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NOTE AND COMMENT

The future of sustainability science: a solutions-oriented research agenda

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Abstract Over the last decade, sustainability science has been at the leading edge of widespread efforts from the social and natural sciences to produce use-inspired research. Yet, how knowledge generated by sustainability science and allied fields will contribute to transitions toward sustainability remains a critical theoretical and empirical question for basic and applied research. This article explores the limitations of sustainability science research to move the field beyond the analysis of problems in coupled systems to interrogate the social, political and technological dimensions of linking knowledge and action. Over the next decade, sustainability science can strengthen its empirical, theoretical and practical contributions by developing along four research pathways focused on the role of values in science and decision-making for sustainability: how communities at various scales envision and pursue sustainable futures; how socio-technical change can be fostered at multiple scales; the promotion of social and institutional learning for sustainable development.

Keywords Sustainability science · Decision-making · Scenarios · Values · Socio-technical change

Science and the sustainability challenge

Over the last several decades, scientific communities have become increasingly concerned with the challenge of utilizing the power of scientific knowledge to address the pressing problems of sustainability such as climate change, ensuring adequate water resources, and protecting marine fisheries (Lubchenco 1998; NRC 1999). Perhaps the most wide ranging of these is sustainability science (Clark 2010; Matson 2009). Kates et al. (2001) laid the foundation for sustainability science, defining three core objectives: (1) understanding the fundamental interactions between nature and society; (2) guiding these interactions along

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sustainable trajectories; (3) promoting social learning necessary to navigate the transition to sustainability. Sustainability science has developed rapidly with the establishment of peer-reviewed journals, the publication of major articles in leading scientific journals, national and international research initiatives, and the creation of academic departments and research centers with graduate and undergraduate programs (Bettencourt and Kaur 2011).

To date, research in sustainability science has focused largely on understanding complex coupled human-natural systems (Clark 2007; Miller 2013). These efforts have made significant contributions to our understanding of coupled systems dynamics, brought sorely needed attention to research that is problem-oriented and spurred explorations of knowledge systems for sustainability (van Kerkhoff and Lebel 2006). However, we contend that theoretically and empirically rich investigations into how society and its institutions can articulate visions of sustainability and guide socio-technical change remain underappreciated and relatively unexplored in sustainability research. In so doing, we hope to advance a transformational and solutions-oriented research agenda for sustainability science (Sarewitz et al. 2012; Wiek et al. 2012). As research and education programs dedicated to sustainability continue to emerge and national and international science funding bodies establish research investment priorities [e.g., the International Council for Science Future Earth initiative and the US National Science Foundation program-wide investment area in Science, Engineering and Education for Sustainability (SEES)], the success of such programs requires that sustainability scholars, practitioners and decision-makers critically reflect on how to best position sustainability research to ensure that knowledge creation enhances decision-making capacity and the ability of our institutions to navigate socio-technical systems along more sustainable trajectories. This article explores the potential for several underappreciated alternative research pathways for sustainability science that will strengthen the theoretical, empirical and practical contributions of the field.

The next decade of sustainability science: searching for socio-technical solutions

Sustainability problems are often characterized by complexity, high and often irreducible uncertainty and contested values (Funtowicz and Ravetz 1993; Rittel and Webber 1973). In such cases, additional scientific knowledge about underlying problem dynamics is rarely a factor in limiting the development of more sustainable outcomes (Sarewitz 2004). Yet, much of the research in sustainability science, and the use-inspired socio-environmental sciences more broadly, is based on the assumption that more knowledge about system dynamics is necessary for improved decision-making and action related to sustainability (Miller 2013; Miller and Neff 2013; Palmer 2012; Wiek et al. 2012). This stems, in part, from an Enlightenment belief in rationality and progress that is embedded in our knowledge-generating institutions and in democratic liberalism more broadly (Ezrahi 1990).

