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OVERVIEW ARTICLE

Constructing sustainability science: emerging perspectives and research trajectories

Thaddeus R. Miller

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Abstract Over the last decade, sustainability science has emerged as an interdisciplinary and innovative field attempting to conduct problem-driven research that links knowledge to action. As the institutional dimensions of sustainability science continue to gain momentum, this article provides an analysis of emerging research agendas in sustainability science and an opportunity for reflection on future pathways for the field. Based on in-depth interviews with leading researchers in the field and a content analysis of the relevant literature, this article examines how sustainability scientists bound the social, political and normative dimensions of sustainability as they construct research agendas and look to link knowledge to social action. Many scientists position sustainability science as serving universal values related to sustainability and providing knowledge that is crucial to societal decision-making. The implications of these findings are discussed with an eye towards creating a space for a more democratic and reflexive research agenda for sustainability.

Keywords Sustainability science · Boundary work · Reflexive · Science and technology studies · Knowledge to action · Research agenda

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Handled by Karel F Mulder, Delft University of Technology, The Netherlands.

T. R. Miller (✉)
Nohad A. Toulan School of Urban Studies and Planning, Portland State University, P.O. Box 751-USP, Portland, OR 97207-0751, USA
e-mail: trm2@pdx.edu

Introduction

Sustainability science aspires to link knowledge to social actions that advance visions of natural and social well-being (Cash et al. 2003; Clark 2007; Jasanoff 1996). While science and technology will undoubtedly play a key role in sustainability transitions, how societies choose to construct and pursue visions of sustainability will be an intensely social, political and cultural process (Miller et al. 2009; Norton 2005; Thompson 2010). Yet, how sustainability scientists grapple with the deeply social, political and normative dimensions of characterizing sustainability problems and potential solutions has received little attention. As sustainability science continues to develop rapidly, this paper explores how sustainability scientists are constructing research agendas and the implications for the development of the field, its ability to provide relevant, contextual and useful knowledge, and for the way sustainability as a concept and discourse is constituted in society, more broadly.

Based on extensive interviews with leading sustainability scientists and a content analysis of the relevant literature, this paper focuses on three core issues in the development of sustainability science: (1) how sustainability scientists define and bound sustainability; (2) how and why research agendas are being constructed to address these notions of sustainability; and (3) how scientists see their research contributing to societal efforts to move toward sustainability. This study advances knowledge of the structure and trajectories of sustainability science and addresses the strengths and limitations of the approaches in sustainability science that emerge in the analysis. The purpose is not simply to critique sustainability science; but to lay the foundation for a deeper dialogue amongst sustainability scientists, decision-makers and other concerned stakeholders over the purpose of sustainability and future directions for the field. The results of this analysis will contribute to more open and informed discussions about the development of the field and form the foundation of a more reflexive science for sustainability—one that appreciates and explores the social, political and normative dimensions inherent in the articulation and pursuit of visions of sustainability (Grunwald 2004). This will foster a deeper and lasting conversation about the most effective role for sustainability science relative to the values and goals of sustainability as set by different communities and society writ large.

The paper begins with a brief overview of the development of sustainability science. This is followed by a discussion of the analytical approach taken to examine sustainability science, which focuses on boundary work (Gieryn 1983, 1999), and an explanation of the methodological approach. Following this, the results of the interviews and content analysis are presented. The paper concludes with a discussion of the implications of various forms of boundary work for sustainability science and an argument for a more reflexive sustainability science.

Science and sustainability

The US National Research Council's (NRC) Board on Sustainable Development 1999 report, *Our Common Journey*, defined a sustainability transition as occurring over the next two generations that "should be able to meet the needs of a much larger but stabilizing human population, to sustain the life support systems of the planet, and to substantially reduce hunger and poverty" (NRC 1999, p 31). Such a transition is possible but requires "significant advances in basic knowledge, in social capacity and technological capabilities to use it, and political will to turn this…into action" (NRC 1999, p 7). While both the NRC report and the 1987 Brundtland Report made clear the importance of the roles of technology, social organization and political action, they carved out a significant role for science in the pursuit of sustainable development. Sustainable development, as Jasanoff (1996, pp 185–186) notes, was framed as attainable "…through a universally acceptable marriage between scientific knowledge and rational stewardship."

It is out of this context that the field of sustainability science has emerged. The NRC report proposed the development of a "sustainability science" that is place-based and problem-driven, integrating knowledge from different disciplines, across geographical and temporal scales, and between scholarship and practice. The concept began to gain significant traction in academic circles with the publication of "Sustainability Science" in *Science* (Kates et al. 2001); in this paper (p 641), Kates and colleagues defined sustainability science as a new field that seeks "to understand the fundamental character of interactions between nature and society" and enhance "society's capacity to guide those interactions along more sustainable trajectories."

Sustainability science is now characterized widely as a transdisciplinary field motived by problem-solving and the understanding of complex human–natural systems (Clark 2007; Jerneck et al. 2011; Kajikawa 2008; Komiyama and Takeuchi 2006; Wiek et al. 2011). The field emerged from human–environment and coupled human–natural systems research in the natural sciences, especially ecology, biogeochemistry, and Earth systems science as well as geography (Kates 2011). While it is a broad and evolving field at this point, sustainability science is characterized by several structural elements, including fundamental research with a place-based focus on coupled human-natural systems from an interdisciplinary, problem-driven perspective (Clark and Dickson 2003; Kates et al. 2011; Kumazawa et al. 2009).

Since the publication of the NRC report and Kates et al. (2001), research agendas and the institutional elements of a growing scientific field including the establishment of research and education institutions, dedicated peer-reviewed journals and various funding opportunities, have gained significant momentum. Early and ongoing efforts of sustainability scientists have been supported by several national and international scientific bodies, including the American Association for the Advancement of Science (AAAS) Forum on Science and Technology for Sustainability, the Roundtable on Science and Technology for Sustainability Program at the National Academy of Sciences, and the Initiative on Science and Technology for Sustainability and the Earth System Sustainability Initiative sponsored by the International Council of Science. Several peer-reviewed journals have emerged including *Sustainability Science*, *Sustainability: Science, Practice and Policy*; *International Journal of Sustainable Development*; and *Current Opinion in Environmental Sustainability*. Clark (2007) marked an especially important point in the development of the field with the establishment of a section devoted to sustainability science in the *Proceedings of the National Academy of Sciences*.

