The Global Sustainability Transition: It Is More Than Changing Light Bulbs

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Recommended Citation
Weinstein, M. P., Turner, R., & Ibanez, C. (2013). The Global Sustainability Transition: It Is More Than Changing Light Bulbs. https://doi.org/https://doi.org/10.1080/15487733.2013.11908103
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To cite this article: Michael P. Weinstein, R. Eugene Turner & Carles Ibáñez (2013) The global sustainability transition: it is more than changing light bulbs, Sustainability: Science, Practice and Policy, 9:1, 4-15, DOI: 10.1080/15487733.2013.11908103

To link to this article: https://doi.org/10.1080/15487733.2013.11908103

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Published online: 05 Oct 2017.

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The global sustainability transition: it is more than changing light bulbs

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Current policies and norms to reconcile human demands for resources with the Earth's ability to supply them have resulted in practices that mainly treat the symptoms of unsustainability rather than their underlying causes. Moreover, the increase in our knowledge about humankind’s role in ecosystems is not keeping pace with our understanding of the consequences of our actions, resulting in a deepening inability to address sustainability issues. The extreme complexity and intricate workings of the world require the expansion of our mental models in a systems-thinking framework if we are to realize a sustainable place for humans in it. The challenge of the emerging transdiscipline of sustainability science lies in developing specific tools and processes, including curriculum development and a new generation of systems models, to help us better understand complexity—uncertainty and surprise, scale, hierarchy, and feedback loops—and to educate a new generation of sustainability scientists to design better policies, to facilitate social learning, and to catalyze the technical, economic, social, political, and personal changes needed to create a sustainable world.

KEYWORDS: sustainable development, rights of future generations, interdisciplinary research, technology, education, public policy

Introduction

Un-sustainability is an inevitable emergent property of the systemic interaction between contemporary global society and the ecosphere.

William Rees (2012)

Humankind has become a dominant force of nature, shaping the global landscape, exerting unprecedented pressures on the planet’s resources, and pushing the Earth’s biophysical system far outside of its historic operating range (Steffen et al. 2005). It is not just the patterns and functions of many ecosystems that have changed during the Anthropocene era (Crutzen, 2006), it is that they are also increasingly framed within the context of climate change, habitat degradation, globalization of species distribution, and loss of biodiversity, all caused by the evolving suite of intense human activities. Peterson-Meyers & Reichert (1997) ask, “[H]ow much of the Earth’s ecological integrity can we disrupt before we pass a threshold in the loss of life support services?” In fact, “threshold behavior” may already be a pervasive characteristic of key global social-ecological systems, including trade (e.g., market “bubbles”), finance (stock-market collapses), food (famine), and resource extraction (supply-demand cycles) (Westley et al. 2011).

Defying our best intentions, the future consequences of these changes will likely be to dehumanize and stratify society and to create catastrophic instabilities, but unfortunately, not to effect a transition toward qualitatively desirable sustainability. Although important, the “sustainable practices” that society increasingly engages in are insufficient to create sustainable systems because, as Sterman (2012) notes,

[M]ost efforts by firms, individuals, and governments in the name of sustainability are directed at symptoms of unsustainability rather than causes…policies to reduce waste, cut energy and material use, reduce greenhouse gas emissions, promote green products and local consumption…fail to address the underlying source of the unsustainable world we have created…[a] focus on symptoms and low-leverage policies reflects a widespread failure of systems thinking.

In other words, we seem to be moving along a path where innovation is primarily leading to optimi-
zation of the status quo rather than to system innovation. As van der Leeuw (2010) comments, there are warning signs that technological innovation, “far from serving human needs, is driving development in directions potentially opposed to sustainability.” Clearly, the transition to sustainability will require more than changing light bulbs!

The issues of sustainability are, therefore, broad, interrelated, and all-encompassing. This situation is problematic because opinions about how to transition to a sustainable world are about as diverse as their proponents! We adopt here a systemic approach to building capacity for the necessary transition by: 1) providing a general overview summarizing six major challenges; 2) addressing these challenges within the context of the nascent field of sustainability science; and 3) providing suggestions for key areas of attention. We do not claim that these are the only ways forward, but rather that they are essential, fertile components in bringing an obvious set of conclusions within the sustainability community to the general population and to various governance institutions and functions.

Knowing the Challenges

Challenge 1: Naiveté and the Bretton Woods Conference

World leaders assembled in Bretton Woods, New Hampshire in the waning days of World War II to plan the aftermath of the most devastating conflict in human history. In his concluding remarks at the conference, Henry Morgenthau, then Secretary of the Treasury of the United States, commented that the goal was to rebuild Europe and Asia by recreating:

A dynamic world economy in which the peoples of every nation will be able to realize their potentialities in peace…and enjoy increasingly the fruits of material progress on an earth infinitely blessed with natural riches [emphasis added] (quoted in Daly & Farley, 2004).

