Available online at www.sciencedirect.com

SciVerse ScienceDirect

journal homepage: www.elsevier.com/locate/envsci

Opening up knowledge systems for better responses to global environmental change

Sarah Cornell [a,1,*], Frans Berkhout [b], Willemijn Tuinstra [c,d], J. David Tàbara [e], Jill Jäger [f], Ilan Chabay [g], Bert de Wit [c], Richard Langlais [h], David Mills [i], Peter Moll [j], Ilona M. Otto [k], Arthur Petersen [b,c], Christian Pohl [l], Lorrae van Kerkhoff [m]

[a] Stockholm Resilience Centre, Stockholm University, SE-106 91 Stockholm, Sweden
[b] Institute for Environmental Studies (IVM) and Amsterdam Global Change Institute, VU University Amsterdam, 1081 HV Amsterdam, The Netherlands
[c] PBL Netherlands Environmental Assessment Agency, PO Box 30314, 2500 GH, The Hague, The Netherlands
[d] Open University The Netherlands, School of Science, PO Box 2960, 6401 DL Heerlen, The Netherlands
[e] Institut de Ciència i Tecnologia Ambientals, Universitat Autònoma de Barcelona, Campus UAB, 08193 Cerdanyola del Vallès, Spain
[f] Initiative on Science and Technology for Sustainability, Arbeiterstrandbadstrasse 61, A-1210 Vienna, Austria
[g] Helmholtz Alliance ENERGY-Trans on Sustainability and Social Compatibility of Future Energy Infrastructure, Department of Social Science and Technology Assessment, University of Stuttgart, Germany
[h] NORDREGIO, Box 1658, SE-111 86 Stockholm, Sweden
[i] CEFAS, Pakefield Road, Lowestoft, Suffolk NR33 0HT, UK
[j] Science Development/Dr. Peter Moll, Hagenauerstr. 30, 42107 Wuppertal, Germany
[k] Potsdam Institute for Climate Impact Research (PIK), Telegrafenberg A51/0.34, 14412 Potsdam, Germany
[l] Network for Transdisciplinary Research (td-net), Schwarztorstrasse 9, 3007 Bern, Switzerland
[m] Fenner School of Environment and Society, The Australian National University, Canberra ACT 0200, Australia

ARTICLE INFO

Article history:
Received 17 January 2012
Received in revised form
24 September 2012
Accepted 12 November 2012
Published on line 16 January 2013

Keywords:
Sustainability science
Knowledge democracy
Knowledge systems
Mode 2 science

ABSTRACT

Linking knowledge with action for effective societal responses to persistent problems of unsustainability requires transformed, more open knowledge systems. Drawing on a broad range of academic and practitioner experience, we outline a vision for the coordination and organization of knowledge systems that are better suited to the complex challenges of sustainability than the ones currently in place. This transformation includes inter alia: societal agenda setting, collective problem framing, a plurality of perspectives, integrative research processes, new norms for handling dissent and controversy, better treatment of uncertainty and of diversity of values, extended peer review, broader and more transparent metrics for evaluation, effective dialog processes, and stakeholder participation. We set out institutional and individual roadmaps for achieving this vision, calling for well-designed, properly resourced, longitudinal, international learning programs.

* *Corresponding author at*: Stockholm Resilience Centre, Stockholm University, SE-10691 Stockholm, Sweden. Tel.: +46 8 674 70 70; fax: +46 8 674 70 20.
E-mail address: sarah.cornell@stockholmresilience.su.se (S. Cornell).
[1] Formerly at the School of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK.

1462-9011
http://dx.doi.org/10.1016/j.envsci.2012.11.008

1. Introduction: open science for sustainability

The broad goal of sustainable development is to meet the needs of current and future generations. Supporting this goal requires both the production of knowledge and also close attention to the nature of the processes involved in the generation and validation of knowledge claims. Scientific knowledge has played a vital role in framing the global problems of unsustainability, and there is strong consensus that it also plays a critical role in informing societal responses to these problems, driving substantial research investment and scientific effort worldwide. Yet to a large extent, old knowledge systems are still being deployed for these new emerging social and environmental challenges. This means that urgent knowledge needs are not well met, resources risk being dissipated, and vital skills and capacities are either not developed or not adequately supported. Here, we identify how structures and processes at the interfaces between issue identification, the production and the use of knowledge could be changed to promote a more engaged and reflexive role for science in a 'knowledge democracy' (a concept explored in in't Veld, 2010) that is more oriented toward sustainability in the face of accelerating global social-environmental change. This article draws on work carried out in the European Science Foundation/COST Frontiers of Science Forward Look '*Responses to Environmental and Societal Challenges for our Unstable Earth*' (RESCUE; www.esf.org/rescue, 2009–2011). It is based on discussions of the international Working Group charged with reviewing the current state of interactions and addressing improved approaches at the interface between science and policy, communication and outreach.

Meadows et al. (1982) observed that: '*It is better to state your biases than to pretend you don't have any*' (p. xxv). We cannot easily list them all, but we can state that in this Working Group, we had a very diverse set of biases, and we often had to confront our own profound differences in worldview in the course of our discussions. In this article, we try to expose the main areas of debate. In terms of our own initial academic formation, our group had about equal numbers of social scientists and natural scientists, but all of us now work across disciplinary divides, and operate at the interface between science, policy, and wider society. We work with a shared assumption that research is – and should be – expected to have a positive societal impact.

Before we proceed, some initial clarifications are needed. First, we use the word *science* in its broadest sense, to include both the body of knowledge about the world in which we live, and the systematic and accumulative processes of inquiry in pursuit of that knowledge. This meaning encompasses all the academic disciplines of the natural, physical and social sciences. A defining characteristic of this knowledge (and the practices that structure it) is that it traditionally 'belongs' within universities and other specialist knowledge institutions. It is in these particular spaces where procedures are designed to select, generate, document, debate, and ultimately accept or reject what is understood as valid knowledge. In this traditional system, interfaces with other actors in society are oriented toward the post hoc dissemination of this knowledge. There is growing top-down pressure for change in this regard from funders and research policy-makers wanting greater social and economic research impact (e.g., Eynon, 2012), but it has not yet translated into widespread change in practices. Because of this, one of our core focal areas in this article is the institutional aspect of research.