Several collaborative networks have also emerged to support sustainability science research throughout Europe, Asia and the United States; in particular, the European Sustainability Science Group, the Earth System Science Partnership and the Integrated Research System for Sustainability Science hosted by the University of Tokyo. Funding opportunities for sustainability research and education are also proliferating. For example, the United States National Science Foundation has established a crosscutting, program-wide investment area in Science, Engineering and Education for Sustainability (SEES), which includes several innovative opportunities for research and education funding including several large-scale, multi-year Sustainability Research Networks. Finally, research and education programs and centers are developing rapidly. These include the Global Institute of Sustainability and School of Sustainability at Arizona State University, the Center for Interactive Research on Sustainability at the University of British Columbia, Lund University Centre for Sustainability Studies (Sweden), the Center for International Development Sustainability Science Program at Harvard University, the Graduate Program in Sustainability Science at the University of Tokyo, the Institute for Sustainable Solutions at Portland State University, and the Sustainability Institute at Stellenbosch University in South Africa.

Analytical and methodological approach

Several recent studies have analyzed the structure of sustainability science (Bettencourt and Kaur 2011; Kajikawa et al. 2007; Schoolman et al. 2012; Yarime et al. 2010). Using bibliometric data, Schoolman et al. (2012) examined the extent to which sustainability science research draws from the three "pillars" of sustainability—environmental, economic and social sciences. They conclude that, while sustainability is more interdisciplinary than other fields, greater incentives are needed to enhance the ability of sustainability scientists to draw from multiple fields. Similarly, Bettencourt and Kaur (2011) analyze the geographic and disciplinary structure and evolution of sustainability science (which they define quite broadly). The authors argue that the field is fast-growing, as evidenced by an expanding and unifying network of collaboration and citation. With a slightly different focus, Wiek et al. (2011) present the results of a broad literature review on key competencies for sustainability science education and academic program development. Wiek et al. (2011) conclude that there is a convergent set of key competencies in sustainability science (e.g., systems thinking), but that there remains a need for theoretical justifications for why certain competencies are essential and empirical evidence illustrating their effectiveness in solving real-world problems.

While this study is ostensibly an analysis of sustainability science, it differs from this literature in three important ways. First, it takes a more qualitative approach to the study of sustainability science—utilizing in-depth interviews and a content analysis of the literature to explore the epistemic and normative reasoning behind the development of sustainability science research pathways. Secondly, this analysis draws heavily from science and technology studies (STS) in seeking to understand and interpret how sustainability scientists are bounding the normative, scientific and political dimensions of sustainability. The papers discussed above are focused more narrowly on the disciplinary structure and content of the field and do not draw on theories and insights from STS. Finally, following an initial analysis of the results, this study pivots to a more critical discussion about the development of sustainability science. It aims to ensure that the social, political and normative dimensions of sustainability are not prematurely settled by scientists and remain open to public debate and deliberation as sustainability is pursued in different contexts.

From the 1980 World Conservation Strategy to the Rio + 20 Earth Summit, scientists have played a crucial role in advancing conversations about sustainability. Science and technology have been positioned as key components of society's ability to move towards sustainability (however defined) (Jasanoff 1996; Sarewitz 1996). So too has science been shaped by the problems and concerns associated with sustainability as ecology, geography, environmental science, and many other disciplines move to conduct applied and use-inspired research (Lubchenco 1998; Stokes 1997; Palmer et al. 2004). In other words, science shapes, and is shaped by, sustainability. They co-produce one another (Jasanoff 2004, 2005; Latour 1993, 2004). As Jasanoff (2005, p 19) notes, "the products of the sciences, both cognitive and material, embody beliefs not only about how the world is, but also how it ought to be. Natural and social orders…are produced at one and the same time."

As scientists move to conduct research relevant to sustainability, they help to define sustainability. In selecting theories and problems for sustainability science, scientists shape the concept of sustainability in society more broadly. Scientists are often motivated by a desire to produce useful knowledge and a belief that access to the necessary knowledge will result in better decisions (Bocking 2004; Kinzig 2001; Lubchenco 1998; Palmer et al. 2005; Raven 2002) as well as a need to seek out the latest sources of funding (Braun 1998). The ways in which scientists construct the research agenda(s) for sustainability science will have implications for both the ability of the field to provide useful knowledge and for how sustainability is constituted in society. STS scholars are well positioned to offer an analysis of how sustainability science is taking shape, and the consequences for the field.

In this context, the concept of boundary work is particularly useful. Gieryn (1999, p 4) defines boundary work as "the discursive attribution of selected qualities to scientists, scientific methods, and scientific claims for the purpose of drawing a rhetorical boundary between science and some less authoritative residual non-science." For the purpose of this analysis, boundary work allows for an examination of how questions around the definition of sustainability, the emerging agendas for sustainability science and its relationship to society are being understood, articulated, bounded and settled by sustainability scientists. The concern is not on boundary work as the expulsion of rival authorities; rather, the focus is on the construction of epistemic authority through scientific discourse and knowledge and how sustainability scientists deploy this authority to control discussions of research goals and demarcate social, political and normative discussions as either settled or beyond the scope of their claim-making territory (Gieryn 1983, 1999).

Methodologically, this analysis follows Takacs' (1996) study of conservation biologists and biodiversity. Through interviews with leading figures in conservation, Takacs examines how they have defined, shaped and promoted the concept of biodiversity, including its normative character. In a similar fashion, the present analysis provides a rich description of how sustainability scientists are constructing sustainability science and how they envision the knowledge produced by the field contributing to society. In-depth interviews were conducted with 28 key researchers[1] in sustainability science between June 2009 and January 2010. Interview subjects were identified through their involvement in important developments in the sustainability science literature (including papers in *Science*, *Nature*, *Proceedings of the National Academy of Sciences* and *Sustainability Science* as well as major reports including *Our Common Journey* and the more recent US National Science Foundation funded *Toward a Science of Sustainability*), association with sustainability research programs (including the Sustainability Science Program at Harvard, the Stockholm Resilience Centre, and the Graduate Program in Sustainability Science at the University of Tokyo) and by key informants. While the list of interview subjects does not capture all of the major researchers in the field, it provides a robust sample with which to understand the major developments and perspectives in this young field. In addition to the interviews, a literature review of the leading journals (including *Science*, *Nature*, *Proceedings of the National Academy of Sciences* and *Sustainability Science*), reports, funding proposals and conference proceedings in the field was performed. These documents were analyzed for definitions of sustainability, construction of research agendas for sustainability science, and the role of sustainability in decision-making or social action.