During the intervening years, the world’s population has roughly tripled, per-capita resource throughput has increased more than nine-fold, and billions of people have been unable to overcome poverty. Morgenthau’s first goal, realizing our human potential, was directly linked to economic prosperity perceived as having no fixed limits. The coupling of human potential (above a minimum need) with economic development was an acceptable premise in the 1940s, and today remains the dominant development paradigm. We treat the world’s material resources and ecological systems as infinitely regenerative.

However, as William Rees (2012) notes, “the growth-oriented values and assumptions underpinning contemporary economic models and consequent ‘environmental’ behavior are fundamentally at odds with the biophysical laws and dynamics governing vital ecosystem and geophysical processes.” It is difficult to envision any politically acceptable reform of the prevailing paradigm that would produce a sustainable relationship between the modern human enterprise and “nature” if we are to have shared governance. Rees and many others have also suggested that the global human enterprise is currently in a state of overshoot. Our aggregate energy and material consumption and waste production have begun to exceed the ecosphere’s regenerative and -assimilative capacities. Thus, the magnanimity of Morgenthau’s goal for humanity is compromised by the naïveté of the linked economic paradigm.

Moreover, decision makers throughout society increasingly recognize that the policies we implement have not only failed to solve our persistent sustainability problems but are, in fact, causing them (Sterman, 2012). Well-intentioned programs, for example, may create unanticipated “side effects.” The pesticide DDT and polychlorinated biphenyls (PCBs), for instance, have wondrous industrial properties that dramatically improved human health, safety, and quality of life in the short term, but the result has been “policy resistance,” the tendency for interventions to be defeated by the system’s response to the intervention itself (Sterman, 2012). The challenge, therefore, is to embrace a new narrative about human well-being without the slavish attachment to illusory economic compromises.

Challenge 2: Earth Demands in the Anthropocene

How do we reconcile human use of the Earth’s natural resources with the planet’s ability to provide them at sustainable levels? The challenge is to learn how to make the transition from the threatening set of present circumstances to a sustainable Earth system that encourages, not just allows, realization of Morgenthau’s human potential. One way is to examine the assumptions and outcomes of our own decisions. Even though human society cannot be manipulated as if in a laboratory experiment, the interactions between humans and their environment are, as many have suggested, suitable subjects of rigorous scientific analysis and advancement to improve our understanding of the threats to, and opportunities for, sustainable development (NRC, 2002). Tradeoffs, sacrifices, and compromises will be needed to make use of this improved understanding, and so learning about the consequences of how we manage the global commons is essential. Successful conflict manage-
ment and consensus building is also important. Both require innovative approaches and the rediscovery of proven ones. A successful transition to sustainability will involve critical advances both in new knowledge and in humankind’s social and technological capacity to turn that knowledge into action (NRC, 2002). This is the essence of the emerging field of sustainability science (Kates et al. 2001; Clark & Dickson, 2003), and is the core fabric of the modern institution that seeks the knowledge, experiential base, and wisdom necessary to maintain human-environment interactions on sustainable trajectories.

The sustainability transition must, therefore, consider the dynamics of evolution and the complex interplay of social, economic, and natural systems. The required integration of disciplines goes beyond individual areas of study—population, economy, water, food, energy, and climate—to identify the common threads and drivers of systemic change.

**Challenge 3: Economies and Energy Use**

An example of these integrative biophysical-social dynamics is the dependence of the world’s economy on energy and other resources to manufacture goods, to provide services, and to create capital. The direct relationship between energy use and Gross Domestic Product (GDP) reveals the central role of energy in the economies of nations and underscores the limits imposed on any global economic growth model.

Several emergent properties of the relationship are shown in Figure 1. First, the ecological footprint of humans on Earth, or the aggregate influence of per capita resource consumption and waste production, increases with energy use and GDP. It has not been possible to increase socially desirable goods and services without raising the use of resources or increasing environmental degradation, i.e., climate change, habitat loss, pollution, and reduced biodiversity. Second, to support the projected global population of 9.5 billion by mid-century with a standard of living approaching that of the United States would require about 268 terawatts (1 terawatt = 10^{12} watts) of energy, or about sixteen times current global energy use (Brown et al. 2011). Third, of the eleven recessions in the United States since World War II, ten, including the most recent, were preceded by a spike in oil prices (Murray & King, 2012). Finally, although some economists have dismissed warnings that energy shortages might ultimately limit economic growth because of the belief that technological innovations will always meet demand, there is little or no scientific support for the latter proposition (Brown et al. 2011).

