evaluation communities in academia and the UN system can support linkages between data and its application in decision-making and action.

None of these experiments are likely to produce "panacea" solutions. But many have latent in them valuable lessons that could inform efforts to shape a more effective learning system for the SDGs.

Knowledge Governance

Efforts to craft usable knowledge also need to build a capacity for recognizing and reshaping the rules and norms governing the relationships of coproduction. Knowledge governance is concerned with the formal and informal rules that govern knowledge processes, including production, sharing, access, and use (49). It includes familiar incentives such as promotion criteria, and regulatory devices such as intellectual property law. But it also encompasses less formal rules and norms that govern social expectations and judgments about how public decisions should be made. Building a capacity to understand prevailing systems of knowledge governance, and to reshape them in the interests of sustainability is important for at least three reasons: i) transplanting projects from one site to another; ii) scaling up research outcomes to larger programs or policies; and iii) broader structural issues (50).

First, at a project scale, the assumptions and experiences we gain by learning to operate effectively within our own existing knowledge governance arrangements can create unrealistic and unsubstantiated assumptions about knowledge governance in different cultural or socio-political contexts. For example, the regular academic credentials such as recognized qualifications from respected institutions, peer-reviewed publications records, and project grant history may have little meaning or traction in contexts where knowledge becomes trusted through the personal connections, customary status or local champions. Similarly, expectations such as transparency or objectivity in decision-making (both of which tend to facilitate the application of science) may not be the same in other cultural settings. In other words, understanding knowledge governance can help us to better navigate what salience, credibility, and legitimacy actually mean in different socio-political contexts, as we conduct projects that take us beyond those places we are most familiar with.

Second, analyzing knowledge governance arrangements can help detect where, why and how promising successes in particular projects or places, can 'scale up' to broader social change. When projects work because they have successfully changed the rules, norms or values of those participating, we should remember that the original rules, norms and values typically still hold sway outside the microcosm of the project. Understanding how knowledge processes work at a level beyond the project, can help participants identify strategic ways to collaborate and build trust that will give the project reach outside its immediate team and setting.

Finally, at the broadest scale, recognizing the dynamics of knowledge governance can help researchers identify and advocate for rules that support those discoveries, inventions and insights with a strong public good character that are needed to advance sustainable development. Where prevailing rules favor knowledge production through private rather than public organizations, innovations for sustainability will continue to be disadvantaged and under-produced. For example, in early 2000s, researchers noted that of 1,393 new pharmaceutical entities registered between 1975 and 1999, only 16 were for tropical diseases and tuberculosis that together caused 11% of the global burden of disease, as it was not profitable for pharmaceutical companies to develop such drugs (51, 52). Advocacy from public health researchers and practitioners led to the London Declaration of 2012, where private companies agreed to provide resources requested by affected countries for drugs to tackle these "neglected" diseases. Awareness of the structural barriers that prevented the creation of new knowledge (profits) and the application of existing knowledge (lack of political pressure)together reconfigured the whole knowledge-to-action landscape (through new public-private agreements). This example shows solutions can be integrated into the overall knowledge governance system, in ways that address the bigger, more structural knowledge-to-action challenges, rather than 'papering over' weaknesses through a few successful, but isolated projects here and there.

Understanding the ways in which knowledge production and use are governed is our collective responsibility as researchers, and advocating for change where it is most needed offers practical strategies for connecting small-scale innovations to larger-scale structural change.

Researcher Training

Finally, a research community interested in promoting sustainable development should build capacity that extends its traditional training regime. Needed are approaches that incorporate the additional skills and perspectives that will help to produce knowledge that is not only academically rigorous, but also usable. Usable knowledge for sustainable development has long been produced by researchers in the absence of formal training, suggesting that informal and experiential approaches should not be underrated. Indeed, each of the authors of this paper, and many of the successful sustainability researchers we know, learned the craft of creating usable knowledge by muddling through in the field rather than studying books in the classroom. But while learning the craft of producing usable knowledge, like learning any other craft, certainly benefits from on-the-job training and mentoring, they not enough for the sustainability challenges that confront us. Bigger and better formal training programs are also needed, covering (at least) the ideas presented in this paper.

