Sustain Sci (2015) 10:17–31
DOI 10.1007/s11625-014-0261-9

ORIGINAL ARTICLE

Sustainability science in action: a review of the state of the field through case studies on disaster recovery, bioenergy, and precautionary purchasing

Arnim Wiek · John Harlow · Rob Melnick · Sander van der Leeuw · Kensuke Fukushi · Kazuhiko Takeuchi · Francesca Farioli · Francis Yamba · Ann Blake · Chris Geiger · Robert Kutter

Received: 21 June 2013 / Accepted: 30 July 2014 / Published online: 15 August 2014

Abstract Sustainability science still struggles with transitioning from problem-focused to solution-oriented endeavors that yield positive impacts on mitigating sustainability challenges. This article presents and compares three sustainability science studies on the reconstruction after the 2011 triple-disaster in Japan; limited energy and livelihood options in rural Africa; and toxic chemical dispersion in San Francisco. Research varied in design and conduct, with opportunities for improvement in transdisciplinary collaboration, institutional incentives and rewards, competency development in future researchers, articulation of relevant political economies, and orientation towards feasible solution options. Of particular interest are insights synthesized across the cases, mainly success factors and their transferability, sustainability science pedagogical opportunities, and potential future research areas. These insights emerged from presentations and breakout discussions of the three studies at the 2012 International Conference on Sustainability Science held at Arizona State University.

Keywords Sustainability science · Disasters · Urban sustainability · Bioenergy · Precautionary purchasing · Developing countries

Introduction

Sustainability challenges threaten the long-term viability and integrity of societies and species worldwide, as they often exceed the collective problem-solving capacities of

Handled by Fabrice Renaud, UNU-Institute for Environment and Human Security (EHS), Germany.

A. Wiek (✉) · J. Harlow · R. Melnick · S. van der Leeuw · R. Kutter
Arizona State University, School of Sustainability, Tempe, AZ, USA
e-mail: arnim.wiek@asu.edu

S. van der Leeuw
Arizona State University, School of Human Evolution and Social Change, Tempe, AZ, USA

K. Fukushi · K. Takeuchi
The University of Tokyo, Integrated Research System for Sustainability Science, Tokyo, Japan

K. Takeuchi
United Nations University, Institute for Sustainability and Peace, Tokyo, Japan

F. Farioli
Sapienza University of Rome, Interuniversity Research Centre for Sustainable Development, Rome, Italy

F. Farioli
Department of Mechanical Engineering, Sapienza University of Rome, Rome, Italy

F. Yamba
Centre for Energy, Environment and Engineering Zambia (CEEZ), Lusaka, Zambia

A. Blake
Environmental and Public Health Consulting, Alameda, CA, USA

C. Geiger
San Francisco Department of the Environment, Toxics Reduction Program, San Francisco, CA, USA

governments, businesses, and civil societies (Kates et al. 2001; Clark and Dickson 2003; Spangenberg 2011). Ranging from high-risk technology disasters to persistent poverty, violent conflicts, and overconsumption of public goods in industrialized nations and industrializing, sustainability challenges call for profound changes in natural resource management, conflict resolution, the conduct of business, the valuation of consumer goods, and the process of technological innovation. In short, transformational change has become a necessary condition for a sustainable future for societies around the globe (Chapin et al. 2011; Van der Leeuw et al. 2012).

Sustainability science, since its inception a decade ago (Kates et al. 2001), has made significant strides in better understanding the structures and features of urgent and complex sustainability challenges. This has mainly led to more descriptive knowledge, as opposed to the transformational changes and widely applicable solution options to which the field aspires. Yet, sustainability science is slowly developing a stronger commitment to research on feasible, effective, and efficient solution options to address sustainability challenges (Chapin et al. 2011; Sarewitz et al. 2012; Wiek et al. 2012b). This commitment requires novel institutional support for and methods of research and education (Crow 2012; Van der Leeuw et al. 2012).

Solution-focused approaches differ from and build on the conventional academic triumvirate of descriptive (vs. design) research, classroom (vs. real-world) pedagogy, and publication-centered (vs. impact-centered) reward structures (Wiek et al. 2012c). Transformational sustainability research coordinates collaborative efforts that lead to lasting solutions (instead of turning into the next set of academic problems to be studied). Sustainability science education empowers students to be visionary, creative, and rigorous leaders and participants in the transition toward a sustainable world (Komiyama and Takeuchi 2006; Crow 2010).

This article reviews three case studies of sustainability science projects intended to provide and support real-world solutions to demanding sustainability challenges. The three case studies address: the recovery from the Great Eastern Japan earthquake; the development of bioenergy in Africa; and, precautionary purchasing in San Francisco. Similar to previously conducted comparative studies (Blackstock and Carter 2007; Wiek et al. 2012b), the case studies offer the opportunity to reflect on the accomplishments and pitfalls of current sustainability science research, as well as critical factors such as collaborative efforts between science and society, institutional contexts, educational opportunities, as well as power and politics in sustainability science.

The article is based on several years of research in the individual projects as well as the working sessions of the 3rd International Conference on Sustainability Science, which took place in Tempe, Arizona, on February 20–23, 2012 (Wiek et al. 2012c). The presented results are intended to offer insights on novel and inspiring research approaches, partnerships, and institutional structures that have begun to coalesce into a rich platform for sustainability science research and education at universities and other organizations around the world.

Research design

The three individual case studies reviewed below have the following units of analysis (Yin 1994): the sustainability challenge addressed, solution options explored, and open issues (further research needed)—specified for each case. They follow different research designs, which are detailed elsewhere (Yamba et al. 2008; Norio et al. 2011; Raphael and Geiger 2011; Takahashi 2011; Wiek et al. 2012b), and also have key differences regarding geography, topic, stage of development, and institutional setting, among others. This diversity is intentional, in order to illustrate the current spectrum of sustainability science projects. However, in this article the focus is primarily on similarities among the cases, e.g., each case illustrates on-the-ground efforts to conduct problem-driven and solution-oriented sustainability science research.

Each case study is problem-driven, i.e., addresses a sustainability problem, namely, the triple-disaster in Japan, lack of rural livelihoods in Africa, and toxic chemical dispersion in San Francisco. Similarly, each case study is solution-oriented, namely, sustainable rebuilding and reconstruction in Japan, biofuel development in Africa, and precautionary purchasing based on alternative assessments in San Francisco. Together, the cases provide a spectrum of sustainability science projects and showcase the diversity of topics covered by this developing field. The cases add important insights to today's discourse on progress and quality standards in sustainability science (Siebenhüner 2004; Blackstock and Carter 2007; Matson 2009; Spangenberg 2011; Lang et al. 2012; Wiek et al. 2012a, b, c; Clark et al. in press), and offer vital platforms for future sustainability science research.