This study has a few limitations. First, it focuses on developments in sustainability science in North America, Europe and Japan. Second, the analysis does not include a discussion of the role of technology in sustainability. This is a study of sustainability science, which, to this point, has not been engaged thoroughly with engineering and technology. In such a young and diverse field, choices must be made to bound the analysis and focus on recent developments in sustainability science in order to capture core arguments and perspectives.

Results: constructing sustainability science

Examining how sustainability scientists aim to define sustainability, contribute to sustainability efforts and how they attempt to translate knowledge into action can provide insight into how scientists might shape research agendas and their relationship to society going forward. In what follows, responses and analyses are grouped into themes that emerged in the interviews and literature review that serve to illustrate varying approaches to and implications for sustainability science. It is important to note that the following discussion does not attempt to group individual scientists as adhering to certain definitions; instead, the point is to analyze and discuss various definitions of sustainability that are motivating the development of research agendas and influencing the sustainability discourse. Furthermore, the categories discussed below should not be viewed as mutually exclusive or as having hard, definitive boundaries. The categories characterize major themes and perspective that are motivating the development of sustainability science.

Defining sustainability

In discussions on sustainability there is one question that is inevitably raised—"What is sustainability?" Follow up questions typically attempt to ask what is being sustained, for whom it is to be sustained, and for how long the good or process in question is to be sustained. The answers to such questions are anything but trivial and are value-laden (Norton 2005). As Beck (1992, p 174) observes, "…which interests they [scientists] select…on whom and what they project the causes, how they interpret the problems of society, what sort of potential solutions they bring into view—these are anything but neutral decisions."

The purpose of examining scientists' definitions of sustainability is not to refute or endorse one or another. In fact, during the course of an interview, some scientists discussed and endorsed multiple and, at times, conflicting definitions. Definitions of sustainability serve as an important point to analyze the performance of boundary work. Two primary themes emerged (which are defined below) in discussions on the meaning of sustainability: *universalist sustainability* and *procedural sustainability*.

[1] See supplementary material for list of interview subjects.

Importantly, each of these definitions involves normative notions of sustainability but with varying emphases and implications. How do scientists define sustainability? To what extent do scientists address these value-laden questions related to sustainability? How might this influence how society comes to define sustainability? What are the implications for the role of science in the sustainability discourse? How do they envision their research contributing to it? These are the questions that will be addressed in the following discussion.

Universalist sustainability

Many of the interview subjects and much of the literature refer, perhaps not unsurprisingly, to one of two definitions—those put forth by the WCED (1987) and the NRC report. Parris and Kates (2003, p 8068), for example, define a transition to sustainability as "stabilizing world population, meeting its needs and reducing poverty and hunger while maintaining the planet's life support systems." Similarly, a report from the Third World Academy of Sciences (Hassan 2001, p 70) defines sustainability as "meeting current human needs while preserving the environment and natural resources needed by future generations." Carl Folke sums this perspective up nicely: "How can we develop and continue to improve human well-being and our life as a species on [this] planet…? That's really what sustainability is about for me."[2] I refer to this set of definitions as *universalist (or thin) sustainability*—meeting human needs, both now and in the future, without degrading the planet's life support systems. This is echoed in recent work on planetary boundaries (Rockström et al. 2009) and Earth systems science (Reid et al. 2010).

Political theorist Michael Walzer (1994) uses "thin morality"[3] or "moral minimalism" to describe concepts that encourage widespread agreement but do not translate substantively to the level of individual behavior changes nor conflict with more contextual notions of what is moral or desirable. Thin morality is universalist. For example, Walzer notes that virtually every human society can agree that the idea of justice is one worth pursuing; however, what justice looks like in various places or contexts can be very different and even conflicting. This does not mean that thin or morally minimal descriptions of justice are meaningless or morally shallow. Instead, thin morality can assume a deeply compelling character as it consists of moral notions on which all can agree. It is this universalism that has allowed thin sustainability to gain traction in both science and society. As Thomas Parris notes, the NRC definition "was chosen… intentionally as a minimalist definition. It's the part that everybody can agree on."[4]

It is worth highlighting that each of these definitions is anthropocentric or human-centered. For example, McMichael et al. (2003, p 1919) define sustainability as "transforming our ways of living to maximize the chances that environmental and social conditions will indefinitely support human security and well-being." At the core of sustainability is a concern that current human activities and their effects on the environment are undercutting the ability of that environment to support the well-being of both current and future generations. "Despite the awe in which we hold nature and the value we place on its conservation," argues Clark (2010, p 82), "ours is ultimately a project that seeks to understand what is, can be, and ought to be the human use of the Earth."

Thin sustainability serves as a general normative frame, or as Jan Rotmans notes, a "normative orientation,"[5] for sustainability scientists. It is both a source of motivation and a normative goal for research. Sustainability scientists are able to tap into the moral underpinnings of sustainability to express concern for the impacts of human activity and justify research agendas (more on this latter point in the following section). Moral minimalism "is everyone's morality because it is no one's in particular; subjective interest and cultural expression have been avoided or cut away" (Walzer 1994, p 7). So too is science perceived by many scientists and the public as universalist, objective and free of cultural context. A sustainability from which "subjective interest and cultural expression [has] been avoided or cut away" reinforces this image of science and maintains its authoritative role in society (Collingridge and Reeve 1986; Jasanoff 1987).