Instead, a combination of social values, political contexts, technological innovation and diffusion and the obduracy of infrastructure and economic and institutional structures often impede effective social, political and technological action (Fischer et al. 2012; Kinzig et al. 2013). If the goal of sustainability science is to contribute to society's ability to operate along sustainable trajectories, then more scientific knowledge about coupled systems will not suffice. Several scholars and organizations have recognized as much, conceptualizing the role of knowledge in broader knowledge systems comprised of social and political actors with different motivations and knowledge types (e.g., Clark et al. 2011; ICSU 2002; Muñoz-Erickson 2012; Reid et al. 2009). However, theoretically and empirically rich research pathways that both recognize these limitations and remain relevant to the pursuit of more sustainable solutions have yet to be fully realized. We contend that sustainability science must link research on problem structures with a solutions-oriented approach that seeks to understand, conceptualize and foster experiments for how socio-technical innovations for sustainability develop, diffuse and scale up.

We offer four research pathways that move beyond the understanding of coupled systems and toward theoretically and empirically rich solutions-oriented research. These pathways have been gleaned from the literature and from an analysis of how science can be positioned to contribute to sustainable outcomes, which drew from a diversity of sources, including sustainability science, science and technology policy, science and technology studies, innovation studies, decision-making and environmental values (Miller 2013; Sarewitz et al. 2012; Wiek et al. 2012). Sustainability, as we understand it, is ultimately a question about how communities at various scales envision and pursue social and natural well-being. Sustainability science has a crucial role to play in working with such communities in crafting a viable vision of the future; deliberating on those visions and the values they represent; exploring the potential socio-technical pathways that might realize such a vision; and developing the social and institutional structures that enable communities to continually learn and adapt to new knowledge, values, technologies and environmental change. These research priorities position sustainability scientists as not just generators of knowledge but also as knowledge-brokers and change agents (Miller et al. 2011a).

Mapping and deliberating sustainability values

Inquiries into values are largely absent from the mainstream sustainability science agenda. Yet, at its core, sustainability is a fundamentally ethical concept raising questions regarding the value of nature, responsibilities to future generations and social justice (Norton 2005). Unless those values are understood and articulated, the unavoidable political dimensions of sustainability will remain hidden behind scientific assertions, thus preventing necessary democratic deliberation and convergence on more sustainable pathways. Values—or ideas about the world that are held to be important—underlie key concepts in sustainability including the ways in which problems are framed and defined (Voß et al. 2005), resilience and vulnerability (Adger 2006; Turner et al. 2003), and tipping points that indicate shifts to regimes less desirable for human development (Rockström et al. 2009). The values underlying sustainability visions, goals, targets and thresholds need to be elicited, mapped and discussed in order to support societal deliberation over what values should guide sustainability transitions (Norton 2005; Robinson et al. 2006).

While sustainability scientists acknowledge the importance of the values motivating sustainability research (Clark 2007; Matson 2009), they are widely neglected as a subject of inquiry. Values often fall outside of the field of analysis as sustainability science (and its precursor environmental science) has typically addressed social issues by adopting approaches and frameworks from what Rayner and Milone (1998) call the descriptive (rather than interpretive or transformational) side of the social sciences, rarely venturing into the realm of the humanities. As a result, the ability of sustainability science to provide timely and relevant knowledge that speaks to social values has been impeded.

Recent progress has been made in research on the role of values in complex decision-making and trade-offs between sustainability goals. Conservation and ecosystem management research has shown that what were assumed to be mutually reinforcing goals of conservation and economic development are rarely aligned as such (McShane et al. 2011). How trade-offs between goals are evaluated and navigated needs to be informed by both science and social values (Gibson 2006; Miller et al. 2011b). Stakeholders also have different, and often conflicting, values and worldviews that they bring to decision-making processes. Recent research has engaged in mapping complex decision situations with multiple stakeholder groups and explored the change of beliefs and values through deliberation and learning (van den Hove 2006). Such values are, of course, also mediated differently in different institutional settings at various scales.