The case studies were collaboratively reviewed during the 2012 International Conference on Sustainability Science (ICSS 2012). ICSS 2012 followed two preceding conferences, which similarly intended to review aspects of the state of the field: in 2009 at the University of Tokyo (Kauffman 2009), and in 2010 at Sapienza University of Rome (Wiek et al. 2012a).

At ICSS 2012, the three case studies were used as lenses with which to examine and discuss state-of-the-art practices, including emergent accomplishments and challenges in sustainability science. Each day of the conference focused on just one case, engaged by participants in three parts: (1) researchers and relevant local stakeholders introduced the case; (2) a panel of experts on the case topic discussed the case based on their expertise and experiences; and (3) participants broke out into groups of 5–10 and discussed opportunities and challenges of sustainability science research along the case study.

Different conference sessions yielded not only insights on the current state of the field, but also ideas on how to improve the practice and outcomes of sustainability science. The setting gave conferees the chance to engage each case in depth, differing from the standard conference model of short engagement with many topics. Discussions were documented and analyzed, which provided a small set of topics deemed by conferees to be particularly relevant to the current state and future of sustainability science. The discussion section of this article synthesizes emergent themes from conference panel discussions and breakout groups dedicated to each case, and those themes are the foci for discussion (transacademic collaboration; institutional structures; politics and power) (Wiek et al. 2012c).

Case studies

As stated above, each case study is structured along three sub-sections. The first section characterizes the sustainability challenge addressed. The next one outlines solution options (realized and potential) that sustainability science aspires to support. Finally, each case study is concluded with issues to consider when moving forward toward mitigating or resolving the sustainability challenges characterized. The key features of the three case studies are summarized in Table 1.

Rebuilding from the 2011 Great Eastern Japan Earthquake

Sustainability challenge

On March 11, 2011, a 9.0 magnitude earthquake struck northeastern Japan, and caused a tsunami that damaged over 600 km of coastline in the region (Mimura et al. 2011; Suppasri et al. 2013). The earthquake and tsunami killed thousands, destroyed property, disrupted basic services, damaged the environment, and ruined livelihoods (Mimura et al. 2011). Agricultural, fishing, and tourism industries in the disaster areas were severely damaged (Reconstruction Design Council 2011).

Makoto Hatakeyama was at sea fishing when the tsunami struck. He characterized the subsequent 10 days as, “hell on earth” (Wiek et al. 2012c). The earthquake and resulting tsunami caused a series of accidents at a nuclear power plant in Fukushima, already one of the hardest hit areas (Dauer et al. 2011). In total, several hundred thousand people were displaced by the earthquake, tsunami, and nuclear disasters (Mimura et al. 2011; Norio et al. 2011).

This triple disaster will likely be the costliest in Japan’s history, with long-lasting financial, political, and social impacts (Matanle 2011; Shaw 2011). This case displays key features of a sustainability problem (Wiek et al. 2012b). We see complex and long-lasting impacts that threaten the integrity of the regional society, economy, and environment. In turn, affected areas urgently require sophisticated responses capable of matching the complexity of impacts in-kind. This case was positioned as an opportunity for sustainability science to inform post-disaster relief and reconstruction efforts.

In some regions, responses to the Great Eastern Japan Earthquake have benefited from precautionary measures and disaster preparedness efforts (Norio et al. 2011). High-speed trains, designed to shutdown automatically during earthquakes, successfully halted, and quickly came back on-line after shutdown (Mimura et al. 2011). The Japanese people themselves responded in an orderly way, despite the tremendously chaotic situation (Gilligan 2011).

The cascade of nuclear accidents, however, left the Fukushima region and residents in critical condition despite all preceding disaster preparedness efforts (Perrow 1984, 2011). While scientists believed a tsunami as large as the

Table 1 Overview of the key features of the three case studies

Case study	Sustainability challenge	Solution options	Open issues	Key insight
Rebuilding from the 2011 Great Eastern Japan Earthquake	Earthquake, tsunami, and Fukushima meltdown	Sustainability science research for sustainable energy systems and eco-parks	Opposition from interest groups invested in the status quo	Sustainability science requires innovative institutional structures to connect research to action
Bioenergy and sustainability in Africa	Low quality of life, limited energy access, and lack of livelihood opportunities in rural Africa	Internationally influential policy documents and support for small-scale pilot projects	Uncertain climate change impacts, scalability of technology, competition for land and water	Large bureaucracies and small villages have different priorities and can be difficult to balance
Precautionary purchasing in San Francisco	Toxic chemical dispersion from products	Precautionary purchasing ordinance and alternative assessments	Urgency of challenges, unintended consequences, and transferability of approach	Collaboration between scientists, government, and citizens is complex and takes time, but can be very successful

one from March 11th was possible, the nuclear community largely ignored this information (Davis et al. 2012). Japan's governance of nuclear power was flawed, and regulators often relied on uncooperative nuclear power companies to voluntarily comply with safety guidelines, which they failed to do. Government and business could have done more to prevent serious nuclear accidents through regulation, design, training, and anticipation (Perrow 2011).

Post-disaster studies have provided ample evidence of how secondary adverse impacts resulting from insufficient responses to a disaster can amplify a disaster's direct impacts (Chamlee-Wright and Storr 2010; Wiek et al. 2010). Impact amplification particularly affects vulnerable populations such as women, children, and minorities, who are usually hit hardest by disasters and flawed recovery processes (Thomas et al. 2013). In this case, paucity of coordination, inadequate communication, lack of stakeholder engagement, general incompetence, and the dominance of partial interest groups have put additional pressure on affected populations and hindered a speedy recovery (Park et al. 2011).

The ineffective and inefficient use of aid funds provides an especially prominent and well-documented post-disaster emergency response and recovery issue (Wiek et al. 2010; Dong 2011; Dovers and Handmer 2012). In the Great Eastern Japan Earthquake case, problems with assistance have appeared in short-, medium- and long-term recovery efforts. In the short term, insufficient governmental and non-governmental coordination and delivery structures squandered ample emergency aid. In the medium-term, local governments struggled to find people with the necessary administrative skills and local knowledge to advance recovery efforts. Several other medium-term problems, if unaddressed, may become long-term problems. For example, fish farmers receiving government subsidies may be unmotivated to work, and financial investment for rebuilding has flowed to graft instead of need. Because of problems managing the response to the nuclear disaster, many Japanese people have lost trust in the government's ability to respond to such disasters. Another widespread fear is that radiation contaminated large regions will continue to damage farming and fishing industries across the country (Takahashi 2011; Kurihara et al. 2012).