"Thick morality" or "moral maximalism," on the other hand, is contextual and embedded in a certain place or unique to a certain people. Maximalism "is idiomatic, particularist, and circumstantial…[it] is the socially constructed idealism of *these* people" (Walzer 1994, p 39). Norton (2005) picks up on this, arguing that sustainability has the potential for constructing an improved language for discussion of environmental problems because it is both descriptive and evaluative—i.e., it is a "thick" concept that can (1) encapsulate a great deal of information, and (2) present that information in a way that makes explicit its importance to widely held social values. Sustainability scientists have embraced thin sustainability and its universalism, limiting the degree to which deeper discussions over a "thick sustainability" and the role of science take

[2] Carl Folke, Interview, 30 September 2009.

[3] Walzer borrows this term from Geertz's (1973) "thick description." Walzer's (1994,p xi) aim, however, is not to present a thick description of moral argument but to refer to argument that is thick—"richly referential, culturally resonant, locked into locally established symbolic systems or network of meanings.".

[4] Thomas Parris, Interview, 8 July 2009.

[5] Jan Rotmans, Interview, 24 November 2009.

place. Furthermore, as Jamieson (1995, 1998) notes, attempts to provide scientific or technical definitions for highly normative concepts, such as sustainability or ecosystem health, often result in a circumvention of ethical and political issues or lead to a bedeviled debate in which ethical, political and scientific issues are confused.

The values of sustainability motivate scientists. At the same time, scientists are careful to control the degree to which such values infiltrate science. Parris and Kates (2003, p 8068), for instance, believe that "defining sustainability is ultimately a social choice about what to develop, what to sustain, and for how long." Pam Matson separates the values of society from the values of the scientist:

> …the values are the values of the decision makers. And, of course, scientists all have their own value systems, too. And mine would say…meeting the needs of people while protecting the life support systems of the planet. I'm including the ecosystems and the species within them, on land and in the oceans, because I think they provide all of the [ecosystem] services that we need.[6]

Boundaries are drawn between the personal values and those that might influence the way society and decision-makers understand sustainability. The values and motivations of scientists and sustainability science are acknowledged but at a level that is universal. It is "everyone's morality because it is no one's in particular" (Walzer 1994, p 7).

The context and conflict that come with thickness are absent in thin sustainability. "With thickness," notes Walzer (1994, p 6), "comes qualification, compromise, complexity, and disagreement." Parris again notes that there is a reason for choosing a thin definition of sustainability: "It's the part that everyone can agree on… The point is that there's a core…because people don't universally agree to the various additional layers that people add on to it…"[7] By embracing a universal sustainability, scientists are able to avoid opening up an arena in which the role of science and the knowledge produced by scientists may be contested along with other components of sustainability.

Procedural sustainability

The National Research Council (1999, p 48) also notes that sustainability is a "process of social learning and adaptive response amidst turbulence and surprise." This way of defining sustainability is referred to as *procedural sustainability*—a methodological-oriented approach that focuses on how sustainability comes to be defined and how pathways are developed to pursue it.

John Robinson provides perhaps the most succinct explanation of this view and the difference between universalist and procedural sustainability:

> I have two answers [to the question of how I define sustainability]: a substantive one and a procedural one. The *substantive* one is a version of the many-legged stool approach that's very common. So I like thinking of sustainability as the reconciliation of three imperatives: ecological imperative [to] stay within…physical carrying capacity, an economic imperative to provide adequate material standard of living for all, and a social imperative to provide systems of governance that propagate the values people want to live by… But my preferred definition is the *procedural* one because I think those substantive ones are fine, but they just sort of lay out domains. The procedural one is that sustainability is the emergent property of a discussion about desired futures that's informed by some understanding of the ecological, social, and economic consequences of different courses of action. (emphasis added).[8]

Rather than being defined in thin, universalist terms, sustainability is defined through a participatory or democratic process contingent on place and time.[9] As Norton (2005, p 335) argues, "…the problem of how to measure sustainability… is logically subsequent to the prior question of what commitments the relevant community is willing to make to protect a natural and cultural legacy."

Rotmans, the former Director of the Dutch Research Institute for Transitions (DRIFT), also makes a case for procedural sustainability (while still embracing the normative orientation of a universalist understanding):

> [Sustainability] is very context dependent…[I]n practical environments, my opinion is that what is sustainable is defined by the stakeholders that will be involved in this process… It means that it might be different in Rotterdam than in Amsterdam… [I]t's more the process itself where…you are continually making tradeoffs in time, and in space, and in domains, and if you do that systematically and continuously, then the outcome for me doesn't matter as much as the process itself.[10]

[6] Pam Matson, Interview, 26 September 2009.

[7] Thomas Parris, Interview, 8 July 2009.

[8] John Robinson, Interview, 5 October 2009.

[9] How this process is shaped, by whom and who is included are important issues involving deliberative ideals and procedural justice that will influence how sustainability comes to be defined. These issues are, however, beyond the scope of this paper.

[10] Jan Rotmans, Interview, 24 November 2009.

This is different from the participation of stakeholders in scientific research or the process of linking knowledge to action, which will be discussed below. Procedural sustainability has to do with an understanding of sustainability as a process for identifying important societal values and pathways for a desirable future. It emphasizes difference and context rather than agreement on a broad definition. It is not that procedural sustainability is in opposition to thin sustainability; rather, a thin definition is only useful insofar as it aids in the process of developing a contextual understanding of sustainability in a certain place or community.

Research agendas

Regardless of the way scientists define sustainability, there is widespread agreement (Lubchenco 1998; Palmer et al. 2004; Levin and Clark 2010) that science should contribute to sustainability efforts—"promoting the goal of sustainability requires the emergence and conduct of the new field of sustainability science" (Friiberg 2000, p 1). Two major themes in the construction of research agendas for sustainability are the *coupled systems approach* and the *social change approach*.