Many training models and modes are possible. We suggest that effective training would usually involve some mix of specially developed curriculum materials, innovative ways of integrating those materials into the existing training regimes of researchers, and internships in established programs that are crafting usable knowledge for sustainable development. Collaboration with other stakeholders to address sustainability issues in the community, for instance, can be successfully integrated with learning experiences of students and academic development (53, 54). Several other relevant experiments in training scientists for crafting usable knowledge for sustainable development have already been launched, and provide a rich trove of experience and approaches to draw on. These range from the pioneering efforts of the *International Center for Diarrhoeal Disease Research in Bangladesh* (now *icddr,b*), to Sayer and Campbell's manual on *The Science of Sustainable Development* for natural resource managers striving to promote sustainable practices in the developing world (55), to the hundreds of academic programs now addressing sustainability issues. Each of the authors of this article has benefited through involvement in one or more such efforts.

An effort to pool and analyze the lessons from these many training experiments might be a rewarding next step for the sustainability science community (54, 56). Developing practical curricula would also benefit from assembling or creating a number of rich case histories, documenting for a variety of contexts, the trials, tribulations, surprises, and lessons of past efforts to craft useable knowledge. Some such histories already exist (42, 57-58), but few have been incorporated in the normal training of young research scientists and engineers.

With regard to effective ways of teaching relevant curriculum materials, important unresolved issues include when and how. One possibility is to introduce ideas on useable knowledge to graduate students as part of their normal training. Another option is to provide short courses later on as young researchers begin their professional research careers and become more directly concerned with problems of moving from knowledge to action. Integrating material into existing courses taken by researchers as part of their current training may be best, but harder to accomplish than creating stand-alone courses. Perhaps even more difficult, building capacity for researcher training ought to include creating opportunities for researchers to spend a period in "user" settings, ideally under the guidance of experienced mentors. More such internships linking active researchers with a wide range of business, civil society and government decision makers around the world, would almost certainly raise our collective capacity to craft usable knowledge for sustainability. Again, a concerted effort to collect and assess the experiences of multiple experiments being conducted around the world in the "when" and "how" of usable knowledge training would be worthwhile.

Conclusion

Researchers studying sustainable development have long appreciated the merits of thinking in terms of *systems* that: integrate the social and environmental dimensions of the problem; address multiple scales of interactions; and acknowledge multiple actors with multiple perspectives.

Less well recognized, but no less important, is that in such social-environmental systems, knowledge making and decision-making are continually reshaping one another in relationships of "coproduction." We have argued that understanding those coproduction

relationships is important for researchers who want not just to produce more knowledge, but also to craft more usable knowledge. In particular, we have argued that such understanding can be obtained by viewing the coproduction of knowledge and decision making in SESs, from the "ICAP" perspectives of how they function as **I**nnovation systems, **C**omplex systems, **A**daptive systems, and **P**olitical systems. Each of these lenses yields insights into the behavior of social-environmental systems, the relationships among the key actors potentially involved in the co-production of knowledge, and the opportunities for researchers to craft more usable knowledge in support of sustainable development.

Turning those insights into actions however, also requires building appropriate capacity to do so – not just in a few demonstration projects, but at appropriate levels throughout the world. Additional capacity is needed in building stakeholder collaboration, for social learning to deal with uncertainty and surprise, for knowledge governance to address formal and norm-based rules, and for training programs to increase the skills and efficacy of those researchers who want to craft usable knowledge for sustainable development.

Who are those researchers? Motivation was not covered in this paper. It is clear that for many researchers, the moral case for sustainable development is enough to bring them to the table. For this group, especially those newly arrived, we have tried to distill some of the lessons from scholarship and experience that will help them be more effective in realizing their goals of crafting usable knowledge. But because today's need for usable knowledge to advance sustainable development so outstrips the supply, more motivation is needed. Providing such motivation will certainly require progress in articulating public interests and corporate responsibilities, and raising private incentives. But we also believe that individual researchers have a responsibility to help make knowledge more useable. This paper suggests some ways how to start. First is to join efforts to pursuing sustainability in real-world messy systems. Second, is to support others currently engaged in such work, in whatever ways are appropriate. Third, is to share lessons learnt as a peer or teacher. Fourth, is to reflect on one's own experiences, and the insights shared by others, and use these – enthusiastically but humbly – as a guide to improving future practices.