More resilient technological systems might have withstood the disasters (Park et al. 2011), but a resilient society displays more than robust infrastructures (Tweed and Walker 2011). A technological system's resilience depends on robust social systems and human-environment relationships. Insufficient economic opportunities in eastern Japan had been causing depopulation and social disintegration for years before the earthquake, reducing the region's resilience and the people's response capabilities (Matanle 2011).

Solution options

If well designed, sustainability science research can play an important role in understanding the Great Eastern Japan Earthquake disaster in its complexity, and in developing solution options for a sustainable recovery. A transformational sustainability science research agenda focused on developing and testing viable solution options would be most suitable for guiding such efforts (Wiek et al. 2012b; Matson 2012). That process requires close collaboration among sustainability scientists, stakeholders, and the public to create ownership and encourage implementation. To ensure implementation success, research must be linked with evaluation, outreach, and teaching efforts to continuously enhance the capacity of researchers, professionals, institutional stakeholders, and the public.

The participatory feature of transformational sustainability science is critical in this case. Sustainability scientists need to collaborate with local communities in designing and selecting sustainable solutions (Talwar et al. 2011; Lang et al. 2012). Local communities should carefully consider who benefits from proposed solutions, because in complex cases such as this, winners and losers are inevitable. Complex solution options often display a high degree of uncertainty and might result in unintended consequences. When exploring solutions, communities therefore need to consider future developments, such as impacts from demographic transitions or climate change. Communities should choose clear success criteria to use in evaluating each solution proposal over time, and decide when proposed activities have been successful, so that they can devote their resources to new initiatives. Solving problems always requires resources, so sustainability scientists and stakeholders need to determine the cost of each solution option and compare it to available resources and priorities.

A key component of transformational sustainability research is a creative, structured, and participatory visioning process that generates systemic and shared visions for future recovery (Wiek and Iwaniec in press). Resilience could be used as a key principle for such visioning processes, if considered from a systemic perspective (Tweed and Walker 2011). Recent studies support rebuilding communities with more resilience, a stronger social capital base, and more interconnections (Aldrich 2011).

Yet, a great deal of any reconstruction effort is path dependent, aiming simply to restore pre-disaster conditions and modes of operation. For example, Japan's government largely responded to the disasters through conventional mechanisms such as special economic and tax regulations. While there have been grassroots recovery efforts (e.g., Fisker-Nielsen 2012), Japan does not currently have the necessary civil society or institutional arrangements for bottom-up reconstruction (Matanle 2011). Community restoration will require the development of innovative planning and governance approaches, including sustainability-oriented planning and anticipatory governance (Guston 2008; Quay 2010; Wiek et al. 2010).

Progress towards sustainability calls for overcoming existing path dependencies and changing the ways communities are perceived, valued, built, governed, and operated. One example is new zoning laws that make towns more compact and strategically placed on higher ground (Reconstruction Design Council 2011). Considering the inertia keeping most communities on unsustainable pathways, disasters present a unique opportunity to divert the course of usual operations towards sustainability (Berke et al. 1993; Birkmann et al. 2010; Wiek et al. 2010).

Another proposal is to finalize the new "Sanriku Fukko (reconstruction) National Park" to memorialize the earthquake and tsunami, educate visitors about geology and geography, and restore biodiversity (Takeuchi et al. in prep). Communities could use the concepts of *satoyama* and *satoumi* to reconstruct wetlands along the coast to create buffer zones, stimulate tourism, and manage ecosystems (Takeuchi 2011). Respectively, *satoyama* and *satoumi* refer to community-based management of forests and coastal ecosystems, informed by traditional knowledge. Much of the Sanriku coast already has natural parks that could incorporate *satoyama* and *satoumi*, or expand into areas already practicing these management paradigms.

The Great Eastern Japan Earthquake has stimulated a broad public debate on climate and energy policy (Ogimoto and Yamaguchi 2012). As Japan reconsiders its energy system, it has the opportunity to pursue societal resilience through an energy transition that could simultaneously reduce vulnerability to disasters and climate change (Barrett 2012). As Germany, Belgium, Spain, and other European countries have decided to or are seriously considering to phase out nuclear power generation over the next few decades, this option is currently explored in Japan, too. As Perrow (2011, p. 44) concludes: "Some complex systems with catastrophic potential are just too dangerous to exist, because they cannot be made safe, regardless of human effort."

Open issues

Some of the solution options in this case would require the substantial transformations envisioned in sustainability transition processes (Loorbach 2007). While the described win-win situation of a sustainable energy transition sounds very promising, it faces strong resistance from powerful interests (e.g., the nuclear and oil industries) that benefit from the status quo. One of the obstacles to bottom-up reconstruction is the entrenched "iron triangle" of elite political, bureaucratic, and corporate interests. Japan needs significant cultural and institutional changes for local people to be able to shape the vision for and implementation of disaster recovery (Matanle 2011). However, at least one of the proposed solutions is already complete: Japan has created a new national park ("Sanriku Fukko (reconstruction) National Park") to restore biodiversity and increase tourism.

Bioenergy and sustainability in Africa

Sustainability challenge

The Competence Platform on Energy Crop and Agroforestry Systems for Arid and Semi-arid Ecosystems in Africa (COMPETE) project was an international biofuels initiative that addressed the interrelated problems of low quality of life, limited energy access, and lack of livelihood opportunities in rural Africa. The project was funded through the European Union's (EU) 6th framework program and ran from 2007 to 2009. It involved 44 partners, including scientists, practitioners, companies and policymakers from Europe, Africa, Brazil, India, and Mexico. This case study illustrates how sustainability science has been used to address complex international development problems (Wiek et al. 2012b).

Roughly half of the people in sub-Saharan Africa live on less than one dollar (US) per day (United Nations 2013), with many in rural areas relying on subsistence farming. Poverty, low levels of development, poor agricultural infrastructure, degraded land, and especially widespread hunger constrain farmers' ability to effectively cultivate their land, despite existing land availability. Additionally, small-scale farmers receive little outside investment, so they have few opportunities to improve or change their livelihoods. Farmers also have to contend with the negative effects of climatic change on their yields. These factors contribute to unsustainable land-use practices that, in turn, degrade ecosystems.