We refer to *knowledge systems* as something broader than science. Knowledge systems are made up of agents, practices and institutions that organize the production, transfer and use of knowledge. Applied to the social goal of sustainability, knowledge systems are '*...a network of actors connected by social relationships, formal or informal, that dynamically combine knowing, doing, and learning to bring about specific actions for sustainable development*' (van Kerkhoff and Szezák, 2010). While science plays a fundamental role in knowledge systems, it is evident that many other actors, institutions and networks also play significant roles (and many researchers of science in society have focused on these actors, e.g., Irwin, 1995; Irwin and Wynne, 1996; Leach et al., 2005). We argue that relationships within knowledge systems shape the flows of knowledge, credibility and power within those systems (cf. Van Kerkhoff and Lebel, 2006; Jasanoff, 2004). We also note that these patterns of relationships are currently undergoing rapid changes. In this fluid context, we need to conceive improved roles for science in contributing to socio-ecologically robust knowledge foundations, decisions and actions toward resolving problems of unsustainability (cf. van Kerkhoff and Szezák, 2010; O'Brien et al., in this issue). Our starting point is that the challenges of achieving sustainability require radical and deliberate changes in knowledge systems (see Jäger et al., in this issue). In particular, the interactions between scientists and other actors in diverse knowledge systems must be intensified, with scientific practices becoming more oriented toward the societal arenas in which sustainability problems are being tackled. We term this the 'opening up' of knowledge systems (cf. Tàbara and Chabay, in this issue).

We see this process of 'opening up' occurring within an emerging global context that may be characterized as a *knowledge democracy*, where governance is being transformed by the mass creation and availability of knowledge. The concept of the knowledge democracy is comparatively new, and presents theoretical, practical and ethical challenges (in't Veld, 2010). The term highlights the relationship between science and the rest of society, which is currently undergoing profound change in the context of phenomena such as the scientization of politics (see Sörlin, this volume) and the politicization of science (e.g., Weingart, 1999; Leach et al., 2005). Using this term reflects our own stance in favor of democratic ideals in the production and use of knowledge: the quality and validity of knowledge systems for sustainability depend on ensuring plurality, transparency and independence; furthermore, sustainability scientists have a responsibility to collaborate openly in knowledge co-production and its translation to action with other social actors within knowledge systems.

In this paper we envision a way forward, which to a large extent consists of research institutions and individual researchers accepting this responsibility. Present-day science is a huge knowledge-generating system. Is it able to tackle such an enormous challenge with the urgency required?

2. The urgent need for knowledge systems change

2.1. *The challenge*

In the face of the complexities and uncertainties discussed by Jäger et al. (this volume), there is a pressing need for people working in purpose-built knowledge institutions – namely, those who make science policy, who fund science, who carry out research, and who organize and implement education systems (see also O'Brien et al., this volume) – to find better ways to bridge the gap between knowledge and action. Fig. 1 illustrates the main features of the 'knowledge arena' where these ways can be developed.

Bridging the knowledge/action gap requires major transformations of the interfacing mechanisms between 'science' and 'policy' and indeed between 'science' and society as a whole (Moll and Zander, 2006). The importance of these interfaces has long been recognized for sustainability, and they are embedded as Principles 9 and 10 in the 1992 Rio Declaration on Environment and Development (www.un.org/documents/ga/conf151/aconf15126-1annex1.htm). But bridging the gap is not an easy task. It requires open cooperation between different science communities and all others with relevant knowledge for contributing to solutions for the complex problems of sustainability. It also requires an awareness and willingness on the part of the science community to accept this responsibility for transformation and engagement, while acknowledging the contested and political nature of responding to global change.

2.2. *The place of academic science in multiple knowledge systems*

To what extent can more open and diverse systems of knowledge production co-exist with the traditional system? We argue that the development of new skills, tools and procedures that support the co-existence of multiple knowledge systems in different countries and societies is both possible and necessary in adapting social learning to meet the pressing challenge of sustainability.

The key challenge is the relationship between knowledge and action. As providers of specialist knowledge that is highly pertinent to the current accelerating trends of global unsustainability, scientists must assume their share of responsibility for the application of this knowledge, together with all the other stakeholders involved, including civil society, industry and the polity. In this process, '*relationships between research-based knowledge and action can be better understood as arenas of shared responsibility, embedded within larger systems of power and knowledge that evolve and change over time*' (Van Kerkhoff and Lebel, 2006). Ravetz (2004) also focuses on the place of research institutions in their wider, democratic context, arguing that because traditional ('normal') processes of scientific knowledge production stand at the '*contested interfaces of science and policy*', they therefore need to be more open to public knowledge and values.

Although academic institutions are consistently important agents in shaping the dynamics of knowledge systems, they are not static organizations. There is already some differentiation among universities regarding the degree to which they foster research with a societal mission. Technical and agricultural universities are widely established examples of institutions specializing in translating knowledge to action. Some other universities present themselves as an alternative to the traditional (research-led) university, emphasizing their societal mission and practices, but they do not see themselves as a fundamentally different science system. In our view, other elements of national science systems might be more conducive to sustainability research and might be of more importance in informing and engaging with a sustainability transition than 'normal' universities. In several countries, research institutes exist that have a hybrid character, positioning themselves as a link between fundamental research and societal actors. Also, the focus on learning for sustainable development that followed Local Agenda 21 has both supported various other forms of knowledge production across wider society, and raised awareness of their existence (e.g., Rip, 2001).

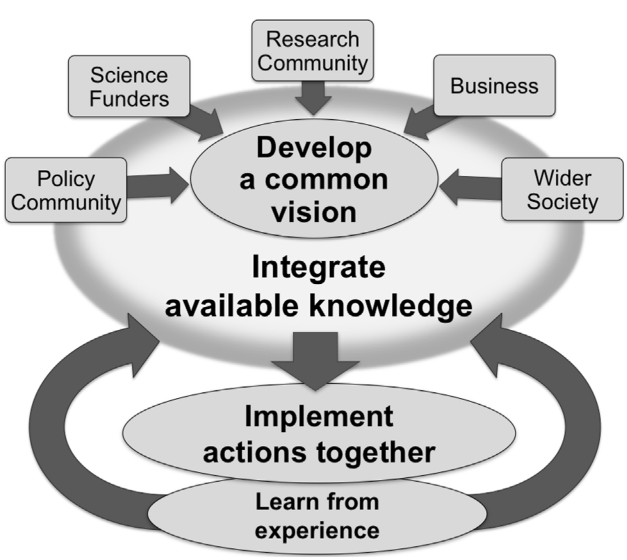

Fig. 1 – The knowledge arena: sustainability science as a collective learning process.