Coupled systems approach

The coupled systems approach is focused on producing knowledge about "the complex dynamics that arise from interactions between human and environmental systems" (Clark 2007, p 1737). Sustainability science "seeks to understand the fundamental character of interactions between nature and society" (Kates et al. 2001, p 641). As Carpenter et al. (2009, p 1305) note, it is "motivated by fundamental questions about interactions of nature and society as well as compelling and urgent social needs." Likewise, Turner et al. (2003a, p 8080) argue "sustainability science seeks understanding of the coupled human-environment system in ways that are useful to the different communities of stakeholders." This set of research agendas is referred to as the *coupled systems* approach to sustainability science. In its broadest sense, as Turner says, "anything that fits under the rubric of how humankind is altering the basic structure and function of the Earth's system…is a critical problem that ought to be studied."[11] The role of sustainability science, argues Parris, is in "understanding how it [the human-environment system] functions."[12] Similarly, Elinor Ostrom contends that sustainability science should be concerned with "developing rigorous methods for analyzing complex systems over time."[13]

The coupled systems approach has several important implications for regarding boundary work both within science and with its relationship to sustainability in society. It positions research on coupled human-natural systems as critical to efforts to move towards sustainability. For example, Clark (2010, p 82) states that "the *core* of sustainability science lies in seeking to understand how society's efforts to promote a transition toward sustainability are constrained or promoted by the interactions between human and environmental systems" (emphasis original). In order to adequately address the problems of sustainability, fundamental knowledge about the dynamics of coupled human–natural systems[14] is required (Ostrom 2009).

Clark (2010, p 82) views sustainability science as problem-oriented yet grounded by a search for fundamental understanding of human–environment systems:

> Like 'agricultural science' and 'health science' before it, sustainability science is a field defined by the problems it addresses rather than the disciplines or methods it employs. For us, those problems are defined as the challenges of promoting a transition toward sustainability—improving human well-being while conserving the Earth's life support systems over appropriate time and space scales. Sustainability science then draws from—and seeks to advance—those aspects of our understanding of human systems, environmental systems and their interactions that are useful for helping people achieve sustainability goals.

This knowledge is produced in conjunction with stakeholders so that it is not just reliable but also salient, legitimate and trustworthy and thus most likely to assist society in transitioning to sustainability (Cash et al. 2006; Clark and Dickson 2003; Kates et al. 2001; National Research Council 1999).

However, as Matson noted in her interview, though "a lot of progress has been made [in understanding life support systems]…there is going to be a lot more [research] needed in decision science, in behavioral research."[15] Knowledge of coupled human–natural systems is viewed as a limiting factor to action. Part of the mission of sustainability science is to determine what knowledge is needed. This is done based on a better understanding of decision-making and perceptions. How and why this knowledge is

[11] B.L. Turner III, Interview, 5 June 2009.

[12] Thomas Parris, Interview, 8 July 2009.

[13] Elinor Ostrom, Interview, 30 September 2009.

[14] Coupled human-natural systems are also referred to as human–environment or social–ecological systems. Broadly, they can be defined as "integrated systems in which people interact with natural components" (Liu et al. 2007, p 1513).

[15] Pam Matson, Interview, 26 September 2009.

linked to societal action and the implications will be discussed in further detail in the following section.

Social change approach

Sustainability science, according to Jäger, "is very much about process and very much about dialogue…it's a process for social change, learning, and transitions."[16] It should "drive societal learning and change processes" and focus "on the design and running of processes linking knowledge with action to deal with persistent problems of unsustainability and to foster transitions to sustainability" (Jäger 2009, p 3). This can be referred to as the *social change approach* to sustainability science.

The social change approach seeks to construct, inform and study processes for defining and pursuing sustainability. Rather than producing knowledge about underlying dynamics that are sustainable or unsustainable, it both participates in and produces knowledge about the processes of sustainability transitions. Raskin argues that we must focus on "the ultimate drivers" that cause unsustainability or that might result in positive action—"culture, power, politics and values."[17] Following the notion of procedural sustainability discussed earlier, Swart et al. (2004, p 138) argue that sustainability science must "emphasize the need to develop approaches for evaluating future options, recognizing diverse epistemologies and problem definitions, and encompassing the deeply normative nature of the sustainability problem."

The social change approach is envisioned by some scientists as a mode of governance. The field of transitions management highlights this issue. Loorbach and Rotmans (2009, p 3) define transitions management as "a deliberative process to influence governance activities in such a way that they lead to accelerated change directed towards sustainability ambitions." Loorbach (2007, p 18) defines a transition "as a continuous process of societal change whereby the structure of society (or a subsystem of society) changes fundamentally." Transitions management is a form of meta-governance—"how do we influence, coordinate and bring together actors and their activities in such a way that they reinforce each other to such an extent that they can compete with dominant actors and practices?" (Loorbach and Rotmans 2009, p 3).

This approach is concerned with how sectors of society or certain communities define sustainability in context, the process that facilitates a dialogue about this as well as the strategies that might be pursued to meet the goals that are set. While not always referred to as sustainability science by its adherents, it too is stakeholder-oriented, interdisciplinary and incorporates a systems perspective. The social change approach potentially creates a privileged role for science as a designer of and key participant in procedural sustainability. Epistemic authority emanates from knowledge shared and developed through the process of transitions management rather than knowledge about underlying system dynamics. It should, however, be noted that in focusing on the process it is recognized that there is a continual negotiation between actors about goals, knowledge and strategy for action. The social change approach creates a space for sustainability science as necessary to procedural sustainability as part of the process and as a source of knowledge on how to design an effective process.

Linking knowledge to action

Whether sustainability scientists are producing knowledge about complex coupled human–natural system dynamics or about sustainability transition management processes, in each case science is a knowledge provider. But the role of knowledge in society, how it is developed and deployed, and how scientific knowledge is viewed relative to other types of knowledge is complicated. How might scientific knowledge help society solve problems and create solutions that will help a transition to sustainability?

Building on the previous discussions, this section analyzes how scientists envision the knowledge produced by sustainability science contributing to society. Two broad themes emerged: the *knowledge-first* approach and the *process-oriented* approach.

Knowledge-first approach

Cash et al. (2003, p 8089) argue that, without drastically increasing the contribution of science and technology, "it seems unlikely that the transition to sustainability will be either fast or far enough to prevent significant degradation of human life or the earth system." Carpenter et al. (2009, p 1305) contend that "compelling and urgent social needs" stress "the urgency and importance of accelerated effort to understand the dynamics of coupled human-natural systems." Sustainability science performs fundamental research on problems identified by society which, scientists argue, will help move towards solutions. I refer to this vision of the role of science in society as the *knowledge-first-approach*; i.e., "science characterizes problems in terms of their causes and mechanisms as basis for subsequent action" (Sarewitz et al. 2010, p 1).