Ominously, there is evidence of threshold changes appearing. Since 2005, for example, the oil market has tipped into a new “system state” that is similar to a phase transition in physics: oil production is now “inelastic” and unable to respond to rising demand (Murray & King, 2012). Among the challenges we have to recognize and address are the subtleties and compromises of our relationships with nonrenewable energy, to optimize what we use, and to prepare for pending scarcities.

**Challenge 4: Urbanization**

The climate crisis won’t be solved by changing light bulbs and inflating your tires more, planting a tree and driving a little less. It’s going to require a truly fundamental shift in how we build our cities and live in them.

Richard Register (2009)

A second example of these complexities is a worldwide process of urbanization that increasingly defines the human ecological niche and its planetary “footprint” (Rees, 1992). Cities comprise the major habitat of the dominant species on the planet and make unmatched biophysical demands on the ecosphere. The future organization and functions of cities will demonstrate how well we are creating sustainable systems. Urbanization is the greatest mass migration of people in history, and its pace is accelerating. The United Nations projects that the world’s cities will add 2.9 billion people over the next 40 years, which is more than had accumulated on Earth in the entire history of H. sapiens up until 1957, and...
more than the anticipated increase in total human numbers of 2.3 billion (Rees, 2012). Like the ecosystems, cities are self-organizing dissipative structures existing far from thermodynamic equilibrium. They are open, growing, dependent subsystems of the materially closed, non-growing finite ecosphere. Yet, while the ecosphere evolves and maintains itself by “feeding” on an extraterrestrial source of energy and by continuously recycling matter, cities grow and maintain themselves by “feeding” on the rest of the ecosphere and ejecting their wastes back into it (Rees, 1992; 2012). Cities are heterotrophic nodes of intense energy/material consumption and waste generation that are entirely dependent on the productive and assimilative capacities of complementary producer ecosystems often located at great distances from the cities themselves. They are urban parasites of the rural landscapes. In other words, cities can grow and increase their internal order only by “disordering” the ecosphere and increasing global entropy (disorder) elsewhere.

Importantly, this process of urbanization creates a dramatic shift in city-dwellers’ spatial/psychological relationships to the land, but there is no corresponding change in eco-functional relationships. Despite this psychological shift, decoupling people from nature, in a material sense, urbanization generally increases human per capita “load” on the cities’ surrounding ecosystems. Failure to understand the basic facts of urban human ecology may doom our quest for sustainability and increase the vulnerability of cities to global ecological change. Understanding the ecology and management of cities and their dependent relationships with the countryside is a fundamental challenge of sustainability science.

Challenge 5: Controlling Nature
Humans have a duty to restructure nature for their survival.

Freeman Dyson (quoted in Dawdoff, 2009)

This anthropocentrism expresses humankind’s faith in its technology and knowledge to manage nature, with the supposition that “survival” is sufficient. We are a product of evolution and have been “trained” to do whatever it takes to survive, which is perhaps the “duty” that Dyson refers to. The polar opposite to this knowledge-based worldview is an ignorance-based one that holds we know very little about many things, and not much about most (e.g., Vitek & Jackson, 2008; Turner, 2009). The problem is not whether natural systems are going to change because of human influences—but how this happens and to what end. There was more than just survival in mind when Morgenthau spoke of the human “potentials in peace.” Because fluctuations in nature impose problems in meeting production goals, the strategies for controlling environmental variability and natural disturbance become essential for managing nature. Unfortunately, such practices create a model in which humans attempt to dominate nature in the sense that nature is to be conquered, controlled, and ruled (sensu Holling & Meffe, 1996; Folke et al. 1998).

This “command and control” approach to environmental management is still today’s modus operandi and has not been effective in keeping global growth tracking along sustainable trajectories. In fact, a case can be made that reducing uncertainties in natural systems themselves damages the values that we aim to preserve. The “paradox of the dual mandate” remains at the very heart of the matter (Roe & van Eeten, 2001): whereas complexity, interdependence, high levels of uncertainty, unpredictability, and dynamism characterize natural systems—traits that prevent competitive dominance by any one species—human-dominated systems seek predictability and stability to ensure uninterrupted provision of resources for human use. The need for resolution of the paradox arises from society’s desire to preserve, restore, and rehabilitate natural ecosystems that are defined by disorder in key factors (see below), while at the same time ensuring the provision of reliable, predictable, and stable supplies of goods and services (Roe & van Eeten, 2001; Weinstein et al. 2007). The acceptance and/or resolution of this paradox is at the forefront of the sustainability transition.