3. The co-production of knowledge

3.1. *Sustainability as social learning*

Although environmental sustainability is sometimes seen in terms of limits, boundaries and thresholds (Rockström et al., 2009), another perspective views sustainability not as a state but as an open-ended process of social learning in which a new balance is continually being sought between multiple social, economic and environmental challenges and goals. Fundamental to a vision of future knowledge and learning is the recognition that change occurs over temporal and spatial scales, involving complex social-ecological interactions and feedbacks. Knowledge is put to use in understanding these changing circumstances and in making the trade-offs inherent in moving toward sustainability. Knowledge production that takes place in the context of its application results in 'socially robust knowledge' (Gibbons et al., 1994; Nowotny et al., 2001). When viewed as a learning process, sustainability research can be conceptualized as the co-production of knowledge arising from the engagement of multiple knowledge producers (Lemos and Morehouse, 2005; Robinson and Tansey, 2006). As the process of co-production becomes of central importance, issues arise at each of its three main stages (Hirsch Hadorn et al., 2008) as depicted in Fig. 1: joint problem framing (e.g., Ehrman and Stinson, 1999; McCreary et al., 2000; Adler, 2002; Karl et al., 2007), knowledge integration (e.g., Pohl et al., 2008; Jahn et al., 2006; Bammer, 2005; van Kerkhoff, 2005), and experimentation (e.g., Groß and Hoffmann-Riem, 2005; van den Daele and Krohn, 1998).

3.2. *Knowledge arenas*

3.2.1. *New opportunities (and challenges)*

Just as industries have been reshaped by use of information technologies, so science and its relationships with society are also being reshaped. The new media have brought about a fundamental change in access to information. Through the Internet, new kinds of repositories of knowledge and information have become available more rapidly to a broader public. These technologies and the new social practices they enable provide new ways of constructing an *agora* as envisaged by Gibbons, Nowotny and other commentators. The new media provide new public and private spaces for the transmission of information, the exchange of knowledge claims and the structuring and 'mediatizing' of public discourses (Hajer, 2009). In so doing, they are causing shifts in the distribution of power in politics and in knowledge-mediating institutions. Traditional knowledge holders and vested interests are now inevitably confronted with new voices and interests, creating new sources of expertise and authority, and to varying degrees undermining the old (e.g., Leach et al., 2010). However, the new media may just as likely reinforce old inequities, or create new ones.

These changes come against the background of wider social, institutional and political changes, which have led to the growing power of business and the media in influencing public discourses, and during a period when citizens in many countries have become more scientifically literate and more prepared to challenge authority of all kinds. Empowered secular skepticism and the declining capacity of politics and the state to order public discourse, together with the new social energies unleashed by the new media, have created new conditions for the agora. This may be read as a profound democratization of the public sphere. On the other hand, the public and private spheres have become increasingly intertwined, and there are clear dangers that public goods and private rights (such as personal privacy) may be imperiled. Science faces new risks, as the 'climategate' experience showed (Leiserowitz et al., 2010; Nerlich, 2010). We can also observe that the opening up of a new media-enabled agora may also lead to a declining quality of public discourse. Transparency and access to truthful information is not evenly distributed. Many traditional gatekeepers and filters of the ordinary media (newspapers, radio, TV) have been weakened, and new procedures and norms for establishing trust and quality in knowledge systems are yet to emerge.

3.2.2. *New needs*

Knowledge production that is credible, legitimate and salient (Cash et al., 2003) to sustainable development imposes challenging requirements on the process of engagement and communication among scientists and with the whole spectrum of private and public actors who collectively influence global environmental systems. What meets the criteria of credibility, legitimacy and salience is context-specific and is dynamic over time. In a knowledge democracy consisting of multiple literate, empowered voices able to express their diverse perspectives and interests, more effort needs to be put into generating these conditions. Where the 'best' paths for the application of knowledge are conditional and provisional (as in today's rapidly changing world), more effort needs to be devoted to engagement, interactive problem framing, knowledge integration and real world experimentation (e.g., Chabay, 2010). More and more, teaching, learning and research will need to be blended, and reinforce each other, oriented toward new social practices that promise to contribute to sustainable development. The transdisciplinary research of the universities requires integration into a responsive and lifelong education system, building up people's experience, and developing new skills and networks. In these conditions, an effective curriculum will incorporate 'T-shaped skills' – the development of a depth of understanding in a specialist discipline coupled with a capability to understand and interact with specialists from a wide range of other fields.

4. Characteristics of open knowledge systems and effective knowledge arenas

We are not starting from a position of ignorance and inexperience in calling for a transformation of 'science for sustainability'; all around the world, there are initiatives that provide exemplars (see Table 1), yet in our view too many new sustainability-oriented research programs that promise to be transdisciplinary set out as if they were the first one ever devised. The core elements for success are well-understood and well-documented in academic and research policy literature (e.g., Thompson Klein, 2010; Hirsch Hadorn et al., 2008; COSEPUP, 2004; EURAB, 2004), but this literature rarely informs new practice. These core elements are discussed in more detail in the following section, but briefly, they include collective societal agenda setting and problem framing, integrative research processes, broader and more transparent review and evaluation that accommodates a diversity of values, and effective processes for stakeholder and dialog participation.

To make our general discussion about knowledge systems more concrete, we briefly present some successful examples of institutional contexts designed to achieve the functions of a knowledge system, involving the production, transfer and use of knowledge. These knowledge arenas are microcosms of the general arguments we have been making, and that we suggest

Table 1 – Examples of effective interfaces between knowledge and action.