Another problem for people living in rural sub-Saharan Africa is getting affordable, clean energy. Most people use biomass, like charcoal and firewood, because they cannot afford fossil fuels or renewable energy (Taele et al. 2012). Without alternatives to traditional use of biomass, increasing demand for energy and food will increase pressure on the African ecosystems that support rural farmers' livelihoods (Amigun et al. 2011). The sustainability problem constellation outlined above includes many other aspects, as indicated in the conceptual figure below (Fig. 1).

Solution options

COMPETE produced a number of policy documents, including the "Declaration on Sustainable Bioenergy Development for Africa" (Yamba et al. 2008; Janssen and

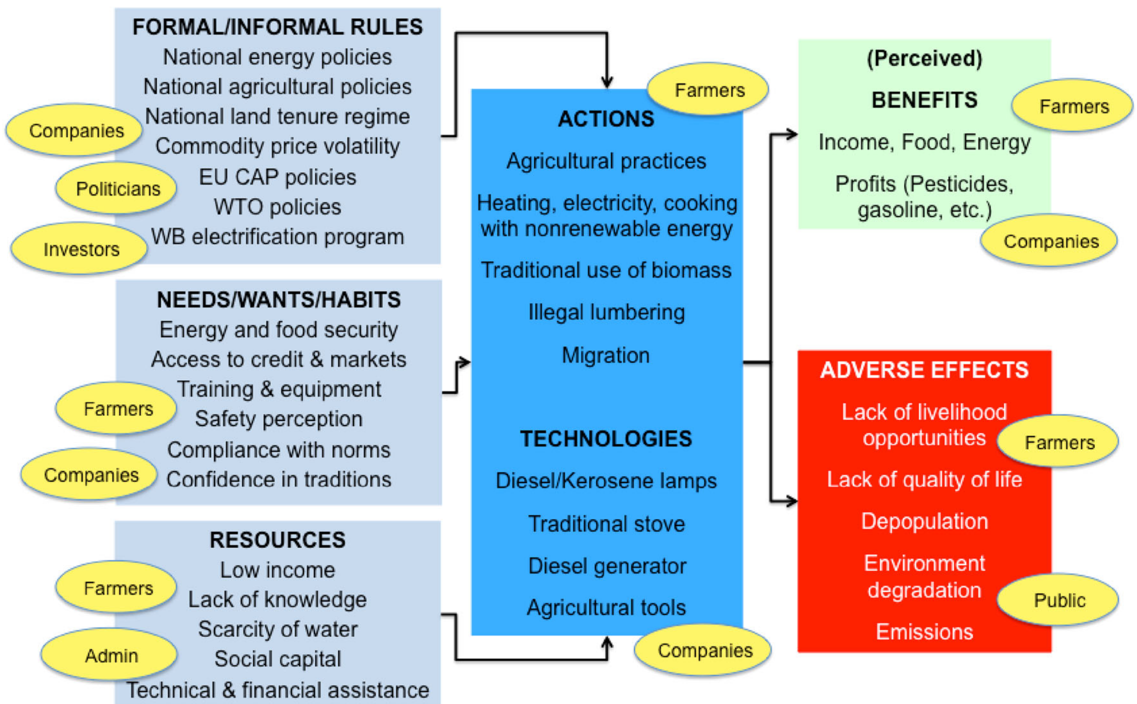

Fig. 1 COMPETE's sustainability problem constellation (conceptual model developed by Farioli and D'Ippolito; based on Wiek 2009)

Rutz 2012; http://www.compete-bioafrica.net). To this day, they influence international dialogue, and national and regional policy on biofuels (Wiek et al. 2012b). They recommend policies and guidelines for biofuels development in Africa that increases livelihood opportunities while preserving critical ecosystem functions. The policy documents are designed to address sustainability concerns and make sure that local farmers benefit from biofuels production, which requires that policy and decision makers in related sectors coordinate their efforts. COMPETE's best practice guidelines support locally-oriented, context-specific assessments of biofuel projects that fulfilling the energy needs of the local population, working towards the millennium development goals (Dalal-Clayton et al. 2003; Janssen and Rutz 2012; Farioli 2013).

Bioenergy development may help address this case's interrelated problems (Lynd and Woods 2011). Bioenergy systems offer opportunities to diversify production, stimulate socio-economic development, and provide sustainable energy for local needs. However, even though studies show significant potential for bioenergy development (Smeets et al. 2007; Hoogwijk et al. 2005), concerns exist that it might have adverse effects on biodiversity, livelihoods, and access to natural resources, because of increasing competition over land and water resources, and inequitable distributions of benefits (Amigun et al. 2011; Janssen and Rutz 2012).

Under COMPETE, researchers used Geographical Information Systems (GIS), supplemented with research on traditional knowledge and land use practices, to identify the land best suited for growing biofuel feedstocks. Generally, the assessment identified land that could be used for cultivating feedstocks for biofuel with minimal environmental damage and minimal threats to existing livelihoods. The assessment excluded land that had high biodiversity, was used for agriculture, or was unsuitable for production (such as deserts). This research revealed substantial lands in arid and semi-arid regions with potential for cultivating biofuels (Watson and Diaz-Chavez 2011).

For some of that land, COMPETE supported on-the-ground efforts to develop biofuel as an industry. The potential for biofuel production using *Jatropha curcus* as feedstock is significant in rural Africa. Jatropha is a hardy plant with inedible oil seeds that grows on land unsuitable for food crops, which means it interferes less with agriculture for food than other biofuel feedstocks (Romijn and Caniels 2011).

Marli Investments Zambia Ltd. in Kabwe, Zambia led a COMPETE project (German et al. 2011; Farioli and D'Ippolito 2012a), contracting with farmers to grow jatropha and process their crops. Farming methods are a combination of traditional and modern techniques; and, Marli provides inputs, seeds, and training to farmers who cultivate jatropha on their own land. By 2012, there were roughly 25,000 participating farmers.

In 2007, TaTEDO, a Tanzanian development organization, began another COMPETE project in Leguruki, Tanzania (Farioli and D'Ippolito 2012b). Leguruki is a rural farming village unconnected to the electricity grid, growing coffee, banana, beans, and corn. Villagers were already familiar with jatropha, using rows of it as fences and property markers. TaTEDO's project aimed at supporting income-generating activities by electrifying the village using jatropha oil diesel generators.

TaTEDO connected project organizers and community members, who defined problems and potential solutions together. TaTEDO also formed an "energy team" of villagers, government officials, and TaTEDO staff, with villager selection based on their motivation and ability to be representative of the village's residents. At the end of this pilot project, TaTEDO and the energy team successfully installed a diesel generator powered by jatropha oil. Farmers intercropped jatropha, or used it for hedges, so it did not compete with their food crops. Electricity from the generator went to a mini-electrical grid that powered residences and businesses in the evening. Children were able to study longer, and better street lighting improved safety. TaTEDO attributes the project's success to participation by community members and the cost-effectiveness of the diesel generator.