Challenge 6: Ecosystem Resilience
Sustainability implies maintaining the capacity of ecosystems to support social and economic systems over the long term. This capacity for ecosystem resilience is an underlying feature of sustainable systems (Gunderson & Holling, 2002) that cannot be predicted or understood simply by understanding its parts. As Berkes et al. (2003) note, it has three defining features: 1) the change that a system can experience, but still retain the previous controls on structure and function and degree of attraction within a sustainable trajectory; 2) the capability of the system for self-organization; and, 3) the ability to optimize capacity for learning and adapting. Resilience is a promising concept because it provides a framework for maintaining stability in the face of change, and as Berkes et al. (2003) comment, “[I]t’s synonymous with ecological, economic and social stability.” But it is also important to note that ecosystem resilience is not defined as a return to equilibrium; rather as a consequence of complexity, multiple states, or domains of attraction and multiple equilibria coexist simultaneously in ecosystems. Understanding and promoting ecosystem resilience is another key chal-
challenges of the sustainability transition.

These six challenges (C1–C6) together constitute a substitute narrative for the present paradigm. The new paradigm effectively confines a worthwhile goal of developing human potentials with a shallow economic framework (C1) functioning within present (and frequently unknown) complexities (C2) that involve precarious dependencies on energy (C3) that in turn drive massive urbanization at the planetary scale (C4). Working our way toward a high-quality sustainable system requires the acceptance of uncertainties of the natural system, even as predictability in the social goals is sought (C5), along with formal appreciation in the governance structure and function of ecosystem resilience as a precondition for societal well-being (C6).

Meeting the Challenge(s): Systems Thinking

Because of the complex relationships among people, ecosystems, and the biosphere, human health and well-being are closely linked to the integrity of local, regional and global ecosystems.

National Science Foundation (2002)

The challenges described herein are significant and deeply-rooted, so that any worthwhile sustainability transition will require a comprehensive understanding of the complexity and interactions within coupled human-environment systems (CH-ESs), and an ability to forecast the consequences of our actions. Knowing the challenges is one thing, but addressing them makes it necessary to develop the specific tools and processes that will help us design better policies, facilitate social learning, and catalyze the technical, economic, social, political, and personal changes needed to create a desirable and sustainable society.

It is a challenge to synthesize new knowledge emanating from sustainability science in policy-relevant ways (Carpenter et al. 2009), because this requires problem solvers at all levels to harness science and technology from anywhere in the world (Steffen et al. 2005). Synthesizing new knowledge also addresses the widely recognized problem of the application of scientific results for decision support and decision making. The decision process itself needs analysis (Anderties et al. 2010) and it is absolutely essential to understand what kinds of institutions can best perform these complex bridging roles, i.e., act as boundary organizations between science and policy across multiple scales and across the social and natural science disciplines and do this under a wide range of social circumstances (Steffen et al. 2005).

Partnerships are needed to facilitate the engagement of scientific, technological, and political and social sectors to support environmentally sustainable human development globally and to build a truly international community for sustainable development. It is important to engage nontechnical with technical fields and lay and professional communities in ways that allow all to participate meaningfully and at different scales and dimensions. Doing this is a task of sustainability science, a new field of formal inquiry with immediate relevance. It is worthwhile, we think, to look at its origins to understand its potential for further development.

The Emergence of Sustainability Science and Systems Thinking

Today’s challenges are the result of systems that we have created...it is the unanticipated side-effects of our own actions, side-effects created by our inability to understand and act in consonance with our long-term goals and aspirations...[To address this issue] system dynamics will help us expand the boundaries of our mental models...help people see themselves as part of a larger system, so that we become aware of and take responsibility for the feedbacks created by our decisions...that shape the world in ways large and small, desired and undesired.

John Sterman (2002)

Two insightful and influential reports from workshops held at Friibergh (Sweden) and at the Airlie Center, Warrenton, Virginia (United States), in 2000 and 2009, respectively, summarized the global sustainability challenges and led to a formal definition of sustainability science (Kates et al. 2001; Levin & Clark, 2010). The discussion at Friiberg revealed profound differences in perspectives among scientists in developed countries versus those in developing countries (Kates, 2012). Scientists in the former focused primarily on global issues, whereas their colleagues in the latter addressed principally local matters. The two groups were separated by a variety of economic, technological, and capacity divides. Northern scientists worried about the effects of affluence and consumption as well as climate change and its causes, and undertook theory-driven research. Southern scientists, in contrast, worried about the effects of poverty and underconsumption and the impacts of climate change, and pursued action-driven investigations. Such differences notwithstanding, the workshop also reflected broad agreement that science and technology have an enormous potential to facilitate a sustainability transition. As Kates (2012) notes, realizing that potential will require serious efforts to promote a science for sustainability.