Example	Description	Novel approaches	References/sources
Joint problem-framing and shared vision			
Venice's mobile flood gates – the MOSE Project, Italy	Construction of Venice's mobile gates as a response to sea-level rise began in 2003 and is due to be completed in 2014. Tensions have abounded since the scheme was mooted, between Venice's Local Authorities, the government-created Consorzio Venezia Nuova implementing the scheme, subcontracting companies and the local community.	Local decision-making needs to take account of the complexity and uncertainty related to global environmental change and the performance of alternative adaptation measures. This project has implemented dialog processes to address the frequent conflicts among stakeholders and disagreements among researchers representing different scientific fields.	www.consorziovenezianuova.com/uk/natura_struttura.htm
Integration			
The Intergovernmental Panel on Climate Change (IPCC)	As an international, scientific intergovernmental body, the IPCC is a way of constituting 'the science-policy interface' at the global level. Its activities have shaped norms for the production of global assessment reports, in terms of the handling of evidence, transparency and traceability, and about the role of science in policy-making.	A user-driven process – national governments in plenary determine the structure and content of reports. Clear principles for expert nomination and approval process. Comprehensive review and consensus process. Produces both technical reports and summary reports, ensuring key messages are widely available and comprehensible. Concerns have been raised about the status of scientific knowledge in public and policy debate, the legitimacy of its fundamental procedures, and the role of critical actors in global change debates.	www.ipcc.ch
Analysis of the Dutch energy innovation system	The Rathenau Instituut made an assessment of innovation for sustainable development in the energy sector. This study found that interaction with stakeholders (clients, companies, enterprises) is a weak point in the energy innovation system. The sector is not oriented to the needs of energy-consuming companies and citizens.	Identification of the critical junctures in the innovation system (in this example, a lack of continuity of government policy; a lack of corresponding instruments to promote innovation for the long term). Collation of evidence on local transition processes that shape the regional processes: effective science-policy interface includes a broad range of stakeholders and is driven by a long-term vision.	RMNO (2009) Energy Innovation Agenda, NOI/Creative Energy (2008)
Parliamentary Hearings, Denmark, since 1996	Regular dialogs of the Danish Parliament and Danish Board of Technology. The goal of parliamentary hearings is to give the politicians the opportunity to explore questions of current concern.	Creation of a space for debate and deliberation between politicians and people with specific expertise on topical issues.	www.tekno.dk/subpage.php3?survey=11
Collaborative implementation			
Conservation and use of *Coffea Arabica* in the Montane Rainforests of Ethiopia (CoCE, 2003–2009)	An Ethiopian-German project led by the Center for Development Research (ZEF) Bonn and University of Addis Ababa with other institutional partners in Ethiopia and Germany. Its aim was to develop science based concepts for concrete, 'implemen-table' solutions for the urgent problems of conservation and sustainable use of Ethiopian coffee forests.	Regional-scale, implementation-oriented project with strong stakeholder involvement. A non-governmental organization linking knowledge and action was founded by Ethiopian and German researchers that lives on beyond the time-frame of the science project and successfully contributes to coffee forest conservation.	www.coffee.uni-bonn.de, www.ecff.org.et Hindorf et al. (2010)

Table 1 (*Continued*)

Example	Description	Novel approaches	References/sources
Temporary Research Institutes (Institute auf Zeit), Germany	The German Science Council first established temporary research institutes in the 1990s, with time-limited public funding, recognizing that traditional institutions have limited flexibility to adapt their mission and internal structures.	Mechanism allows responsiveness to local and diverse knowledge needs. Exposes researchers to different hybrid research contexts and shifting demands.	Battis and Kersten (2002)
National Centre of Competence in Research (NCCR) North-South	A programme jointly funded since 2001 by the Swiss National Science Foundation, Swiss Agency for Development and Cooperation, and other research institutions, now encompassing a network of over 400 researchers in 40 countries worldwide. Its aim is to find sustainable, practicable solutions to specific challenges of global change.	Collaboratively conducted research with a special emphasis on the needs of developing and transition countries.	www.north-south.unibe.ch
Transforming the link between research and education			
Barefoot College in Rajasthan, India	In 1972, a collective of urban educated professionals in India registered as the Social Work and Research Centre, engaging rural communities in sustainability matters. The goal is to support sustainability and self-sufficiency. The philosophy has extended to a wider network in the South, supported by diverse public and private funding streams.	Example of South-South sustainability learning initiative, using different languages and communication forms (art, drama) to engage and teach.	http://vooruit.be/en/page/1491; http://thoughtsandtalks.so-on.be; www.barefootcollege.org
Lund University Centre for Sustainable Studies, Sweden	Established in 2000 at Lund University, the Centre is an interdisciplinary platform for education, research and cooperation inside and outside academia on problems related to sustainable development.	Academic structure (external to main faculties) allows bridging of natural and social sciences. Sustainability focus explicitly addresses knowledge for real-world action.	www.lucsus.lu.se/html/about_lucsus.aspx
Awards for transdisciplinary research	td-net grants the *Swiss-Academies Award for transdisciplinary research* (ca. €60,000) every 2 years in recognition of outstanding transdisciplinary research by an individual or a research group.	Increases the visibility and academic recognition of new modes of knowledge production.	www.transdisciplinarity.ch/e/Award
Case-study methods in teaching, ETH Zürich	Transdisciplinary case studies are hybrids combining learning, research, and application of competencies and skills to problems of sustainable development.	The case study approach provides institutional facilities for science-society dialog. The idea of a 'transdisciplinarity laboratory' allows scientists and non-scientists to cooperate, aspire to a mutual learning process, and conduct useful research.	www.uns.ethz.ch/translab/ Scholz et al. (2006)

need now to become mainstreamed. These projects and institutional settings are exemplary in their focus on practical implementation, as the case of the Ethiopian-German cooperative *Coffea Arabica* project; collaborative learning and knowledge integration, as in the cases of the Barefoot College in Rajasthan and the analysis of the Dutch energy system; and the explicit linking of research, teaching and application, as in the transdisciplinary case-study teaching method of the ETH in Zürich, and the academic structure of the Lund University Centre for Sustainable Studies that was developed to accommodate such approaches.