Researchers working with COMPETE evaluated the sustainability of these two on-the-ground projects using principles that reflect a balanced sustainability concept and different stakeholders' perspectives (e.g., Farioli 2009). The Zambian central government has started to evaluate the potential of biofuels, but has not yet started any biofuel initiatives. Tanzania's central government created a Biofuels Task Force in 2005, and the country has developed guidelines for the biofuels sector. They are also supporting initiatives, like biofuels education for government workers, to spur development of the sector (Janssen and Rutz 2012). With strong governance and incentives, the biofuels sector in Tanzania seems to have good prospects.

Open issues

The sustainability of bioenergy depends largely on coping with detrimental environmental, social, and cultural impacts connected to crop grown, technologies employed, and the integration of the bioenergy supply chain into existing economic and social systems (Janssen and Rutz 2012; Farioli 2013). In industrialized countries, biofuels have attracted attention for their potential to reduce greenhouse gases and dependency on fossil fuels. For African countries, on the other hand, rural development and investment in agricultural infrastructure have driven demand. Researchers are still investigating whether and how much biofuels reduce greenhouse gas emissions (Pearce and Aldhous 2007). Developing countries may benefit economically from biofuels regardless of their global warming benefits. But, if research shows that they do not reduce greenhouse gas emissions, demand for biofuels in developed countries may collapse along with international investment in the sector. Even currently, biofuels are seemingly unable to scale to a market solution. They have proven valuable examples of sustainable systems, in principle. But, the large majority of biofuels are viable only because of subsidies or small, closed loop systems.

Because most current biofuel feedstocks are food crops, concerns arise about arable land-use competition, vulnerable communities, water resource constraints, deforestation, and risks to food security, especially for subsistence farmers. Though using marginal land can reduce competition with food crops, irrigation for jatropha may take away from irrigation for food crops (Cotula et al. 2009; Amigun et al. 2011).

Land is not merely a means for food production. Observers and activists worry that the spread of biofuels may exacerbate existing inequities in land access, compounded, of course, by land's historical, political, cultural, and spiritual value. Marli's and TaTEDO's projects seem to avoid these problems, but both emphasized community involvement and ownership. It is not hard to imagine large-scale projects funded by foreign companies that disproportionately reduce access to land for poor and vulnerable farmers and pastoralists.

Precautionary purchasing in San Francisco

Sustainability challenge

The central sustainability challenge in this case was the human health effects (Landrigan et al. 2002; Muir and Zegarac 2001) of toxic chemicals dispersed into the environment. Toxic chemicals have a wide range of other effects worth mitigating, such as worker health issues, environmental degradation, and uncertainty about chemical interactions, to name but a few. However, it proved strategic to narrow from broad sustainability criteria (environmental impacts, economic impacts on communities, sustainable material sourcing, etc.) to focus specifically on human health effects that were understandable for decision makers and the public.

One implicit sustainability challenge within toxic chemical dispersion is the path dependence of risk assessment methodology. Traditionally, the risk associated with an event is the product of the probability it will occur and its impact when it does occur. A high impact, extremely improbable event would be considered low risk. A very low impact and frequent event would also have a low risk. In order to assess risk, both the impact and probability need to be known.

The San Francisco Department of Environment's (SFDoE) Precautionary Principle Ordinance (SF Environment Code, Chapt. 1) began to ask a different question: "Is it necessary?” It shifted emphasis from exposure reduction to questioning the necessity of using a hazardous material in the first place. This ordinance was a policy statement, but did not mandate specific actions. The subsequent Precautionary Purchasing Ordinance (SF Environment Code, Chapt. 2) was the first formal implementation of the initial Precautionary Principle Ordinance. The second ordinance would eventually lead to assessments of alternatives, which measured alternative products on a variety of indices, and suggested changing or eliminating purchasing, if appropriate. The SFDoE partnered with state agencies, consultants, and scientists who would carry out their alternative assessments.

SFDoE held several open meetings to get input from residents on precautionary purchasing. These were well attended during the first round of meetings (2004), primarily by activists who had participated in the city’s precautionary principle policy development. However, few residents attended later meetings, which exemplifies a consistent problem in participatory sustainability science research: stakeholder recruitment. Even when stakeholders were identified and engaged, stakeholder groups had different priorities and vernaculars, making communication a challenge. For example, researchers communicated about materials in terms of their toxicity potential, purchasers focused on the costs of switching suppliers, and end-users were most concerned with the relative performance of new and old options. Finding solution options that meet the needs of researchers, purchasers, and end-users is no easy task, and takes significant effort on the part of everyone involved. It can be frustrating to bring together disparate actors in interconnected systems, but it is crucial for generating solution options for sustainability problems.

Solution options

The opportunity for legislating the precautionary principle arose in 2000, when NGOs lobbied receptive San Francisco officials to draft ordinances that would mandate the use of the precautionary principle in city activities, especially purchasing patterns. As the city spends more than $700 million annually on products and services (Raphael and Geiger 2011), this mandate had the potential to significantly influence suppliers and supply chains. The final draft of the Precautionary Principle Ordinance was passed in 2003, and established the precautionary principle as City policy without requiring any specific actions. The follow-up Precautionary Purchasing Ordinance contained the first specific mandates under the precautionary principle, and passed in 2005. After the latter ordinance passed, NGOs gradually shifted their focus to state legislation, and city officials interpreted and implemented the ordinance.

Over time, the two ordinances provided a novel approach to risk management. When information about product impacts is incomplete, but significant risk is apparent, the precautionary principle prescribes action based on the best available scientific evidence, rather than waiting for conclusive scientific evidence. Instead of evaluating and comparing products’ potential risks to levels deemed acceptable by regulatory bodies, the precautionary approach looks broadly at other products/solutions to find the lowest risk option. The question: “How much exposure to toxics is tolerable?” was gradually replaced with: “Is this exposure necessary?” (cf. Sarewitz et al. 2012). This shift in perspective led to alternatives assessments with many criteria, including performance, durability, and toxicity. The city contracted with scientists for very specific tasks, directly linking their assessment research with the subsequent action of purchasing sustainable alternatives. Officials used the assessments’ results to suggest changes in city purchasing, most notably in pesticides and cleaning supplies.