At the more recent event in Virginia (Levin & Clark, 2010), six sets of thematic research were iden-
tified, including the necessary tradeoffs between natural and human systems and the need for rigorous evaluation of sustainability trajectories focused on a systems approach and a new generation of models. Emphasis on CH-ES tradeoffs and sustainability trajectories was an underlying theme of the workshop. Both the Fribergh and Airlie Center meetings identified the basic need for better theory and models to bridge the gap between scholars with expertise in modeling (but not in CH-ES) and empirical scientists knowledgeable about CH-ES (but not modeling complexity). Participants suggested that only in climate modeling had there been a significant improvement in the merger of theory and models.

The participants at Airlie Center noted that “the time is ripe for developing a general characterization of how alternative patterns and processes in the human use of nature result in different tradeoffs, with the goal of understanding how maximal human well-being can be secured from the available ‘natural capital’” (Clark & Levin, 2010). The attendees concluded that advances in agent-based and network approaches to the modeling of complex systems “offer promise of doing better as do several approaches to the nonlinear systems and the development of [transdisciplinary], multi-scale scenarios.” Attending scientists expected major gains from employing new modeling approaches to a few well understood human-environmental systems, and similar benefits might be realized by developing model systems such as those employed in ecological and medical research (Clark & Levin, 2010). The “technology transfer” of forecast outcomes of CH-ES interactions would, for example, be facilitated by adaptive governance, collaboration, and institutional flexibility (Armitage et al. 2007).

One of the key challenges in forecasting future trajectories was also discussed at Airlie Center: What are the likely unintended consequences—both social and environmental—of adaptation and diffusion of new technologies and how well can these consequences be predicted before wide-scale adoption and diffusion of new technology? (Chan et al. 2010). It is here that the systems approach and systems thinking take center stage.

**Systems Theory and Complex Adaptive Systems**

Systems theory is concerned with both wholes and wholeness. It emphasizes connectedness, context, and feedback as underlying components and processes. The understanding arising from systems theory comes from integrating knowledge of how parts of the system work together, rather than how they work in isolation. Of particular interest to sustainability scientists is the observation that complex adaptive systems (CAS) also have emergent properties and phase transitions not normally observed in simpler systems: nonlinearity, uncertainty, multiscale interactions, emergence, hierarchy, and self-organization (Levin, 1998; Anderies et al. 2010; Solé, 2011). CAS structure is often hierarchical or nested. Phenomena at each level tend to have their own emergent properties that are coupled by feedback loops and allow the system to be self-organizing and buffered against external forcing. Most importantly, because of the multiplicity of scales, there is no one “correct” perspective on a complex system. CASs are comprised of agents that interact locally based on information they use to adaptively respond to their environment. Behaviors typically emerge from such interaction that are not imposed or predetermined (Levin, 1998; 2010). Unlike their linear counterparts, numerous potential equilibria may co-occur as multiple stable states or stability domains in CASs (Holling, 2001).

The concept of CASs may be extended further to address the interrelationships between humankind and nature in CH-ESs (Gunderson & Holling, 2002; Berkes et al. 2003; Anderies et al. 2010). CH-ESs can also organize around one of several equilibrium states (or “attractors”). When conditions change, feedback loops act to maintain the current state, but at a certain threshold the system may move to a new stable state. Like any CAS, CH-ESs are often unpredictable. An important observation of the behaviors in CH-ESs is that they cannot be understood, let alone managed, through scientific activity organized along traditional disciplinary lines (Jasanoff et al. 1997), but require a transdisciplinary approach. While sustainability science focuses on macroscopic interactions between humans and their environment, it must be recognized that control may rest at lower levels of organization (Levin, 2010). Thus, a more complete, more systemic understanding of emergent behavior in CH-ESs is critical to unraveling how such systems can promote sustainable development (Anderies et al. 2010).

**Where Do We Go From Here?**

If the “naïve” narrative is abandoned by governance institutions and decision makers, as it should be, then a stronger, more appealing sustainability narrative must take its place. A potent vision is needed, therefore, to maintain the compass heading, and there is nothing quite like an “unfair” system to undermine cooperation and a sense of community (Turner, 2012). For instance, Wilkinson & Pickett (2009a; 2009b) have shown in myriad of ways how economic stratification is correlated with social dysfunction, e.g., teenage pregnancies, imprisonment, health problems, educational disparities, and other social problems including mental illness, incarceration, obe-
Wilkinson & Pickett (2009a; 2009b) discuss numerous direct relationships between the scale of income disparity and negative social attributes. Source: http://www.slideshare.net/equalitytrust/the-spirit-level-slides-from-the-equality-trust.

At some threshold, or series of thresholds, we lose the time and resources to make wise choices.