Acknowledgements

References:

1. Dasgupta PS (2013) The nature of economic development and the economic development of nature. *Economic & Political Weekly* 48(51):39-51.
2. Polasky S, *et al.* (2015) Inclusive Wealth as a Metric of Sustainable Development. *Annual Review of Environment and Resources* 40(1):445-466.
3. UNDP (2014) *Sustaining human progress: reducing vulnerabilities and building resilience. Human Development Report 2014* (United Nations Development Program, New York).
4. Fazey I, *et al.* (2014) Evaluating knowledge exchange in interdisciplinary and multi-stakeholder research. *Global Environmental Change* 25(0):204-220.
5. Hegger D, Lamers M, Van Zeijl-Rozema A, & Dieperink C (2012) Conceptualising joint knowledge production in regional climate change adaptation projects: success conditions and levers for action. *Environmental Science & Policy* 18(0):52-65.
6. Eakin H & Luers LA (2006) Assessing the vulnerability of social-environmental systems. *Annual Review of Environment and Resources* 31:365-394.
7. Ostrom E (2009) A general framework for analyzing sustainability of social-ecological systems. *Science* 325:419-422.
8. Liu J, *et al.* (2015) Systems integration for global sustainability. *Science* 347(6225).
9. Jasanoff S (2004) *States of knowledge: the co-production of science and the social order* (Routledge).
10. Lemos CM & Morehouse JB (2005) The Co-production of Science and Policy in Integrated Climate Assessments. *Global Environmental Change* 15:57-68.
11. Brooks H (1980) Technology, Evolution, and Purpose. *Daedalus* 109(1):65-81.
12. Fagerberg J, Mowery D, & Nelson R (2005) *The Oxford handbook of innovation* (Oxford University Press, Oxford).
13. Geels FW (2005) Processes and patterns in transitions and system innovations: refining the co-evolutionary multi-level perspective. *Technological Forecasting and Social Change* 72:681-696.
14. Anadon LD, *et al.* (2015) Making Technological Innovation Work for Sustainable Development. *Harvard Kennedy School Faculty Research Working Paper Series* RWP15-079.
15. Pingali PL (2012) Green Revolution: Impacts, limits, and the path ahead. *Proc Natl Acad Sci USA* 109(31):12302-12308.
16. Kesavan PC & Swaminathan MS (2008) Strategies and models for agricultural sustainability in developing Asian countries. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 363(1492):877-891.
17. Norberg J & Cumming GS eds (2008) *Complexity theory for a sustainable future* (Columbia University Press, New York).
18. Ostrom E, Janssen MA, & Anderies JM (2007) Going beyond panaceas. *PNAS* 104(39):15176-15178.
19. Naylor R, *et al.* (2007) The ripple effect: biofuels, food security, and the environment. *Environment* 49(9):31-43.
20. Hertel TW, *et al.* (2010) Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Market-mediated Responses. *BioScience* 60(3):223-231.
21. Heady D & Fan S (2010) *Reflections on the global food crisis: How it happened? How it hurt? And, how we can prevent the next one?* (*International Food Policy Research Institute*, Washington, D.C.).
22. Matson P, Clark W, & Andersson K (2016) *Pursuing sustainability: A guide to the science and practice* (Princeton University Press, Princeton, NJ).
23. Jasanoff S (2003) Technologies of humility: citizen participation in governing science. *Minerva* 41(3):223-244.
24. Levin S, *et al.* (2013) Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environment and Development Economics* 18(02):111-132.