We believe that learning from and mainstreaming the experience of existing knowledge arenas requires a *systematic program of knowledge arena demonstration projects*, designed to allow for the range of approaches needed for sustainability science. Contributing projects for such a program should emerge from open and interactive knowledge systems, where diverse actors co-produce knowledge, drawing upon and integrating methods that are salient and effective for them in their own contexts of action. Given that many knowledge arenas are transnational, we believe there should be strengthened international collaboration, particularly in defining the

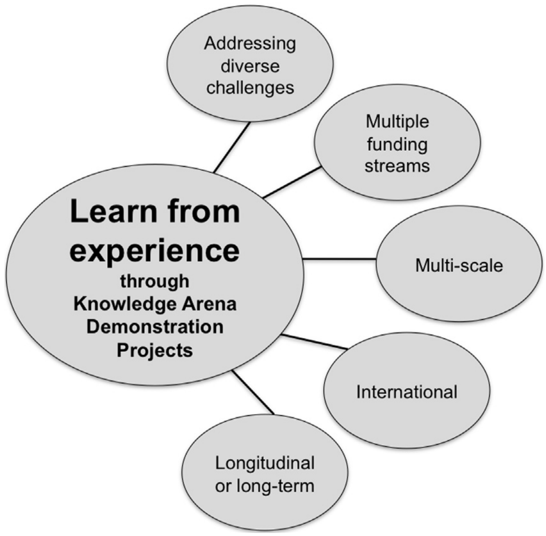

Fig. 2 – Characteristics of a knowledge arena demonstration program for sustainability science.

priority research issues for the sciences. Fig. 2 summarizes the characteristics of such a program.

An aim of this demonstration program is to test and learn from the many ongoing research innovations, establishing and extending connections that allow individuals, communities, and institutions to engage with each other across cultures and social settings to support common goals of sustainability. A vital feature is that stakeholders can contribute to the design of the arena (including agreeing on priorities for funding decisions), rather than being brought in as participants once goals have been set. New tools, methods and patterns of interaction are being developed in the interface between science, policy, the media and citizens, providing many different opportunities for engagement – but these approaches need to be evaluated and refined.

5. Creating knowledge arenas for sustainability

Open knowledge systems able to address the complex social-environmental issues of global change and tackle unsustainability require broad societal engagement, ideally through all available engagement avenues, not just changes in practices and assumptions within the scientific community. The institutional structures of science within its current disciplines and boundaries affect the relationships between science, policy and society, and many shortcomings are now well known. Our priority areas for transformed engagement processes are outlined below, before we address the barriers to these transformations.

- *Ensuring accountability* between actors involved in knowledge arenas is important because it lies at the heart of building the trust and legitimacy that are needed for effective deliberative and inclusionary processes in environmental decision-making (Munton, 2003). We need to acknowledge the deeply embedded norms and power relations of science institutions within knowledge systems, while also paying more attention to the individual responsibilities of scientists within these systems.
- *Facilitating engagement and dialog* involves using locations and forms that are familiar and accessible to participants drawn from diverse communities and providing time for learning and reflection. Knowledge arenas can take many forms, depending on the actors involved and the problems and interests at stake. They should be tailored toward achieving credibility, legitimacy and salience for the greatest number of participants.
- *Innovating for engagement and dialog* involves experimenting with new social media and technologies such as visualization and miniaturized sensing technologies. These offer a multitude of new ways to engage people in knowledge arenas in ways that emphasize collaboration and co-design of solutions, and lower barriers to participation and learning.
- *Strengthening the competences of 'knowledge integrators'* involves recognizing and institutionalizing more flexible mechanisms in education as well as in research, to support the understanding, assessment and management of complex social-ecological systems.

5.1. *Barriers affecting science as a whole*

Much current science practice is still organized in what we characterize as a closed knowledge system: self-regulated; organized in disciplines; setting the research agenda autonomously; and substantially detached from society, politics and the media. Science in this mode has specific, restricted ways of engaging with societal demands for knowledge and in societal discourses, but generally on its own terms and through intermediaries, including the media and think-tanks. Transdisciplinarity, a vital condition for participating in knowledge arenas, is still weakly institutionalized compared to traditional disciplinary science (Scholz et al., 2006), and indeed is even be seen as contradictory to the basic tenets of the closed model. Fig. 3 shows an 'institutional roadmap' that can help redress this situation.

Many of the arrangements and beliefs inherent to the 'closed' model of science appear to be in conflict with the development of an open, diverse yet integrated science for sustainability. Applied, policy-oriented and user-engaged research is often regarded as a lower-value activity than basic science, so at present academics devote comparatively little effort to outreach and engagement. Addressing the procedural, political, institutional and cultural barriers requires a shift in the mandate of science. We propose that science needs to be seen as more than a set of rules and practices organized for understanding the world, but rather as being part of a chain of reasoning, interaction and action within knowledge systems. For addressing sustainability challenges, the objective of these systems is to build robust and valid representations of the multiple constraints affecting social-ecological systems, and negotiating informed pathways through them.

The evaluation of research that bridges disciplinary boundaries is problematic where existing scientific cultures

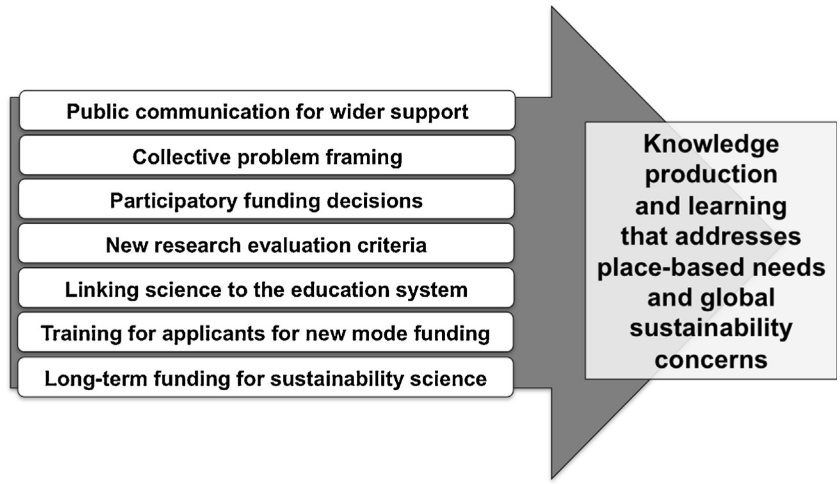

Fig. 3 – The institutional roadmap to open knowledge systems for sustainability.