As Matson (2009, p 41) notes, "the purposeful intent [of sustainability science is] to link knowledge to action. Much of sustainability science is hard-core fundamental research, but the field is essentially use-inspired and oriented toward

[16] Jill Jäger, Interview, 18 November 2009.

[17] Paul Raskin, Interview, 17 December 2009.

decision-making of all kinds." Sustainability science, says Matson, can "help make better decisions" but there has to be a "pull" from decision-makers.[18] That is, decision-makers have to signal to scientists what kind of information is needed to make better decisions. Simon Levin, for example, notes that scientists have "no special expertise to deal with ethics, and certainly not with politics, so I see the role of scientists as not making decisions, but as informing decision-makers."[19] Part of this process, then, is finding out what decision-makers need.

Knowledge, it is argued, must be co-produced with stakeholders and decision-makers (van Kerkhoff and Lebel 2006). Co-production is not used in the same sense here as Jasanoff (2004) and others use the term. Co-production of knowledge in the case of sustainability science refers to the act of producing information "through the collaboration with scientists and engineers and nonscientists, who incorporate values and criteria from both communities" (Cash et al. 2006, p 467). Organizing and facilitating co-production of knowledge at the interface of science and society is referred to as boundary management (Cash et al. 2003). These actions are meant to ensure the salience, credibility and legitimacy of the knowledge produced.

The knowledge-first approach views the problem of sustainability as a problem of decision-makers not using available knowledge due to lack of credibility or legitimacy, having insufficient knowledge or not having knowledge about the necessary aspects of the system (salience). If sustainability science can provide the knowledge that is needed about coupled system dynamics, for example, then better and more informed decisions may be made (i.e., decisions that will move society towards sustainability).

As both "basic" and "applied," knowledge-first sustainability science creates a boundary zone (see Fig. 1) where it justifies its usefulness to society and decision-making for sustainability while maintaining epistemic authority by keeping its core research fundamental and free of values. As Kristjanson et al. (2009, p 5049) conclude, "there is certainly a role in sustainability science for both traditional, curiosity-driven research and for context-specific problem solving— so long as both are conducted within a larger framework that ensures rigor and usefulness."

Clark, for example, links sustainability to the political project of how we ought to use the Earth while making clear that it is through scientific understanding that proper use can be determined:

> Despite the awe in which we hold nature and the value we place on its conservation, ours is ultimately a project that seeks to understand what is, can be, and ought to be the human use of the Earth. We pursue this goal, however, in the conviction that what is possible and desirable for people can only be understood through an appreciation of the *interactions* between social and environmental systems. (Clark 2010, p 82; emphasis in original).

The knowledge-first approach attempts to be both free of and concerned with affecting values and politics. Sustainability scientists attempt to externalize the potential risk politics (i.e., how to determine what ought to be the proper human use of the Earth) pose to the epistemic core of sustainability science, while at the same time claiming to produce the knowledge that was heretofore limiting societal action.

Process-oriented approach

Olsson argues that sustainability science can be called "action research or…social intervention research…[where scientists] intervene and then that intervention becomes [a subject] of study… [R]ather than…simply understanding…how do you actually feed into [the intervention]?"[20] Here, the focus is on setting up, participating in and conducting research on social and technological processes attempting to define and move towards sustainability. I refer to this approach as the *process-oriented* approach.

In some instances, the process-oriented approach goes beyond collaborative or participatory research to facilitating or actively participating in what Rotmans calls "arenas for change or transition." For example, in the field of transitions management, a "transition arena" is created where this work takes place. Loorbach and Rotmans (2009, p 7) define a transition arena as an "informal network…within which a group process unfolds, often in an unplanned and unforeseen way." These arenas are sites for boundary management and joint knowledge production by scientists, decision-makers and other stakeholders (Kemp and Rotmans 2009).

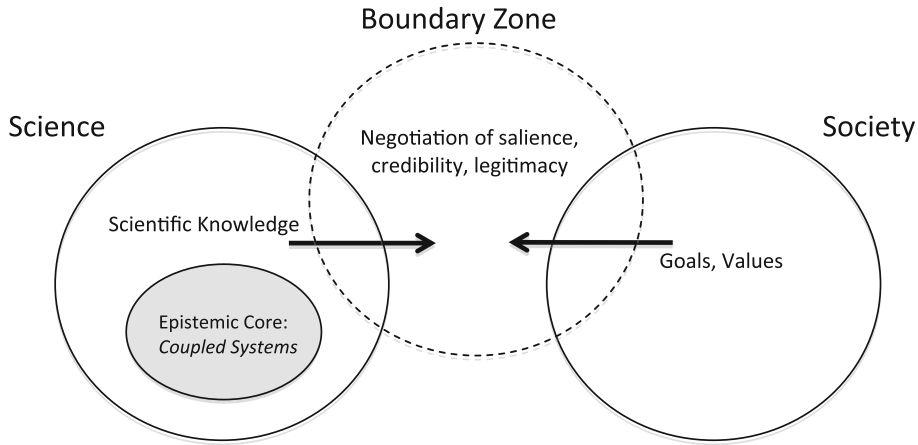
The aim of boundary work in this case is not necessarily to ensure that knowledge produced about coupled human-natural systems will be salient, credible and legitimate; rather, it is to facilitate a process for determining multiple trajectories for a transition and continual, mutual learning (Kemp and Rotmans 2009). There is an active role for science and scientists in establishing, facilitating and participating in mechanisms or dialogue for change as

[18] Pam Matson, Interview, 26 September 2009.

[19] Simon Levin, Interview, 16 December 2009.

[20] Lennart Olsson, Interview, 30 October 2009.

Fig. 1 Relationship between knowledge-first sustainability science and society



opposed to simply providing knowledge from a more removed position.

