EDITORIAL

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Sustainability science: the emerging paradigm and the ecology of cities

Introduction

Humans are a true force of nature and human actions have taken their place alongside the biosphere, lithosphere, hydrosphere, and atmosphere as defining processes shaping the global landscape (Ellis & Haff, 2009). Much like forecasting the weather and trends in the economy, the interactions of humans and complex ecosystems (such as a food web in a tropical rainforest) are fraught with complexity, multiscale interactions, unexpected behaviors, nonlinearities, delayed responses, feedback loops, and extensive temporal-spatial heterogeneity (Levin, 1999; Wu & Marceau, 2002). In light of these circumstances, system modelers embrace spatial heterogeneity as a central attribute of ecological systems and hierarchy as a central structural theme of complexity. Accordingly, they suggest that complex ecosystems have both horizontal and vertical structure. As Sterman (2002) comments,

[S]ystem dynamics helps us expand the boundaries of our mental models...helps 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.

It is simply no longer practical to ignore the interactions between managed and natural systems in sustainable ecosystem management. Effecting a sustainability transition in the Anthropocene, or the Age of Humans (Crutzen, 2006), requires a new degree of transdisciplinary training along with better forecasting of the consequences of human actions (Naveh, 2005).

Why?

Two contexts frame the modern human condition as it affects the world’s ecosystems: 1) humankind is not living sustainably, and 2) humans are migrating to urban settings worldwide in accelerating numbers. Few priorities are as relevant or pressing in human-dominated ecosystems as the need for a sustainability transition vetted partly in the reduced ecosystem costs of population growth and urbanization. A successful sustainability transition demands critical advances in basic knowledge, in humankind’s social and technological capacity to utilize it, and in the political will to turn that knowledge and know-how into action (NRC, 2002). Moreover, the transition must consider the dynamics of evolution and the interplay of social, economic, and natural systems, ultimately combined into an integrated, or transdisciplinary, curriculum. The process goes beyond individual stakeholders and themes—populations, economy, water, food, energy, and climate—to identification of common threads and drivers of systemic change (NRC, 2002). Sustainability science seeks real world solutions to sustainability issues and aims to break down artificial and outdated disciplinary gaps between the natural and social sciences through the creation of new knowledge and its practical application to decision making (Clark & Dickson, 2003; Palmer et al. 2005; Weinstein et al. 2007).

A “New” Paradigm

In their seminal paper, Kates et al. (2001) emphasize that the resolution of competing interests is a central challenge for the sustainability transition. Both Kates et al. (2001) and the U.S. Commission on Ocean Policy (2004) note that it is impossible to maximize all competing interests in a way that will satisfy all stakeholders, or to maintain human-dominated ecosystems at some historic, relatively pristine baseline. The process of integration and the general application of sustainability science to systems research are still in their infancy and fraught with challenges, in addition to those cited above. Clearly, the structure, method, and content of sustainability science must differ fundamentally from most
science as we know it—reductionist methods alone will not be enough; also essential are parallel functions of social learning that incorporate the elements of action, adaptive management, and policy as experiment.1

Thus, sustainability science addresses the fundamental character of interactions between nature and society, and society’s capacity to guide those interactions along sustainable trajectories (Kates et al. 2001):

It has become increasingly clear that much [sic] of the workings of the world, and the challenges and opportunities these workings entail for a transition to sustainability lie in the interactions among environmental issues and human activities that have previously been treated as largely separate and distinct...in the next decade we will see research and problem-solving shift in focus from single issues to multiple interacting stresses (NRC, 2002).

The underlying principles of sustainability science contend, moreover, that a sustainable biosphere is not only necessary, but economically feasible, socially just, and ecologically sound (Lubchenco, 1998). With new science as its underpinning, the discipline must be broadened to encompass the overarching question: at multiple scales and over succeeding generations, how can the earth, its ecosystems, and its people interact toward the mutual benefit and sustenance of all? Answers lie not only in sustainability science’s transdisciplinary nature, but also in the transfer of new findings to practical uses. The practitioners of technological and economic disciplines must find better ways to design new products and processes that result in less environmental harm. Clearly, the concept is catching on in the “green” wave of new products, infrastructure, energy use, and day-to-day living.