There is no learning without feedback or without knowledge of the results of our actions. Traditionally, scientists generate that feedback through controlled experimentation, an iterative process through which intuitions are challenged, hypotheses tested, insights generated, and new experiments run. However, reductionist methods and experiments are impossible to deploy in many of the most important complex systems, including several critical for sustainability. When actual experimentation is impossible, scientists rely on models and simulations that enable controlled investigations in virtual worlds (Steffen et al. 2005; Andersson et al. 2010). Our inability to accurately predict the weather or economic trends without improved models are just two examples.

Simulation models have long been central in sustainability and environmental research; however, simulations are not only useful in knowledge creation, but must also become a main tool in knowledge communication. They are already powerful tools to support management approaches. Integrated earth-system models, for example, allow many scenarios of interacting natural and human-driven changes to be developed and evaluated. In addition, the models and scenario development that follow from them must evolve further through integrated transdisciplinary research and in continuing dialogues between the scientific community and policy makers at a variety of levels (NRC, 2002; Steffen et al. 2005; Kates, 2012). More use-inspired research is needed, however, to support sustainable development at the global scale (Levin & Clark, 2010; Kates, 2012).

There is much more, of course. Carpenter et al. (2009) summarize studies including the Millenium Ecosystem Assessment’s attempts to synthesize scientific knowledge about the capacity of global ecosystems to support human well-being. The authors call for a new generation of integrated quantitative models across a range of coupled social-ecological systems that would be essential for research, synthesis, and projections of the consequences of management actions. Topics would include addressing non-linear changes and improving the assessment and

\[\text{See http://www.maweb.org.}\]
communication of uncertainty. Moreover, these new models would have the capacity to consider spatial boundaries of systems, units of analysis, time horizons, inputs and drivers, scale, as well as key components of the system and their relationships and outputs (Carpenter et al. 2009). Finally, the authors conclude that a great deal of work is still needed to make these models an operational part of the sustainability scientist’s “toolkit” that might also include scenario methods coupled with the evolving models.

To move beyond slogans about interconnectedness and systems, however, we also need specific tools and methods to develop our systems thinking capabilities, methods that avoid both self-defeating pessimism and mindless optimism, while simultaneously embracing the values of the scientific method and ecological realities (Chapin et al. 2010; Graedel, 2010). Interactive, transparent simulations for learning, grounded in the best available science, now exist for a wide range of sustainability issues. To enable learning, Steffen et al. (2005) comment,

> These management flight simulators must give people control over assumptions and scenarios, encourage wide-ranging sensitivity analysis, and run nearly instantly online or on ordinary desktop and laptop computers, so that people receive immediate feedback. When experimentation is too slow, too costly, unethical, or just plain impossible, when the consequences of our decisions take years, decades or centuries to manifest, that is, for most of the important issues we face in building a sustainable world, simulation becomes the main—perhaps the only—way we can discover for ourselves how complex systems work, where the high leverage points may lie.

A new generation of systems models will be required that address 1) spatial and temporal heterogeneity; 2) nonequilibrium properties and scale dependence, and 3) the coupling of pattern and process. In a recent treatise, Liu et al. (2007) review six case studies that explicitly examine complex interactions and feedback in CH-ESs. The authors conclude that future research on complex systems must include not only individual site-specific studies, but also “coordinated, long-term comparative projects across multiples sites [and scales] to capture a full spectrum of variation.”

### Education in a Sustainable World

*Education is critical for promoting sustainable development and effective public participation in decision-making.*

United Nations (1992)

Sustainability science is both problem driven and solution oriented, and is underpinned by “use inspired” research (Stokes, 1997). Grounded by traditional educational goals, among them critical thinking and social learning, sustainability science goes beyond these fundamentals to introduce and apply “new” knowledge as transformational action in participatory, deliberative, and adaptive settings. More than ever, the skill profile of future graduates will be those of problem solvers, change agents, and transition managers. By acquiring “key competencies” for problem solving in a complex world, sustainability science graduates will be set apart from traditional bounded disciplines (Wiek et al. 2011).

Much has been written about emerging sustainability curricula in higher education, but these skills generally fold into a new toolkit that can address multiple interacting stresses on CH-ESs. In addition to “use inspired research” and transdisciplinary curricula, the new education and outreach paradigm will take many forms: 1) improved communication with government, decision makers, the media, and the general public to convey the urgency of sustainability challenges; 2) development of new policy-formulation tools, including systems modeling and other simulations, visualization methods, and appropriate metrics, that recognize the complex, interconnected nature of ecological and socioeconomic systems; 3) introduction of an awareness of ecological systems into commerce, as in the emergence of integrated energy-management services and sustainable architectural practices; and 4) development of mechanisms for integrated dialogue among industry, government, and academia, shifting from an adversarial to a cooperative approach.