Like the knowledge-first approach, science still acts as a knowledge provider in the process-oriented approach. "Science is still playing a big role in that first of all it's a knowledge provider," says Jäger, "but not the only knowledge provider."[21] Robinson makes a similar point—"Science plays the crucial role of providing some of the information about consequences and tradeoffs associated with difference choices, but it doesn't tell us anything about where we want to be. That has to emerge from discussion…We [scientists] want to engage them as citizens of part of a collective."[22] The role of science is to help society or communities deliberate over what sustainability might look like and how communities might move towards it. Both the knowledge-first and the process-oriented approaches are concerned with assisting a sustainability transition by producing credible knowledge. Most sustainability scientists acknowledge the importance of working with stakeholders so that science can provide useful information. However, how they envision the type of knowledge needed and the role of that knowledge in assisting society is quite different.

David Kriebel, co-Director of the Lowell Center for Sustainable Production, cautions that "[scientists] have to be aware not to allow the need to fully characterize the system delay action." Kriebel believes that it's important to make a "distinction between the system in which the problem occurs and the system in which the solution occurs."[23] By focusing on where the solution may occur, he argues, the conversation shifts from a scientific characterization of the system to the social, political, economic and technological processes involved in formulating a desirable outcome. In Jäger's words, "it's trying to find ways to get things done."[24]

In response to a question on the role of sustainability science in society, Robinson asks, "Who needs to know the science?" He sketches three potential ways in which scientists might seek to help society move towards sustainability. The first potential method would be to use guilt to pressure individuals into changing their behavior, which, he notes, has not been terribly successful thus far. A second would be "to do a brilliant analysis, and it's so compelling and convincing that when we give it to policy makers, they change everything." In his own experience, however, Robinson argues that the role of science "has to be [in] a conversation where various forms of certified knowledge are brought together with various ethical and normative views of citizens…in an exploration of where we want to be in the future."[25]

The process-oriented approach at once creates a space for science as a source of credible knowledge and limits its own epistemic authority by acknowledging that it is just one source of such knowledge among many. Scientific analysis is focused broadly on the process of envisioning and pursuing pathways to sustainability (e.g., Robinson and Tansey 2006). Rather than knowledge acting as the limiting factor in the ability to make decisions, it is a matter of constructing a social process in which various forms of credible knowledge, perspectives and values can come together to define sustainability (Table 1). This creates a more open discourse about what sustainability is and how a given community might move towards it (see Fig. 2). The process-oriented approach is more concerned with exploring pathways to sustainability, than with maintaining a core program of fundamental research.

21 Jill Jäger, Interview, 18 November 2009.

22 John Robinson, Interview, 5 October 2009.

23 David Kriebel, Interview, 16 November 2009.

24 Jill Jäger, Interview, 18 November 2009.

25 John Robinson, Interview, 5 October 2009.

Table 1 Summary of sustainability science approaches

Defining sustainability	Universalist	Procedural
	Normative frame	Defining as process
	Universal values	Values of community
	"Value-free" science	Contextual
Research agendas	Coupled systems	Social Change
	Fundamental research	Action research
	Social needs	Processes of transitions
	Co-production	Participant
Linking knowledge to action	Knowledge-first	Process-Oriented
	Problem space	Social intervention
	Salient, credible, legitimate knowledge	Beyond understanding
	Knowledge provider	Facilitate and participate in process

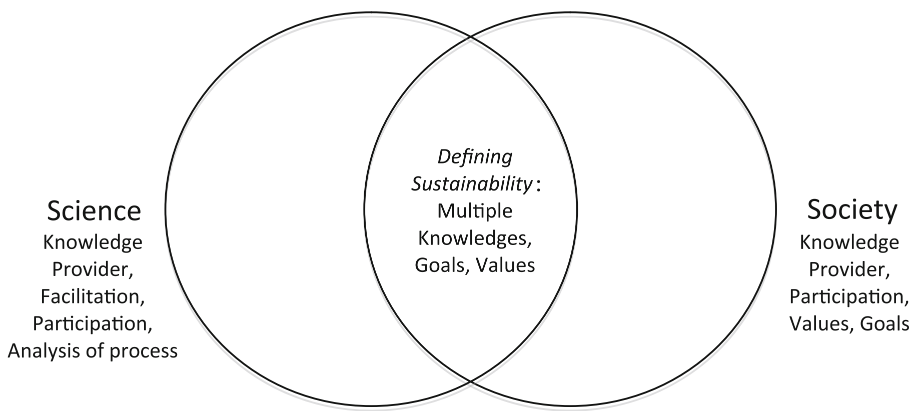


Fig. 2 Relationship between process-oriented approach to sustainability science and society

Discussion: bounding sustainability

In both the universalist and procedural definitions of sustainability, scientists are carving out a role for science and shaping the way society might understand sustainability. For thin sustainability, a universal understanding of sustainability is complemented by the universal applicability of science—"the only universal discourse available in a multiply fragmented world" (Jasanoff 1996, p 173). This limits debate not just over the appropriate or effective role of science but also important social, political and cultural debates over the nature of sustainability, especially in specific contexts. There is a tension between sustainability and sustainability science. A thick sustainability is necessarily contextual, contested and qualified while sustainability science, and science more broadly, often strives for universalism and consensus.

As Jamieson (1998, p 189) argues, at this universal level "there is too little by way of shared beliefs and values to provide enough content to ideas of sustainability to make them effective." Procedural sustainability, on the other hand, attempts to identify social values that are important for sustainability that will result in action. According to Norton (2005, p 405), the question that a more procedural sustainability can help address is, "How can diverse, democratic communities develop procedures that encourage cooperative action to protect their environment?" Considered in light of procedural sustainability, the process-oriented approach to the relationship between science and society establishes a dual role of science as both participant and observer of the procedures Norton proposes.

Key concepts in sustainability science, such as risk and vulnerability (Turner et al. 2003a, b), tipping points (Scheffer et al. 2009; Schellnhuber 2009), planetary boundaries (Reid et al. 2010), and even defining the boundaries and interactions between human and natural systems, are suffused with values. The act of defining aspects of a wicked problem for scientific inquiry is inherently value-laden, with implications for democratic problem-solving and the pursuit of potential solutions (Fischer 2000; Latour 2004). The epistemic power of science, especially when presented or perceived as value-free, can come to dominate normative and political concerns (Douglas 2009; Latour 2004; Sarewitz 2004). The normative limitation of sustainability science is in its potential inability to recognize the degree to which supposedly value-free science is in fact value-laden and how scientific analyses can influence necessary and important political debates in society in complex ways. The challenge is to construct a science that is able to convey important information in a way that allows a plurality of values and understandings to emerge (Leach et al. 2010; Miller 2011).