Sustainability science research into the role of values in societal action must be moved upstream in the research process rather than treated as an important externality to be adjudicated separately and/or later (Jasanoff 2007). Such research can also play an important role in the framing of sustainability problems, potential actions and scientific research itself (Gray 2009). A greater awareness of and deliberations about the ways in which scientists and practitioners frame sustainability issues, the values that are both excluded and included, and potential conflicts that might arise will add a much needed reflexivity to sustainability research (Healy 2007; Jerneck and Olsson 2011; Smith and Stirling 2007). An increased focus on the role of values will enable sustainability science to provide information that speaks to widely held social values and advance knowledge on how certain policies or programs can promote the convergence of values on sustainable pathways and policies. As soon as values become a core part of the sustainability research agenda, then the need for participatory approaches follows, since decisions can no longer be based solely on technical or scientific criteria (the domain of expert knowledge) alone (Wiek 2007).

Envisioning and pursuing sustainable futures

Exploring what future states are desirable to given communities (visions), in conjunction with a broader spectrum of images exploring how the future might play out (scenarios), are key elements for future- and solutions-oriented sustainability science (Brewer 2007; Swart et al. 2002). Scenario and visioning methodologies enable a broad range of actors to jointly explore diverse development trajectories and alterative futures, based on mutually agreed upon criteria and robust stakeholder participation. Critically, such approaches allow explicit treatment of the normative, ethical and political issues that are often obscured by descriptive analysis of environmental and human systems (Robinson et al. 2011).

In an early response to the initial sustainability science research agenda, Swart et al. (2002), building on the work of the Global Scenario Group (Raskin et al. 2002), criticized the lack of consideration of uncertainty and future-oriented research. The authors proposed an extended sustainability science agenda that would complement descriptive-analytical research with anticipatory, normative and participatory research. Despite an increased recognition of uncertainty in predictions and the importance of scenarios in environmental research (Carpenter et al. 2005; Thompson et al. 2012), the actual relevance of scenarios and visions for developing strategies and taking action towards sustainability has been limited, in part due to a lack of concreteness (i.e., how scenarios and visions matter to the everyday life of people) and connection with actual decision processes (i.e., how scenarios and visions inform decision-making). Visions are intended to inspire and provide direction while scenarios ought to reflect the implications (though of course uncertain) of different pathways into the future in a rich sense. Yet, scientifically crafted visions and scenarios often provide compartmentalized expert advice, focus on future constraints and define uncertainty in probabilistic terms. They fail to offer broad appealing images and storylines that also account for choice and opportunity, and a richer conceptualization of uncertainty (Swart et al. 2002). As a result they rarely "speak" to stakeholders or get considered in real decision processes that influence development pathways. For example, greenhouse gas emission models and climate scenarios have typically assumed "spontaneous" technological innovation and that billions of people will remain without access to reliable energy (Pielke et al. 2008).

More recently, however, new concepts, methodologies and practices have been developed for making future-oriented research more meaningful and relevant through solutions-oriented sustainability science. First, scenario studies have employed and further developed approaches for visualization and the crafting of narratives that make future pathways more tangible to decision-makers (Bryan et al. 2011). Second, following a few early movers (Swart et al. 2002; Wiek and Binder 2005), new research on sustainability visions is underway (Robinson et al. 2011; Salter et al. 2010), including systems modeling of critical thresholds in human-natural systems (Rockström et al. 2009; Reid et al. 2010). Third, "anticipatory" approaches that support collaboration between experts and stakeholders increase the relevance of future-oriented scientific insights for decision processes such as governance of emerging technologies (Guston 2008; Philbrick 2010). Finally, particular research facilities have been developed to engage stakeholders in science-based development and use of visions and scenarios, most prominently so-called "decision theaters." Incorporating visualization studios, decision theaters are boundary-spanning organizations that support real-world decision-making through sophisticated research tools and infrastructure (Robinson et al. 2011; Salter et al. 2010).