### What Skill Set and Knowledge Do Students Need to Acquire?

First, many scientists and decision makers have suggested that achieving sustainability will require a “solutions orientation” that includes addressing tradeoffs among different solution pathways. A useful description of the difficulty is that when:

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2 Social learning is vetted in the slow, interactive accumulation of scientific knowledge, technical capacity, management institutions, and public concern over extended periods (generations).
Multiple desirable but competing objectives exist, it is not possible to maximize each... and in any system with multiple competing objectives, it will not be possible to meet every one.

United States Commission on Ocean Policy (2004)

Second, sustainability science graduates should be skilled in moving beyond a limited focus on immediate problems to constructively reframing challenges within complex systems in terms of overall success (Basile, 2011; Vincent & Focht, 2011). That is, they should be able to address challenges not only in classic ways, such as on the factory floor or within institutional reach, but also in terms of success at increasing scales in both the short and long term.

Finally, the competencies gained will function in complex systems when future graduates are engaged with experts and nonexpert decision makers in contexts with inherent uncertainty, i.e., in almost any real-world situation where one seeks sustainable solutions.

Graduates with this mix of skills can help others understand, think, and act across multiple parts of a system. A graduate in sustainability understands mixing use-inspired research with values and cultural and ethical decision-making perspectives across the natural and social sciences as part of the process of building lasting strategic outcomes in the effort to achieve a sustainable world (Basile, 2011; Vincent & Focht, 2011). Rather than the “silo” mentality that has placed us in this untenable situation in the first place, it becomes a matter of the following:

- Redefining planning boundaries and horizons in terms of sustainable success.
- Understanding and managing resource potentials, and handling tradeoffs and compromises while minimizing new sustainability problems.
- Integrating the growing knowledge and tool base into increasingly robust and flexible strategic pathways.
- Supporting cross-sector collaboration and cooperation.
- Embracing uncertainties inherent in our emerging planning reality.
- Translating all of this into practicality given today’s context of unsustainable concepts and institutions.

To be clear, this transition is not limited to higher education. It can be used spectacularly in the K–12 classroom. Peter Senge (2012) tells the story of a 12-year old, Annalise, and her classmates, who, after gaining approval from the school principal, parents, mayor, and town council, built a wind turbine at her school as part of a sustainability teaching module. Following a four-minute project presentation to 250 local residents, she “set aside her notes and standing calmly, some 75 pounds of fierce determination, said, ‘We children are often hearing that “you children are the future.” We don’t agree with that. We don’t have that much time. We need to make changes now. We kids are ready, are you?’”

Sustainable Governance Incubators

Annalise’s sentiment about being “ready” is worthy of further commentary. If a system is too complex to reduce to its component pieces without losing sight of the whole system’s behavior, and if there are more unknowns than knowns, then we are led to the challenges of assembling a new sustainability paradigm. When would we be ready? As we move forward, rather than thinking of a stepwise process of ending one phase (preparation) and beginning another (implementation) we might think of an ongoing integrated process. In other words, we will not be ready all at once, but in stages. Because the clarity of science is an essential component of decision making, and because we are also influenced by our experiences internally and externally, we need to look at the transition as an evolving social contract. The path of transition, therefore, is wide, incorporating social, economic, political, and other fields traditionally engaged less intensely than they need to be.

Numerous initiatives are underway or in planning stages that increase the “what, why, and when” of sustainability in practice as part of this ongoing process (Table 1). The idea is to build something like social incubators, experimental social sets, demonstration organizations, or quality centers that bring all the issues out in the open for the community to work with, and with recognizable consequences. The country of Bhutan, for example, is on a path that seeks to integrate equitable social opportunity and economic development with environmental conservation and participatory governance. The country’s young king has substituted the concept of “gross national happiness” for GDP to indicate priorities in a national program embracing sustainable systems as the goal.

Several watershed-sized agricultural projects in the American Midwest are working on sustainable practices, but with a suite of governance tools restricted by national farm policies, global commodity pricing, and historical precedents. One proposal suggests that society needs to build on the entrepreneurial and innovative energy of Midwestern farm communities by creating examples of shared governance...
that others can follow (Peterson et al. 2011). The participants would have nearly complete oversight over their watershed. This approach can simultaneously address water-quality problems contributing to the “dead zone” in the Gulf of Mexico and increase the productivity and resilience of Midwest agriculture. How might this be accomplished at the level of the whole landscape? Start at a meaningful scale; learn what works; put trust in regional democracy. Do it by creating watershed-scale “incubator” projects that build on the smaller-scale projects. But, at the same time, these projects must be large enough (5,000 square kilometers) to capture the ecological, social, economic, and political complexities of modern farming. They should have watershed-scale governance based on shared responsibilities for clean water, a healthy environment, a robust economy, and equitable access to resources.