have agreed on fixed criteria for quality. There is a general trend toward the use of fixed quantitative metrics for assessing academic research quality, and the 'impact agenda' for public-funded research has a rising profile at present (e.g., Phillips, 2010; Eynon, 2012), but the current evaluation metrics are not appropriate for an open knowledge system. They are contentious even for the existing system (e.g., Kapeller, 2010) – bibliometrics, for instance, show only a weak link between publication outputs and the research budget – and the widening application of impact factors already threatens sustainability research (e.g., Monastersky, 2005; Holden et al., 2006). The focus on impact brings both new challenges and new opportunities for sustainability science. Assessing 'research impact' in economic terms is difficult for individual projects; a strong focus on short-term technological or economic gains privileges certain kinds of technologically oriented research, and also privileges private gains over public benefits of the sort that sustainability provides. In many cases, sustainability research draws on resources from different public and private organizations, effectively resulting in decentralization of research funding. This is far from being an undesirable situation (synergies are possible, and the commitment of multiple actors fits well with our conceptualization of knowledge arenas), but it presents new challenges for evaluation of cost-effectiveness, and requires a different skill set in those applying for resources from such diverse funding streams. If 'policy impact' is sought, then the causal links to research are notoriously weak and hard to trace. For instance, a UK study (Eftec, 2006) reported that in the context of ecosystem services, a 'poster-child' for evidence-based policy, policymakers deal with information gaps by 'informed guesswork' and conversations with their peers, rather than reviewing the available research.

We posit that the evaluation of research and of academic institutions needs to include useful measures of the outcomes of public engagement. In particular, these must recognize that changes in attitudes, behavior, and policies may not be evident in short timescales. Incentives should reward academic faculty and corporate researchers for engaging substantively and well with the public and policy-makers. In short, an open knowledge system will require:

- review processes that straddle and extend beyond traditional disciplinary inputs;
- broader and more complex but transparent metrics for evaluation, over timeframes that better reflect the processes of social learning and change;
- procedures of validation to ensure that both methods and end applications of knowledge production are 'placed in context', considering both social and environmental aspects.

5.2. *Barriers affecting scientists*

The skills of many academic scientists are unfit for the purposes of contributing to sustainability (Corcoran and Wals, 2004). Researchers and practitioners are needed who can deal competently with the diversity and complexity associated with knowledge arenas as we have described them, but for decades in most countries, university education has been a funnel toward specialization. Academic scientists are rewarded for being narrow and specialized, and are often ill-equipped to move beyond the boundaries of their own specialisms. Furthermore, many scientists frequently have superficial understanding of politics, business and society, and the ways in which science may have an impact in society. Linked to this, scientific training generally leaves professional scientists unaccustomed to reflection on their own activities, values and ethics (Stauffacher et al., 2006). The work of scientists is perceived to end with the publication of their results, and does not extend to the potential consequences of the applications of their research on social-ecological systems. We argue that the science community should recognize and accept their social responsibility (indeed, society is already calling for this, and could go further in assigning these responsibilities). This involves acknowledging the political nature of knowledge systems dealing with global change.

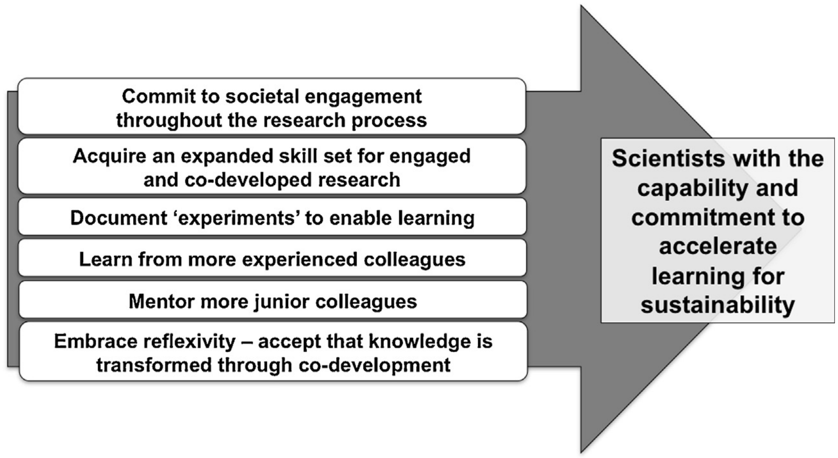

Fig. 4 – A roadmap for scientists working in the sustainability knowledge arena.

In terms of the required competences, scientific and methodological excellence remain essential for researchers, but additional capabilities are needed (Fig. 4). Based on our experiences, we identify the following:

- Humility to recognize the limitations of one's own knowledge and perspectives in dealing with complex issues.
- Active inquiry and openness toward other systems of thought, disciplines and worldviews and other sources of knowledge and learning, both formal and informal.
- The ability to listen to others, being able to communicate in real, multi-way dialogs.
- A willingness to acknowledge that the partial knowledge the researcher brings to the dialog table will be transformed in the process, giving latitude to other contributors.
- Procedural, facilitation and management skills.
- The enthusiasm and ability to share knowledge and learn, rather than impose knowledge.

More generally, each person's educational experience, from earliest childhood through university level and beyond, should build the skills, disposition, and capacities for engaging in complex and socially relevant issues; with training that not only includes academic theory, methodologies and techniques, but also skills such as negotiation, communication and integrative research methods and practices. Training is needed that covers the major problem areas already seen within implementation-oriented sustainability science projects. Important areas are:

- stakeholder analyses and stakeholder involvement;
- robust collective problem framing with a focus on shared objectives and alternative development pathways;
- forward-looking and anticipatory competences;
- effective and efficient project or program management;
- concrete work on knowledge integration and synthesis;
- improved science communication;
- longer-term continuity of research results and relationships in implementation-oriented work.

6. Conclusions

Incentives for operating at the interfaces between science, policy and wider society, and for academic engagement in sustainability-oriented science are weak and generally transient – a function of the demand-driven nature of transdisciplinary work. Disincentives for this kind of work are generally strong and deeply engrained in academic culture. There are evident needs for a new phase of 'democratization of science', but there is also resistance in the research community. Barriers experienced at the individual level include disciplinary differences in language and terminology, methodologies and techniques, norms and expectations about research development and dissemination, and the criteria for prestige and self-actualisation. Individual scientists working across discipline boundaries still need to draw on some important features of established academic cultures, to assure their authority and standing. It is intellectually and practically difficult to move outside of one's own scientific domain. And finally, having embarked on the risky enterprise of participatory, integrative, user-engaged research, there are still very few career opportunities for those individuals who choose to get involved. Academic institutions and science funders have been slow to provide security of employment in ways that ensure the skills required for this work can develop throughout a career.