Sustainability science is well positioned to move forward with this agenda but more pioneering efforts are needed to refine the approaches and scale up the effects described above. Advanced participatory research and integrated educational opportunities can positively contribute to these efforts (Rowe 2007; Brundiers and Wiek 2011). A recent research and teaching project in Phoenix, Arizona, has demonstrated how urban planners and sustainability scientists used the outlined anticipatory approaches to develop science-based visions and strategies for urban sustainability (Wiek et al. 2012). Critical success factors were: the city's recognition of failures in conventional planning practice and the willingness to act upon it; availability of advanced, yet practically-oriented planning research capacities at the university; acknowledging of planning constraints (budget, competence, political context) and creative approaches to deal with them through unlikely alliances and novel forms of combining expertise (mutual learning of planners, researchers, and students); leadership on both sides to overcome institutional and individual barriers (common practice, incentives, rewards) to productive and solutions-oriented collaboration (Fig. 1).

Navigating socio-technical change

Perhaps the most critical component of a transition to sustainability will be society's ability to facilitate socio-technical change—shifts in the configuration of institutions, techniques and artifacts as well as the rules, practices and norms that guide the development and use of technologies (Smith et al. 2005). This research priority is also essential to identifying the obstacles and opportunities to shift to sustainable socio-technical pathways.

Fig. 1 Sustainability scientists working with city representatives, businesses, non-profit organizations and citizens on systemic visions and strategies for urban sustainability in Phoenix, Arizona [*left* at City of Phoenix City Hall; *right* at Arizona State University's Decision Theater]

While socio-technical change has been the subject of research in a number of fields, it has been underappreciated in sustainability science as research has focused on the dynamics of coupled human-natural systems. Transition management and governance, for instance, explores the processes, policies and procedures that might help to accelerate and guide emerging transitions out of existing, unsustainable "locked-in" systems in a desired direction (Loorbach and Rotmans 2010; Schensul 2009). The premise in this research is that patterns and dynamics of transitions can be identified and influenced in terms of speed and direction. Given the inherent uncertainties and complexities related to transitions and the long-term directions desired, transition management provides tools for systematic short-term "learning-by-doing" processes, for example, selectively engaging stakeholders in "transition arenas" to explore how strategies, tactics, roles and responsibilities for socio-technical change are best deliberated and agreed upon (Jerneck and Olsson 2011; Loorbach and Rotmans 2010). Recent studies have also identified social, political, institutional and technological leverage points that will help advance socio-technical change toward sustainable outcomes (Beddoe et al. 2009; Casillas and Kammen 2010; Kemp 2011; Walker et al. 2009).

Research on sustainability transitions is still nascent and must be further developed through a stronger focus on solutions-oriented work, i.e., direct inquiries into real options and their feasibility, potential obstacles and coping strategies, critical alliances and unintended consequences. For this research trajectory, sustainability science ought to learn and benefit from the accomplishments of intervention research, successfully applied to complex problems in social work and public health over the last decade (Fraser et al. 2009). Furthermore, research on socio-technical change is closely linked to the two previous research priorities. How institutions and communities articulate their visions for social and natural well-being is a normative project that is essential to navigating socio-technical transitions.

Enabling social and institutional learning for sustainable development

The problems of sustainability are not bounded by either disciplines or expertise. They are often contingent, complex, contextual and contested and require the engagement of knowledge that lies outside the walls of academia (Funtowicz and Ravetz 1993). The ability of our institutions—at multiple scales—to successfully navigate along more sustainable trajectories will depend on its aptitude to learn from experience and inform and adapt future sustainability visions, values and transition strategies (Norton 2005). Therefore, a critical research priority for sustainability science must be to foster such social and institutional learning and experimentation, advancing knowledge on how "learning by doing" occurs and how to make it more effective in order to build institutional capacity for sustainable development.