Raphael and Geiger (2011) offer many examples of solutions developed under the lens of the precautionary principle. When data collection in city parks revealed toxics leaching from pressure-treated wood often used in city playgrounds, the city had a ready framework for action. After conducting an alternatives assessment, the city found that treating the playground wood with new chemicals reduced toxic leaching, while maintaining the old chemicals in marine applications allowed for lesser leaching into seawater from docks.

Garment cleaning is another example. An alternatives assessment founded a capacity building partnership with the California Office of Environmental Health Hazard Assessment, and led to a robust multi-criteria analysis of alternatives to dry-cleaning chemicals (Wiek et al. 2012c). The preferred method discovered was wet cleaning, and the city quickly began outreach and capacity building with dry-cleaners to market the new practice. Understandably, the dry-cleaners were resistant to change, but city staff have continued to build implementers’ trust, capacity, and comfort with the new technology, as well as again partnering with the state to offer grants of up to 50 % of the cost of new wet-cleaning machinery.

Because purchasing has such extensive reach, the scope of alternative assessments at the city level has expanded to address the broad sustainability criteria initially conceived by the precautionary principle movement. For instance, purchasing has moved beyond worker health and ecotoxicological considerations, and begun to use informal life cycle assessment to consider issues like carbon footprint, packaging, sustainable sourcing, and vendors’ labor practices. To build on its successes, SFDoE tracks vendor sales, so that the green purchasing program can present annual awards and incentivize change. These awards and incentives help businesses differentiate themselves in the market and improve the program's outcomes.

Open issues

One might argue that this particular sustainability challenge of toxic products in a wealthy city is less urgent than other global sustainability concerns. However it is important to note that, to the contrary, place-based sustainability science work necessarily deals with local problems. In the case of San Francisco, other programs dealing with waste management and climate change certainly have positive effects on global problems. In concert, the approach to purchasing in San Francisco is potentially generalizable and applicable in cities worldwide.

Another potential critique is the unintended consequences of the city's ordinance. The rule was a positive contribution municipally, regionally, and at the state level, but what effect might it have globally? Is San Francisco's goal of moving markets toward sustainable processes being realized? If San Francisco's ordinance reduces demand for hazardous chemicals locally, is it reasonable to assume that the suppliers of these chemicals may seek new markets in areas with weaker governance and enforcement? If so, this might mean that San Francisco has simply outsourced rather than solved this problem.

Lastly, San Francisco has wealth, and an especially conducive environment for sustainability transitions. This might lead one to doubt the transferability of this case, and its relevance for developing scalable and portable solution options (Lang et al. 2012). While these are valid concerns, this case study remains an impressive illustration of the "aspirational" state; that is, of a place that has developed a political culture capable of functionally addressing sustainability problems. Though the broader culture may not be portable, the institutional culture of the SFDoE that embraces collaboration, permeability, and long-term capacity building could certainly be a model for other places and institutions striving to begin sustainability transitions.

Discussion

A supporting case study of the Yaqui Valley presented at ICSS 2012 is referenced in the following discussion. The case explores the Yaqui Valley, birthplace of the Green Revolution, for over 20 years. Researchers observed excessive water and fertilizer use, but were initially unable to reduce waste. However, further examination of network dynamics revealed credit unions risk aversion led to pressure on loan recipients to over-fertilize. Subsequent efforts built new partnerships for capacity building and managed to reduce fertilizer use (Matson 2012).

Developing and implementing sustainable solution options through collaboration between sustainability scientists and society

Sustainability science is an endeavor to support societies worldwide as they face urgent problems that stretch across scales, sectors, domains, and actors. Solutions to sustainability problems require collaborative efforts among sustainability scientists, stakeholders, and the public (Blackstock et al. 2007; Talwar et al. 2011; Lang et al. 2012; Clark et al. in press). A prominent long-term sustainability science project in the Yaqui Valley, for example, has built multi-decadal relationships between academics and stakeholders, which have been the foundation for its success (Matson 2012; McCullough and Matson in press). In each of the three cases presented herein, solution options were the goal, but the cases were in different stages of collaboration and employed different participatory settings.

The San Francisco case displayed long-term relationship building between and among government, non-profits, businesses, and citizens (Raphael and Geiger 2011). In contrast, the Japan case represented an ongoing transition from disaster relief to reconstruction and recovery, and relevant relationships are just beginning to emerge. In the COMPETE case, collaboration happened among diverse stakeholders who were arrayed within and between local and international (both North–South and South–South) scales. Solution-oriented sustainability science utilizes diverse collaborative partnerships to move from a science of problem identification and analysis toward a science of solution options for sustainability transitions. However, as Crow (2012) points out, science based on a moral imperative that strives for real-world solutions faces many obstacles and barriers, such as funding, academic recognition, transferability, scalability, mistrust, and political and cultural sensitivities.

Matson's (2012) review of the Yaqui Valley project provides a good example of a diverse web of nontraditional funding supporting long-term transformational research. Sustainable solution options require diverse collaboration throughout problem definition, methodology selection, research processes, and implementation monitoring (Talwar et al. 2011). Deep relationship building takes years, and lack of financial support can make it unattractive to otherwise motivated researchers, in particular, junior faculty.

The COMPETE case also offers a few instructive examples. Although the GIS research to identify areas for potential biofuel development was exemplary academic work (Wicke et al. 2011), the data analyzed were not complete (e.g., pastoral land-use not in the database) or fine-grained enough to be entirely relevant (Watson and Diaz-Chavez 2011). Land use mapping proved effective in safeguarding large-scale food and cash crop production. Yet, it was inadequate for safeguarding the livelihoods of traditional land users and small-scale famers (Watson and Diaz-Chavez 2011; Farioli 2013). Even the options offered by this top-down solution had low relevance, because many potential implementers lacked infrastructure for biofuel use, as well as knowledge and experience growing and processing biofuels (Romijn and Caniels 2011). The option of development for export suffered from political influence on the fair distribution of profits and benefits. This begs the question of whether top-down goals, such as EU research designed to implement development solutions in African nations, will be as relevant and impactful as solutions at the levels where development problems manifest and policies will be implemented.

In the Japanese nuclear accident, the line between disaster relief, research tourism, and sustainability science proved grey, resulting in mistrust and resistance to collaborate. In particular, the research institutions and governments responsible for calculating risk lacked the trust of stakeholders. This dynamic asks sustainability scientists to find more accessible ways to communicate risk and uncertainty (Faulkner et al. 2007). Of course, this means that scientists hailing from distant research institutions must build trust with local people to ensure effective engagement, maximum transparency, and authentic cultural continuity. In the tsunami-affected areas, these goals were achieved, making for rapid sustainability-oriented efforts driven by international and local partnerships (Ministry of the Environment et al. 2012).