Support is needed, as part of research funding, for the development of strong interpersonal connections in more open knowledge arenas involving scientists and researchers in all fields who are addressing sustainability issues. Without these connections, sustainability research efforts risk appearing to be piecemeal, and the effective dissemination of best practices through the research community is hampered. For the necessary interpersonal connections to flourish in these new open spaces, increasing the entrainment of science knowledge for action, it is essential that improved measures of the quality of meaningful engagement across science-society interfaces are agreed upon and established. Without such measures, there is no cover for academic or agency or corporate managers involved in the processes of sustainability to justify their support for outreach and engagement with the public. Formulating these new assessment criteria is itself a major challenge, not least because locally tailored solutions are more likely to be acceptable than the current trend for semi-automated quantitative metrics of impact. Sustainability science would benefit from a move away from a focus on delivering 'more knowledge' (which information technologies can now deliver worldwide, instantaneously) to supporting 'appropriate knowledge', involving targeted involvement by the research community in socially situated knowledge arenas organized around societal problems.

Far-reaching and transformational institutional change is needed to ensure effective interfacing arrangements for translating knowledge to action. Therefore, we call for well-designed, properly resourced longitudinal, international learning programs. Established structures, institutions, funding channels, and career strategies are in conflict with the goals of an engaged, responsive knowledge system for sustainability science. Today's piecemeal approach needs to undergo a step change toward broad cross-sectoral cooperation between government, business, industry, civil society and environmental organizations, to support the implementation-oriented character of the new knowledge system (Fig. 3). Sustainability intrinsically has a long-term perspective (decadal and longer), which is at odds with the tempo of research strategies and political cycles. Adjusting the balance between fundamental inquiry and science that can explicitly respond to societal needs requires procedures to bring a wider range of societal actors into the process of prioritizing research. An effective and fair evaluation system for integrative research on societal themes is needed. A diversity of mechanisms will be needed for engagement in knowledge production, learning and evaluation to link these to place-based needs and global sustainability concerns. Science still needs to consider the challenges posed by the growth of new information systems and technologies as a means of access to knowledge, as a repository of knowledge, as a research tool and as an agora, which all have profound implications for the production, diffusion and use of knowledge in responding to societal problems.

Profound changes in the capacity for sustainability learning begin 'at home', with the commitment of individual scientists (Fig. 4). More integrative and deliberative approaches to dealing with uncertainty and a plurality of perspectives are needed in all training for sustainability. That involves the constructive sharing of experience and expertise. Support for developing science literacy and critical judgment of science needs to be strengthened and expanded to include more integrated and interdisciplinary understanding of global change issues.

REFERENCES

Adler, P.S., 2002. Science, politics, and problem solving. Penn State Environmental Law Review 10, 323.

Bammer, G., 2005. Integration and implementation sciences: building a new specialization. Ecology and Society 10 (2.).

Battis, U., Kersten, J., 2002. Institut auf Zeit: Haushalts-, wissenschafts-, organisations- und arbeitsrechtliche Rahmenbedingungen für die mittelfristige Forschungsförderung. Deutscher Hochschulverband, Bonn.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proceedings of the National Academy of Science 100 (14), 8086–8091.

Chabay, I., 2010. Voices at the table: participation, ownership, and collaboration in social-ecological issues. In: Forrester, J., Gerger Swartling, A. (Eds.), Overcoming the Challenges of 'Doing Participation' in Environment and Development. Stockholm Environment Institute Working Paper, pp. 7–20.

Corcoran, P.B., Wals, A.E.J., 2004. Higher Education and the Challenge of Sustainability: Problematics, Promise, and Practice. Kluwer, Dordrecht.

COSEPUP, 2004. Facilitating Interdisciplinary Research. National Academies Committee on Science, Engineering and Public Policy. National Academies Press, Washington, DC. , www.nap.edu/catalog.php?record_id=11153#toc.

Eftec, 2006. Valuing Our Natural Environment. Final Report. NR0103, Department for Environment, Food and Rural Affairs, London. http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=13902#Description.

Ehrman, J.R., Stinson, B.L., 1999. Joint fact-finding and the use of technical experts. In: Susskind, L., McKearnan, S., Thomas-Larmer, J. (Eds.), The Consensus Building Handbook. Sage Publications, Thousand Oaks, CA, pp. 375–399.

EU Research Advisory Board, 2004. Interdisciplinarity in Research. , In: www.europa.eu.int/comm/research/eurab/index_en.html.

Eynon, R., 2012. The challenges and possibilities of the impact agenda. Learning, Media and Technology 37 (1), 1–3.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M., 1994. The New Production of Knowledge—The Dynamics of Science and Research in Contemporary Societies. Sage, London, Thousand Oaks, New Delhi.

Groß, M., Hoffmann-Riem, H., 2005. Ecological restoration as a real-world experiment: designing robust implementation strategies in an urban environment. Public Understanding of Science 14, 269–284.

Hajer, M.A., 2009. Authoritative Governance, Policy-making in the Age of Mediatization. Oxford University Press, Oxford.

Hindorf, H., Denich, M., Gole, T., 2010. Conservation and Use of Wild Populations of *Coffea Arabica* in the Montane Rainforests of Ethiopia: From Research to Action. Presented at Tropentag 2010: Food Security, Natural Resource Management and Rural Development. ETH Zurich, September 14–16, 2010. www.tropentag.de/2010/proceedings/node504.html.

Hirsch Hadorn, G., Hoffmann-Riem, H., Biber-Klemm, S., Grossenbacher-Mansuy, W., Joye, D., Pohl, C. (Eds.), 2008. Handbook of Transdisciplinary Research. Springer, Dordrecht.