Three challenges confront society’s ability to acquire useful knowledge through research for sustainability planning (NRC, 2002). These take the form of tensions among:

- Broadly based versus highly focused research.
- Integrative research that is problem-driven versus research grounded in specialized disciplines.
- The quest for generalizable scientific understanding of sustainability issues versus the need for place-based understanding of environment-society interactions that result in nonsustainable practices.

In addressing these challenges, the National Research Council (NRC) posited three priorities for sustainability science:

- Promoting research that integrates global and local perspectives in a place-based framework for understanding the interactions between environment and society.
- Focusing, at the outset, on a limited set of understudied questions, those that underpin the understanding of those interactions.
- Promoting more efficient use of existing tools and processes that link knowledge and action.

The NRC notes further that the process should bridge the gulf between the detached practice of scholarship and the engaged practice of engineering and management, and ultimately should broaden knowledge of the interplay of environment, economy, and social systems. The core disciplines that will provide the foundation for moving sustainability science forward include a) the biological system that emphasizes the intertwined fates of humanity and the natural resource base—biodiversity, restoration ecology, and conservation biology are essential components; b) the geophysical system that addresses climate and biogeochemical cycling and is grounded in efforts to understand the earth as a system; c) the social system that concerns itself with how human institutions, economic systems, and beliefs shape the interactions between society and the environment, and lastly; d) the technological system that enhances basic technological knowledge, designs, and processes that produce more social goods with less residual environmental damage.

Sustainability science, therefore, seeks real world solutions by breaking down artificial and outdated disciplinary gaps between the natural and social sciences through the creation of new knowledge and its practical application to decision making (Clark & Dickson 2003; Palmer et al. 2005; Weinstein et al. 2007). Above all, the sustainability transition and sustainability science are committed to bridging barriers through a transdisciplinary approach across biophysical, socioeconomic, planning, and design principles (Naveh, 2005). Sustainability science also addresses issue of scale; for example, while planetary circulation and biogeochemical cycling occur globally, sustainable landscapes (especially where humans dominate) and ecosystems are best managed at a regional or local level (Grimm et al. 2000). This message is amplified by the NRC (2002) statement that, “understanding the links between macroscale...

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1 See in particular http://sustsci.aaas.org.
and microscale phenomena is one of the great queries of our age in a wide array of sciences. The pursuit of such understanding will also be a central task of sustainability science.”

**Integrating Sustainability Science into Urban Research**

By 2050, approximately 60% of the world’s population will live in urban settings; in the United States that percentage is now nearly 80%! This demographic shift has led to regional habitat loss and fragmentation, regional and local climate alteration, depletion of water resources, and degradation of land and water by contaminants. Perhaps more than most human-dominated ecosystems, the urban setting presents a plethora of opportunities to link ecological and social science theories using resource economics concepts (Collins et al. 2000). A realistic understanding of human impacts on ecosystems will necessitate conceptual frameworks that explicitly include humans in the landscape. Such an approach is likely to better inform environmental problem solving (Grimm et al. 2000; Weinstein & Reed, 2005; Weinstein et al. 2007). Obviously, it is the human dimensions that drive political, economic, and cultural decisions that lead to or respond to change in ecological systems.

There are growing opportunities to integrate knowledge of the flows and cycles of critical resources in urban ecosystems with social and governance institutions into a new paradigm for landscape management (Zonneveld, 1989). While urban-rural gradients are complex, multidimensional constructs, the analysis of such systems has become a powerful tool for understanding ecosystems across a wide range of defining variables, stress factors, disturbances, and other drivers. Common themes in urban sustainability science research include questions of hierarchy and scale; how they are related to our ability to understand the dynamics of landscape change, biodiversity, wildlife distribution, and vegetation patterns; and the reciprocal relationships among all of these factors and human activity. Moreover, Pickett & Cadenasso (2006) note that all ecosystems inhabited by humans should be “modeled to include individuals as well as the social aggregations they generate or influence.” They suggest further that “it is perfectly reasonable to incorporate such factors and processes into ecosystem models.”