However, many of the obstacles exemplified in one case are addressed well in another. The San Francisco case provides a useful instance of building trust through participatory collaboration. Over a decade, city administration was able to work with non-profits, community groups, academics, and consultants to reduce toxic chemicals (Raphael and Geiger 2011). This success was built on long-term relationship and trust building between the city and nonprofits and community groups, which transitioned those groups from adversarial to collaborative in their interactions with the city.

COMPETE adapted modular biofuel policy recommendations for each national context, instead of repeating the core of the process. The program aimed to elaborate on best practices and make African voices and interests heard in the international biofuel debate. Sophisticated collaborative schemes like COMPETE can connect local stakeholders' interests with general insights and broader applications from academics (Lang et al. 2012). Additionally, the program drew on South–South cooperation to transfer successful experiences in Latin America and South Asia to Africa for replication. COMPETE also worked to scale projects, finding sufficient land and local expertise to develop jatropha at the necessary economies of scale to make export possible (Romijn and Caniels 2011; Janssen and Rutz 2012). Similarly, the Yaqui Valley case worked to scale best practice recommendations from academic work to Valley-wide standard procedures (McCullough and Matson in press).

Institutional structures for sustainability science research

Sustainability science has, thus far, happened within institutions (sets of rules) built for curiosity-driven, basic research that claims value-neutrality (Crow 2012). Historically, academia has rewarded knowledge production and publication with tenure and reputation, and has followed a unilateral educational model, in which students receive information as the primary mode of learning. In concert, funding bodies articulate their research programs within these dominant paradigms. These current institutional polices simply do not reward action research equally with traditional scholarly research when it comes to promotion and tenure. This is part of a broader challenge for academic research: tradition, reputation, and incentives do not require or even encourage stakeholder engagement in solution-oriented sustainability research. These practices are deeply ingrained in higher education and have proven resistant to change (Van der Leeuw et al. 2012).

Sustainability science purports to develop solution options to problems embedded in real-world practices and communities, and is therefore not well served by these institutional structures. Crow (2012) identifies a key mechanism of traditional academic work hardly conducive to sustainability science's solution orientation: "Universities […] would do research and we would teach students and we would do science and hopefully somebody would do something with that" (p. 9). Traditional academic structures and incentives produce research without explicit articulation and connection to solution options that are actionable.

To build long-term relationships with stakeholders requires new commitments from academic institutions and funding bodies. The diversity of funders in the Yaqui Valley case (Matson 2012), exemplifies support for long-term, embedded, sustainability science work. However, creating a funding network requires time-consuming application and reporting, as well as overlapping areas of investigation, or gaps in support where resources are most needed. The Yaqui Valley project was a successful multi-decade sustainability science project with positive real-world impacts, but one that was conducted through three-year funding cycles (Matson 2012). The uncertainty and patchiness of funding is a significant barrier to incentivizing faculty investment in sustainability science projects.

Of particular interest in the context of the Japanese case study is whether universities can be equally engaged in local and distant communities. Real understanding is not possible without experiencing a place in person (Talwar et al. 2011; Lang et al. 2012), which begs the question: what institutional structures are needed for sustainability scientists to embed themselves in place-based contexts, equipped with participatory and solution-oriented research expertise? Small-scale prototyping to develop scalable and transferable best practices for capacity building among senior scientists may help academics used to traditional structures adapt to new institutional structures.

Sustainability science education in particular offers significant opportunities with project- and problem-based learning experiences (Brundiers and Wiek 2013). Students need to learn skills in public communication, facilitation, and negotiation, as well as co-creation of ideas, practices, and knowledge in real-world learning settings. The University of Tokyo has established case-study opportunities for international graduate students (Onuki and Mino 2009) and is currently adopting this model for work in disaster-affected areas. Similarly, Stanford graduate students have worked in the Yaqui Valley for decades (McCullough and Matson in press). The sustainability programs at Arizona State University (ASU) and Leuphana University of Lüneburg have begun to experiment with such settings, building connectivity to surrounding communities and throughout the universities (Lang and Wiek 2012).

These pedagogies emphasize collaborative efforts throughout the research process (Brundiers and Wiek 2013; Wiek et al. 2011a), from curricula to syllabi, and research design to solution implementation (Yarime et al. 2012). They require a much more robust role for students in their own educations, and move pedagogy into a more experiential space (Sipos et al. 2008). Sustainability science necessitates specific competency development so that students can envision changes and develop evidence-based solution strategies through rigorous research. Although researchers have identified relevant competencies (Wiek et al. 2011a), sustainability science needs to continue to develop frameworks for delivering and evaluating relevant knowledge and skills, to ensure that rapid implementation is possible as university infrastructure evolves (Ferrer-Balas et al. 2010; Whitmer et al. 2010; Yarime et al. 2012). This would both benefit students and demonstrate added value across communities of knowledge (Blackstock and Carter 2007; Talwar et al. 2011; Wiek et al. 2011b). Levels of competency development could range from basic throughout a university, to technical in relevant disciplines, and holistic for majors and graduate degrees (Wiek et al. 2011a).

One key competency gap is in participatory and collaborative approaches (Robinson 2008; Yarime et al. 2012). As an example, in the Japanese case, suicide became a significant issue after the triple disaster. Academics are historically ill equipped to recognize and/or address emotional problems, especially such a delicate and traumatic issue for families. Clearly, working in distressed communities requires sensitive approaches that discover and acknowledge the importance of people's emotional states, as well as prepare researchers to empathize.

A similar competency gap continues to exist in working across academic disciplines. The COMPETE and Yaqui cases show that the funding and time necessary to bring together disparate disciplinary experts into high-functioning and effectively communicating teams is very difficult to acquire and sustain. Even when resources are available, the training of academics makes communicating and collaborating across disciplines troublesome, due to differing epistemologies, methodologies, priorities, language, and definitions. A more sophisticated pedagogy of collaboration is necessary to instill a greater facility for and interest in the interdisciplinary work expected of sustainability science.

The San Francisco case offers excellent examples of what could be very successful pedagogies for solutions. One of the main strengths of the city's sustainability work is the flexibility of the SFDoE to take on a breadth of challenges, and attract appropriate resources to address those challenges. Through academically trained consultants and scientists, San Francisco is able to efficiently marshal extremely specific research in order solve problems. If universities evolved institutions with similar flexibility, focus, and specificity, they could host action research that gives students experience with implementing solutions. A nascent example for such innovative academic institutions is ASU's Walton Sustainability Solutions Initiative.