Recent studies have demonstrated that even advanced transdisciplinary projects encounter various challenges for scientists and local stakeholders to jointly generate new knowledge and support collective decision-making (Clark et al. 2011; Lang et al. 2012). In many cases social learning

Table 1 Core questions for the future of sustainability science

(1) Mapping and deliberating sustainability values
• What are the values held by the legitimate stakeholder groups related to the complex sustainability challenges societies face around the globe?
• How and why do values divert or converge on certain problems, policies or outcomes?
• What values support sustainable outcomes and how can they be activated in sustainable transition and decision processes?
(2) Creating and pursuing desirable futures
• What are viable visions of a sustainable future in response to the complex sustainability challenges societies face around the globe? What choices do they highlight?
• What are effective methods for creating credible, salient and legitimate visions of sustainable futures?
• How does envisioning potential futures translate into action? How can this be done more effectively?
(3) Exploring and fostering socio-technical change
• How have socio-technical changes occurred in the past? What can we learn from these cases?
• How can socio-technical systems be guided along more sustainable trajectories?
• What are promising strategies, tactics, interventions to transition from unsustainable to sustainable states and dynamics?
(4) Enabling social and institutional learning for sustainable development
• What are effective forms of social learning in advancing sustainable outcomes?
• How can social learning be initiated and supported through transdisciplinary research?
• How can research and education institutions facilitate transdisciplinary research and education and enable social learning?

is limited as the time allocated for capacity building is too short, the mode of knowledge generation continues to be rather extractive than collaborative, or the focus remains on the generation of scientific knowledge, which may not necessarily be of use in the pursuit of sustainable outcomes (Smith et al. 2009). While there seems to be widespread agreement that more transdisciplinary-based approaches are required for research and education, we should also be critical of insights, limitations and outcomes of such work (Talwar et al. 2011; Hegger et al. 2013; Lang et al. 2012).

Over the last decade, the need for transdisciplinary research, i.e., to move beyond expert knowledge, to embrace non-expert, public knowledge and enable social learning, has widely been recognized (Pahl-Wostl et al. 2008; Robinson 2008). Innovative forms of participatory sustainability research, including the "go-along" interview and the digital workshop, have been developed to optimize interactivity and enable capacity building (Carpiano 2009). It will be important for sustainability scientists to leave familiar territory and venture into other fields in order to adopt successful practices for social learning and capacity building. The fields of public health and agricultural extension research are among those that can provide guidance, but also research endeavors outside of academia, for instance, management of natural resources, could be of benefit (Caswill and Shove 2000).

Moving forward

While sustainability science has made substantial inroads into our understanding of complex problems in coupled human-natural systems, progress on how this knowledge will foster decisions that lead to more desirable outcomes and analyses of the processes necessary to transition to sustainability are lacking. The proposed research pathways (see Table 1) are not meant to be exhaustive as to the potential fruitful directions sustainability science might take. Instead, they map out a start for the future of this growing field of inquiry while also positioning the field to act as a vehicle to help foster sustainability transitions. In order to ensure that science is focused on facilitating sustainability outcomes we must ask: What is the appropriate role of science in contributing to action and decision-making for sustainability? What kind of science is useful for this purpose? What knowledge, if any, is needed to make better decisions? How can sustainability science best participate in the implementation of sustainable solutions? The pursuit of these questions will come at some cost. Significant changes in the institutional structure of sustainability science are necessary to facilitate the field's successful response to the daunting challenges of sustainability, including a more reflexive approach to the position of the field (Miller et al. 2011a). In addition, there are several critical institutional and educational issues that must be addressed if the field is to move in the proposed direction. For example, some characteristics of academic institutions, including promotion and tenure guidelines, peer-review and disciplinary and departmental structures, may inhibit rather than foster this research (Crow 2010). Similarly, training the next generation of sustainability scientists and practitioners may well require a radical rethinking of how we conduct both undergraduate and graduate education (Rowe 2007).

For sustainability science to contribute to real-world solutions, every sustainability science project must embark on the transformative agenda set forth a decade ago. It is still a long way for the outlined approaches and research pathways to ensure a more relevant future for sustainability science and to deliver on the promise of a science that has a real impact on socio-technological change for sustainability.

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