In order to address the problems of sustainability, Cash et al. (2003) urge that society "harness the power of science and technology." Both the coupled systems and social change approaches to sustainability make "compelling arguments for why science is uniquely best as a provider of trustworthy knowledge, and compelling narratives for why [their] science is bona fide" (Gieryn 1999, p 4). The coupled systems approach does this by maintaining a core of basic science while conceding that it must also be applied in order to link knowledge to action. The social change approach is more critical of the usefulness of science, yet it carefully maintains a space as part of societal processes that define sustainability and as uniquely positioned to analyze such processes.

Scientists, particularly in the coupled systems approach, seek to establish their epistemic authority over facts about the sustainability of system dynamics and its usefulness in decision-making. At the same time, they both cite thin sustainability as a normative goal or motivation, and establish normative discussions as outside of the realm of hard-core science. Boundary work performed by sustainability scientists delineates the analysis of coupled human–natural systems as the scientific purview of sustainability science. Given the complexity of these systems, science is relied upon to reveal and translate for society. This leads to the second act of boundary work—sustainability scientists imagine the effective pursuit of sustainability as in need of fundamental knowledge about coupled systems that sustainability science provides. However, as Sagoff (2008) warns, there is a danger in relying too heavily on science in areas that he argues are of ethical concern. For example, Sagoff (2008, p 207) argues that environmental science "presents nature as a system for interdisciplinary scientists to model and administer for the collective good rather than as an object for moral instruction and aesthetic appreciation for every individual."

Many sustainability problems present deep challenges to traditional scientific analyses and the role of science in society. Sustainability problems can often be classified as wicked problems—defined by high complexity, uncertainty, and contested social values (Funtowicz and Ravetz 1993; Rittel and Webber 1973). Traditional modes of inquiry are unable to produce knowledge that is robust enough to withstand contested values and high complexity. In fact, such problems are often characterized by multiple conflicting and equally valid scientific and social interpretations (Collingridge and Reeve 1986; Grunwald 2007; Sarewitz 2004).

This limitation, then, is not just epistemic, but sociopolitical. Epistemologically, the very idea that science can produce authoritative or reliable knowledge about complex and contested phenomena has been challenged (Funtowicz and Ravetz 1993; Nowotny et al. 2001). At the same time, the reliability and usefulness of scientific knowledge in society and in decision-making contexts has been called into question. The scientific norms and epistemic values governing scientific practice have not evolved to deal with wicked problems and arenas in which the validity of scientific knowledge is challenged outside of the laboratory (Crow 2007; Funtowicz and Ravetz 1993; Gibbons 1999).

Sustainability science, in such cases, is unlikely to reduce uncertainty or provide a common foundation for social action. Such difficulties in the ability of science to inform decision-making often get attributed to social and political factors such as the public understanding of science or the politicization of science (Bäckstrand 2003; Sarewitz 2010; Wynne 1996). However, as Ludwig et al. (1993) argue, it is likely that sustainability science will never reach consensus regarding causal mechanisms and dynamics of complex coupled human-natural systems.[26] More importantly, even if one were to grant that consensus in the scientific community is possible, meaningful social or political consensus on an understanding of an issue or a course of action is unlikely (Blackstock and Carter 2007; Schwarz and Thompson 1990). This has as much, if not more, to do with the epistemic practices of science and the wicked nature of sustainability problems than it does with any perceived problems in the ability of decision-makers to incorporate scientific knowledge into their decisions.

To the extent that sustainability problems become settled, it will be a social and political effort of which science is but a part. Sustainability and its problems cut across disciplinary boundaries and defy both problem definition and easy solutions; they challenge not just the analytical tools and approaches of scientists but the usefulness of scientific knowledge. As Nelson (2003) notes, this is not a comment on the quality of research in fields such as sustainability science. Instead, it is related to limitations of the ability of scientific research to advance action in areas that are highly social and contextual.

[26] The scientific consensus on climate change may seem to counter this claim. However, the consensus on the basic mechanisms behind climate change has not translated into concerted social action. STS research has shown that this consensus is fragile and hides significant and legitimate differences. The ability to achieve consensus is driven by social norms and processes, as well as institutional configurations (Jasanoff and Wynne 1998; Miller 2004). As recent events such as "Climate Gate" have shown, such consensus is liable to be re-opened and challenged, providing a glimpse into the social, political and normative dimensions of scientific knowledge-making. This has as much if not more to do with social norms of scientific communities and institutions and political consensus as it does with the strength of scientific findings (Hulme 2010; Jasanoff 2010).

Conclusion

Sustainability presents a unique set of epistemic, normative and institutional challenges to science and its ability to contribute to positive, more sustainable social and environmental outcomes. Insights from STS and the concept of boundary work, more specifically, have been used to "open up" the various approaches to sustainability science and their implications. In so doing, this analysis presents the opportunity to navigate the issues discussed above. The question then is how is sustainability science to be positioned to assist society in a sustainability transition?

This paper is not meant to give a definitive answer to this query. It should also be noted that the evolution of sustainability science has been the result of coordinated efforts on the part of scientists and other stakeholders and should not be taken lightly. This analysis, however, while reviewing the development of the field also offers an opportunity to continue this dialogue in new directions. Where, for example, is scientific knowledge a limiting factor in decision-making? Where will fundamental understanding of human-natural systems enhance our capacity to make decisions? What are other factors that are limiting decision-making and how will knowledge produced by sustainability scientists affect that context? How is science to be engaged in the social, political, and ethical components of sustainability while maintaining its ability to provide credible knowledge where needed? What can the approaches outlined here offer each other? These questions must be addressed by scientists and society more broadly if sustainability science and related inquiry are to proceed effectively. By exploring (1) how sustainability scientists define and bound sustainability, (2) how and why research agendas are being constructed to address these notions of sustainability, (3) and how scientists see their research contributing to societal efforts to move toward sustainability, it is hoped that this paper can serve as a platform to invigorate an open and more reflexive dialogue on future directions in the field.

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