**Conclusion**

The underlying principles of sustainability science and the new “social contract” for science (Lubchenco, 1998) contend that a sustainable biosphere is not only necessary, but economically feasible, socially just, and ecologically sound. With “use inspired” research as its underpinning, the discipline must be broadened to encompass the overarching

### Table 1 Examples of programs and experiments in CH-ES system transitions to sustainability.

| Content/Subject                                      | Scale                                      | Infrastructure Support                                                                 |
|------------------------------------------------------|--------------------------------------------|----------------------------------------------------------------------------------------|
| Global Visions and Cooperation                       | Rio+20 Summit                              | National governments, United Nations                                                   |
| Strategic visions for biodiversity and ecosystem services | Global                                    | DIVERSITAS                                                                              |
| Global Visions and Cooperation                       | Global                                     | Rockefeller Brother’s Fund, Sustainable Development Program                            |
| Global Visions and Cooperation                       | Global                                     | Tellus Institute, Widening Circle Campaign for a Global Citizen Movement                |
| Consortium on relationships between climate change, agriculture and food security | Low- and middle-income countries | Consortium of International Agricultural Research Centers, United States Agency for International Development, Canadian International Development Agency, European Union, and others |
| Gross National Happiness Index                        | National                                   | Royal Government of Bhutan                                                              |
| Interdisciplinary research on coupled human-environmental systems | National                               | United States National Science Foundation, CH-ES Program                               |
| Study and understand sustainability issues            | Qualitative and quantitative analysis of the institutions, infrastructure, and developing issues | United States National Academy of Sciences, Sustainability Science Section               |
| Biophysical couplings within agricultural policy      | Mississippi River watershed                | United States National Science Foundation, CH-ES program                               |
| Agricultural Landscape: shared governance of sustainable landscapes to restore Gulf of Mexico | 5,000 km²                                | Pew Foundation Recommendation, Macondo Oil Spill                                       |
| Creating community peace at the local level, including with the natural world | Newark Peace Education                    | Tibet House, Foundations, Office of the Mayor of Newark, New Jersey                     |
| Institutional collaboration for sustainable systems    | Global                                     | Stockholm Resilience Center, Arizona State University, Portland State University, Australian National University, and Uppsala University |
| Sustainability programs in higher education           | Arizona State University, Portland State University | Traditional                                                                          |
| Multi-institutional courses in sustainability         | Arizona State University, Cornell University, Florida International University, Harvard University, University of Minnesota, National University of Mexico, Princeton University | National Center for Ecological Analysis and Synthesis                                   |
| Professional journals                                 | Solutions; Current Opinion in Environmental Sustainability; Sustainability: Science, Practice, & Policy; International Journal of Agricultural Sustainability | Foundations, individuals, public agencies, professional societies; for profit publishers |
question: at multiple scales and over succeeding generations, how can the Earth, its ecosystems, and its people interact toward the mutual benefit and sustainability of all? Creating an effective science of sustainability and building the public understanding required for action requires us to develop the skills to recognize the boundaries of our models and then to expand them so that we become aware of, and take responsibility for, the feedbacks created by our decisions (Sterman, 2012). And these feedbacks are not static. Westley et al. (2011) referred to human shortcomings as an “ingenuity gap” between the increasing seriousness of global sustainability problems and the lagging supply of solutions. We come to the realization that knowledge about our role in the environment cannot keep pace with the presently poorly understood consequences of our actions.

John Sterman (2002) wrote that “overcoming policy resistance and building a sustainable world requires meaningful systems thinking coupled with community engagement in promoting the common good.” It requires new knowledge gained from use-inspired research (Stokes, 1997; Kates, 2012) and rigorous applications of that research to expose our hidden assumptions and biases. It entails engagement of all scientists to face the ethical issues raised by growth and inequality and to speak out for a just, equitable, and sustainable world (NRC, 2002; Steffen, 2010). It obliges us to listen with respect and empathy to others. It compels humility and the courage needed to lead in the face of uncertainty. Sterman (2012) said it so very well: “If we devote ourselves to that work we can move past denial and despair to create the future we truly desire—not just for us, but for our children. Not just for our children, but for all the children.”

Acknowledgement
We thank two anonymous reviewers for their insightful comments. The senior author is grateful to PSEG for funding the creation of the Montclair State University Institute for Sustainability Studies. This article, previously distributed as ISS-12-0129, is but one of the many products generated by this thriving partnership. Financial support to RET was provided by the National Science Foundation through Award DEB-1008184.

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