At the graduate level, there is no criterion for putting the best students to work on our most urgent and difficult problems. Rather, students attach themselves to various funding streams articulated to funders' specific outcomes and research agendas. One alternative, carried forward at Lund University (Wiek et al. 2012c), is to fund all students equally without specifying their work. This structure gives students the chance to pursue the most pressing and relevant problems, by learning appropriate methods and content knowledge. In contrast, graduate methods training based on the predilection of funders can often track someone into a career without sustainability science's solution focus.

To solve our most time-sensitive sustainability problems, we could marshal the efforts of the entire education system (Crow 2010). This would require linkages between education levels, a culture of interdisciplinary collaboration, interpersonal capacity building, and a pedagogy of experience using real-world sustainability problems as educational settings (Rowe 2007). The pedagogies we need to solve problems leave behind unilateral lecture models, the path dependence of historical funding bodies, and academic institutional constraints. They are pedagogies of experience, collaboration, and communication designed to create solution options in real-world settings.

Politics and power dynamics in sustainability science research

Tainter (2003) frames sustainability with four questions: Sustain what? For whom? For how long? At what cost? Selecting what to sustain, for whom, for how long, and at what cost necessitates choice, creating winners and losers (Talwar et al. 2011). Historically, powerful interest groups have used their status to become and remain the beneficiaries of such choices. In many cases, this does not produce sustainable outcomes.

Matson's (2012) review of the Yaqui Valley project offers an example (McCullough and Matson in press). Although credit unions held most of the financial power, researchers did not know the extent to which that influenced farmers' decision-making on fertilization. Researchers began capacity building with farmers, in attempts to reduce overuse of fertilizer. However, credit unions advised increasing fertilizer use, to minimize risk. Thus, what was sustained, fertilizer overuse, was determined by the power dynamics of the Yaqui agricultural system, and not by researchers.

In the COMPETE case, potential biofuel implementers worried that they would lose control of their culture and natural resources if they became reliant on an unfamiliar industrial system and the vagaries of export markets. On the ground, solutions can appear to be exportation of Western forms, culture, and values. In line with this, COMPETE advised "to look at the needs of the national market first and forecast the possibilities of the expansion for global markets" (Yamba et al. 2008).

In the Japanese case, exported values came not from the West, but from the cities, where power, money, and decision-making are centered. Small rural communities with long, rich histories resisted relocation in the aftermath of the disaster because of the detrimental effects on their cultures. Both of these examples showcase how what is "sustainable" for society at large, i.e., biofuels to substitute for fossil fuels and lower costs for relocation than rebuilding, are not how rural communities would answer: "Sustain what?" The key point to recognize is that, the world over, cultures without power are not merely subsumed into market-driven Western structures, but also fall prey to what is considered desirable by more powerful actors. Is sustainability doing enough to acknowledge and support cultural continuity? Are solutions for large-scale problems sustainable for less powerful localities and cultures?

One way to empower local cultures is to begin sustainability science work from the bottom and work up (Smith et al. 2009; Lang et al. 2012). For example, stakeholder engagement and embedded research by the University of Tokyo has led to ideas the government might not have conceived on its own. In particular, learning what is most important to fishermen (water radiation levels), the commitment of local villages to their place-based culture, and consideration of semi-permanent university infrastructure has empowered localities to be meaningfully involved in reconstruction decision-making.

In the COMPETE case, local politics impacted biofuel crop siting, refinery and other processing facility ownership, and profit sharing between laborers and landowners. The former president of Zambia sits on the board of a biofuels investor, and was crucial for outreach to tribal chieftains who singlehandedly decide whether or not to make suitable lands in their territories available for development. Though it may seem foreign to consult chieftains about economic development, it is culturally appropriate and effective in this context, and made for one of the few successful COMPETE biofuels projects (Wiek et al. 2012c).

A critically important factor in understanding power and politics is time. In the Yaqui Valley case, decades of funding, academic work, and relationship building were necessary to grasp local politics and locate strategic intervention points. Mapping farmers' decision-making networks and inputs took years and multiple iterations, just to identify all the stakeholders necessary for solution implementation.

Academic work, especially problem identification and analysis, has often failed to adequately address power and how it contributes to problems (Jerneck et al. 2011). This failure in problem definition constrains solution space, because if the political economy of a problem is not present in its definition, the solution will not address relevant power dynamics. Sustainability science must explicitly address power and politics in defining problems and developing effective and relevant solution options, and initial attempts are underway (Jerneck and Olsson 2011; Voss and Bornemann 2011). In particular, the participatory component of sustainability science is only meaningful if the power dynamics between stakeholders and actors are explored and acknowledged. If sustainability science is going to solve problems, it must explore politics and power dynamics to negotiate solution options that answer the questions: Sustain what? For whom? For how long? At what cost?

Conclusions

Sustainability science is value laden and focused on the collaborative development of solution options. This deviates from traditional academic pursuits and requires new pedagogies and new institutional structures and incentives. Mainly, problem- and project-based learning, addressing real-world problems, must become a much larger part of the sustainability student's experience. These pedagogies can provide the appropriate setting for competency development at most educational levels.

New pedagogies require institutional support and training, as well as equal respect in promotion and tenure. A primary challenge is evolving funding criteria in support of solution-oriented research equally with traditional academic work. This particular challenge is relevant to the larger issue of explicit acknowledgment of political economies in sustainability science work.

Finally, as the world's problems continue to expand and accelerate, society is increasingly likely to demand that their universities and other research-oriented institutions provide solutions to vexing problems. In this scenario, the public may well reject more esoteric and self-oriented research communities in favor of investing public funds in institutions that create solution-oriented knowledge that is readily applicable to the problems society faces. This bodes well for the maturation and acceptance of sustainability science, since, at its core, sustainability science is about creating actionable knowledge.

The three case studies presented show various applications, successes, and challenges for sustainability science. Future research areas include: (1) implementation and evaluation of sustainability competencies in sustainability programs; (2) development of long-term trust and relationships with relevant stakeholders; (3) coordination of solution-oriented research efforts among academic, governmental, business, and public actors within explicit political economies; and (4) construction of institutional funding and support appropriate to the specific needs of sustainability science.

Acknowledgments The authors would like to thank all co-organizers, case study presenters, panelists, participants, and volunteers from the 2012 International Conference on Sustainability Science at Arizona State University (Tempe, AZ, February 20–23, 2012) for important contributions to and feedback on this article. We also recognize the support and valuable keynote inputs from ASU's President Michael Crow and Dean Pamela Matson from Stanford University. We acknowledge financial support from the University of Tokyo, Arizona State University, and the U.S. Environmental Protection Agency. We thank Michael Bernstein for editorial support.

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