Holden, G., Rosenberg, G., Barker, K., Onghena, P., 2006. Should decisions about your hiring, reappointment, tenure, or promotion use the impact factor score as a proxy indicator of the impact of your scholarship? MedGenMed 8 (3), 21.

in't Veld, R.J. (Ed.), 2010. Knowledge Democracy. Springer-Verlag, Berlin, Heidelberg, http://dx.doi.org/10.1007/978-3-642-11381-9-2.

Irwin, A., 1995. Citizen Science: A Study of People, Expertise, and Sustainable Development. Routledge, New York, 198pp.

Irwin, A., Wynne, B., 1996. Misunderstanding Science? The Public Reconstruction of Science and Technology. Cambridge University Press, Cambridge.

Jahn, T., Keil, F., Becker, E., Schramm, E., 2006. Transdisziplinäre Integration. In: Becker, E., Jahn, T. (Eds.), Soziale Ökologie–

Grundzüge einer Wissenschaft von den gesellschaftlichen Naturverhältnissen. Campus, Frankfurt, New York, pp. 287–339.
Jasanoff, S., 2004. States of Knowledge: The Co-production of Science and Social Order. Routledge, London.
Kapeller, J., 2010. Citation metrics: serious drawbacks, perverse incentives, and strategic options for heterodox economics. American Journal of Economics and Sociology 69, 1376–1408.
Karl, H.A., Susskind, L.E., Wallace, K.H., 2007. A dialogue, not a diatribe: effective integration of science and policy through joint fact finding. Environment 49 (1), 23–35.
Leach, M., Scoones, I., Stirling, A., 2010. Dynamic Sustainabilities: Technology, Environment, Social Justice. Routledge, p. 232.
Leach, M., Scoones, I., Wynne, B. (Eds.), 2005. Science and Citizens: Globalization and the Challenge of Engagement. Zed Books, London.
Leiserowitz, A., Maibach, E.W., Roser-Renouf, C., Smith, N., Dawson, E., 2010. Climategate, Public Opinion, and the Loss of Trust. Social Science Research Network, In: http://ssrn.com/abstract=1633932.
Lemos, M.C., Morehouse, B.J., 2005. The co-production of science and policy in integrated assessments. Global Environmental Change 15, 57–68.
McCreary, S.T., Gamman, J., Books, B., 2000. Refining and Testing Joint Fact-finding for Environmental Dispute Resolution: Ten Years of Success. Concur, Inc, Working paper 00-01.
Meadows, D., Richardson, J., Bruckmann, G., 1982. Groping in the Dark: the First Decade of Global Modeling. John Wiley and Sons, Chichester.
Moll, P., Zander, U., 2006. Managing the Interface: From Knowledge to Action in Global Change and Sustainability Science. Oekom Verlag, Munich.
Monastersky, R., 2005 October. The Number That's Devouring Science. Chronicle of Higher Education, In: www.ncbi.nlm.nih.gov/pmc/articles/PMC1781329/.
Munton, R., 2003. Deliberative democracy and environmental decision-making. In: Berkhout, F., Leach, M., Scoones, I. (Eds.), Negotiating Environmental Change: New Perspectives from Social Science. Edward Elgar, Cheltenham, pp. 109–136.
Nederland Ondernemend Innovatie/Creative Energy, 2008. Energy Innovation Agenda. , In: www.nwo.nl/files.nsf/pages/NWOA_7QWC3X/$file/Energy%20Innovation%20Agenda%2009-09-2008_tcm24-281800.pdf.
Nerlich, B., 2010. 'Climategate': paradoxical metaphors and political paralysis. Environmental Values 19 (4), 419–442.
Nowotny, H., Scott, P., Gibbons, M., 2001. Re-thinking Science—Knowledge and the Public in an Age of Uncertainty. Polity Press, Cambridge.
Phillips, R., 2010. The impact agenda and geographies of curiosity. Transactions of the Institute of British Geographers 35 (4), 447–452.
Pohl, C., van Kerkhoff, L., Bammer, G., Hirsch Hadorn, G., 2008. Integration. In: Hirsch Hadorn, G., Hoffmann-Riem, H., Biber-Klemm, S. (Eds.), Handbook of Transdisciplinary Research. Springer, Dordrecht, pp. 411–424.
Ravetz, J., 2004. The post-normal science of precaution. Futures 36 (3), 347–357.
Rip, A., 2001. Interesting cases of new modes of knowledge production. Presented at Symposium 8 of the International Conference on Globalisation and Higher Education: Views from the South, Cape Town, 27–29 March 2001.
RMNO, 2009. Innovatie en duurzame ontwikkeling. Duurzame ontwikkeling in onderzoek en onderwijs, , In: www.rmno.nl.
Robinson, J., Tansey, J., 2006. Co-production, emergent properties and strong interactive social research: the Georgia Basin Futures Project. Science and Public Policy 33 (2), 151–160.
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S.C., et al., 2009. A safe operating space for humanity. Nature 461, 472–475.
Scholz, R.W., Lang, D.J., Wiek, A., Walter, A.I., Stauffacher, M., 2006. Transdisciplinary case studies as a means of sustainability learning: historical framework and theory. International Journal of Sustainability in Higher Education 7 (3), 226–251.
Stauffacher, M., Walter, A.I., Lang, D.J., Wiek, A., Scholz, R.W., 2006. Learning to research environmental problems from a functional socio-cultural constructivism perspective. The transdisicplinary case study approach. International Journal of Sustainability in Higher Education 7 (3), 252–275.
Thompson Klein, J., 2010. Creating Interdisciplinary Campus Cultures: A Model for Strength and Sustainability. AAC&U and Jossey-Bass.
van den Daele, W., Krohn, W., 1998. Experimental implementation as linking mechanism in the process of innovation. Research Policy 27, 853–868.
van Kerkhoff, L., 2005. Integrated research: concepts of connection in environmental science and policy. Environmental Science and Policy 8, 452–463.
Van Kerkhoff, L., Lebel, L., 2006. Linking knowledge and action for sustainable development. Annual Reviews in Environmental Resources 31, 445–477.
van Kerkhoff, L., Szlezák, N.A., 2010. The role of innovative global institutions in linking knowledge and action. Proceedings of the National Academy of Sciences www.pnas.org/cgi/doi/10.1073/pnas.0900541107.
Weingart, P., 1999. Scientific expertise and political accountability: paradoxes of science in politics. Science and Public Policy 26 (3), 151–161.