25. Miller JH & Page SE (2007) *Complex Adaptive Systems: An Introduction to Computational Models of Social Life* (Princeton University Press, Princeton, NJ).
26. Webb J (2009) *Humanity's burden : a global history of malaria* (Cambridge University Press, New York).
27. Keusch GT, Kilama WL, Moon S, Szlezák NA, & Michaud CM (2010) The Global Health System: Linking Knowledge with Action—Learning from Malaria. *PLoS Med* 7(1):e1000179.
28. Berkhout F*, et al.* (2010) Sustainability experiments in Asia: niches influencing alternative development pathways? *Environmental Science & Policy* 13(4):261-271.
29. Hilgartner S, Miller C, & Hagendijk R (2015) *Science and democracy: making knowledge and making power in the biosciences and beyond* (Routledge, New York).
30. Jasanoff S (2006) *States of knowledge: the co-production of science and social order* (Routledge, London).
31. Bulkeley H & Newell P (2010) *Governing climate change* (Routledge, Oxon, New York).
32. Cash D*, et al.* (2003) Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America* 100(14):8086-8091.
33. Mitchell RB, Clark WC, Cash DW, & Dickson NM eds (2006) *Global environmental assessments: information, institutions, and influence* (MIT Press, Cambridge).
34. van Kerkhoff LE & Lebel L (2015) Coproductive capacities: rethinking science-governance relations in a diverse world. *Ecology and Society* 20(1):14.
35. Foster-Fishman PG, Berkowitz SL, Lounsbury DW, Jacobson S, & Allen NA (2001) Building Collaborative Capacity in Community Coalitions: A Review and Integrative Framework. *American Journal of Community Psychology* 29(2):241-261.
36. Aas C, Ladkin A, & Fletcher J (2005) Stakeholder collaboration and heritage management. *Annals of Tourism Research* 32(1):28-48.
37. Knight AT*, et al.* (2006) Designing systematic conservation assessments that promote effective implementation: Best practice from South Africa. *Conservation Biology* 20(3):739-750.
38. Reyers B, Nel JL, O'Farrell PJ, Sitas N, & Nel DC (2015) Navigating complexity through knowledge coproduction: Mainstreaming ecosystem services into disaster risk reduction. *Proc Natl Acad Sci USA* 112(24):7362-7368.
39. Clark WC & Tomich T (2009) Global knowledge for local actions: CGIAR Alternatives to Slash and Burn programme as a model knowledge system. . *PNAS* doi:**10.1073/pnas.0900231108**
40. Reed MS*, et al.* (2010) What is social learning? *Ecology and Society* 15(4).
41. Siebenhüner B, Rodela R, & Ecker F (2016) Social learning research in ecological economics: A survey. *Environmental Science & Policy* 55, Part 1:116-126.
42. Social Learning Group (2001) *Learning to manage global environmental risks: a comparative history of social responses to climate change, ozone depletion and acid rain* (MIT Press, Cambridge, USA).
43. Morgan MG & Keith D (2008) Improving the way we think about projecting future energy use and emissions of carbon dioxide. *Climatic Change* 90(3):189-215.
44. Pindyck RS (2013) Climate change policy: What do the models tell us? *Journal of Economic Literature* 51(3):860-872.
45. Reid RS*, et al.* (2009) Evolution of models to support community and policy action with science: Balancing pastoral livelihoods and wildlife conservation in savannas of East Africa. *Proc Natl Acad Sci USA* doi:**10.1073/pnas.0900313106**
46. Kristjanson P*, et al.* (2009) Linking international agricultural research knowledge with action for sustainable development. *PNAS* 106(13):5047-5052.
47. Russell AW, Wickson F, & Carew AL (2008) Transdisciplinarity: Context, contradictions and capacity. *Futures* 40(5):460-472.
48. Selomane O, Reyers B, Biggs R, Tallis H, & Polasky S (2015) Towards integrated social–ecological sustainability indicators: Exploring the contribution and gaps in existing global data. *Ecological Economics* 118:140-146.

49.   van Kerkhoff L (2014) Knowledge Governance for Sustainable Development: A Review. *Challenges in Sustainability* 1(2):82-93.

50.   van Kerkhoff L & Lebel L (2006) Linking knowledge and action for sustainable development. *Annual Review of Environment and Resources* 31:445-477.

51.   The Lancet (2014) Neglected tropical diseases: becoming less neglected. *The Lancet* 383(9925):1269.

52.   Trouiller P*, et al.* (2002) Drug development for neglected diseases: a deficient market and a public-health policy failure. *The Lancet* 359(9324):2188-2194.

53.   Trencher G, Terada T, & Yarime M (2015) Student participation in the co-creation of knowledge and social experiments for advancing sustainability: experiences from the University of Tokyo. *Current Opinion in Environmental Sustainability* 16:56-63.

54.   Yarime M*, et al.* (2012) Establishing sustainability science in higher education institutions: Towards an integration of academic development, institutionalization, and stakeholder collaborations. *Sustainability Science* 7(SUPPL. 1):101-113.

55.   Sayer J & Campbell B (2004) *The science of sustainable development: local livelihoods and the global environment.* (Cambridge University Press, Cambridge).

56.   Wiek A, Withycombe L, & Redman C (2011) Key competencies in sustainability: a reference framework for academic program development. *Sustainability Science* 6(2):203-218.

57.   Lee KN (1992) *Compass and Gyroscope: Integrating Science and Politics for the Environment* (Island Press, Washington DC).

58.   Matson P ed (2012) *Seeds of sustainablility : Lessons from the birthplace of the green revolution* (Island Press, Washington).

Figure

Figure 1. A framework for crafting usable knowledge for sustainable development. The coproduction relations of social-environmental systems are understood through lenses seeing them as Innovation, Complex, Adaptive and Political systems. Capacities to mobilize this understanding for creating usable knowledge are needed in the realms of Collaboration, Social learning, Knowledge Governance, and Training.