Both the Baltimore and Phoenix ecosystem studies, long-term research programs carried out under sponsorship from the National Science Foundation, have provided fertile ground for understanding the ecology of cities and offer a useful framework for extending these efforts into other urban settings. Although it is beyond the scope of this editorial to review the burgeoning literature on the subject, highlighting that emerging conceptual framework will, hopefully, capture the attention and imagination of most scientists, no matter what their current field of practice.

Zipperer et al. (2000) suggested two fundamental approaches to unraveling the dynamics and effective management of urban systems. The first, from an ecosystems perspective, considers the magnitude and control of fluxes of energy, matter, species, and information across landscapes; and the second, from a patch-dynamics perspective, focuses on spatial heterogeneity:

1. Understanding complex ecosystems including cities requires new spatial modeling approaches; among them a wide array of model types: diffusion-reaction, system dynamics, patch (or gap) dynamics, cellular automata, and fractal models (Levin, 1999).
2. Patch dynamics emphasizes spatial and temporal heterogeneity, nonequilibrium properties, and scale dependence, and facilitates the coupling of pattern and process (Wu & Levin, 1997).

Both natural and anthropogenic disturbances are frequently responsible for these processes (Wu & Loucks, 1995). By recognizing that spatial heterogeneity is a central attribute of all ecological systems, that hierarchy is a central structural theme of the architecture of complexity, and that complex ecosystems have both horizontal and vertical structure, hierarchical patch dynamics has become a promising approach to unraveling complexity because it addresses the spatial structure of landscapes; the flow of materials, energy, and information across mosaics/gradations, both as individual architectural components; and the mosaic as a whole. In short, the patch becomes the fundamental structural and functional unit of ecosystems (Wu & Loucks, 1995; Pickett et al. 2000; Wu & David, 2002), and the landscapes thus become spatially nested hierarchies that can be effectively studied as such (Wu & David, 2002).

From a transdisciplinary perspective, the research goals for the Baltimore ecosystem study illustrate the need to build sustainability science into coastal ecosystem management. They are presented here as general questions (Pickett & Cadenasso, 2006):

1. How do the spatial structures of socioeconomic, ecological, and physical features of an urban area relate to one another and how do they change with time?
2. What are the fluxes of energy, matter, human-built capital, and social capital in an urban system; how do they relate to one another; and how do they change over the long term?

3. How can people develop and use an understanding of the metropolis as an ecological system to improve the quality of their environment and to reduce pollution to downstream air, watersheds [and coastal environs]? In short, what are the institutional arrangements, constraints, and opportunities out there that test our mettle as scientists (natural, social, and economic)? My colleagues and I, members of the International Working Group on Sustainability, have tried to incorporate many of these concepts into our own descriptive approach to researching and managing coastal ecosystems (Weinstein & Reed, 2005; Weinstein et al. 2007). Thus, while the knowledge of nature in cities sets the foundation for addressing ecological processes along the urban gradient, it is not sufficient for understanding how those processes ultimately become a function of the feedback dynamics associated with interactions among social, ecological, and economic drivers.

As noted earlier, a central challenge for the twenty-first century is to address the question: how can the earth, its ecosystems, and its people interact toward the mutual benefit and sustenance of both? The urban megalopolis and its watershed present unique opportunities to grow the sustainability science agenda to encompass the following issues:

- With the anticipated doubling to tripling of urban populations worldwide in this century, how can we accommodate new infrastructure that is at once energy efficient, less material intensive, and smaller regarding the ecological footprint?
- How do we choose where and how much new infrastructure to build while understanding the potential environmental offsets in terms of reduced carrying capacity, altered thresholds, and stresses that may shift urban-industrial ecosystems to new less-desirable steady states? A critical challenge concerns the emerging science of restoration ecology and our ability to mitigate (restore/rehabilitate) system functions as the human populace expands.

The NRC (2002) called for informed dialogue on goals for a sustainability transition, a dialogue that is necessary if societies are to adopt a measure of responsibility for their choices. Such a transition should seek to purposefully target rather than passively navigate the currents of economic, environmental change. Research-informed outreach will also be a key to success. Forward-looking institutional structures will be needed to connect local end users–corporations, households, land-use planning commissions, governments, and regional research centers–into a regional management system. From a life-support system perspective, new knowledge and tools are required in three areas: improved understanding of ecosystem processes (e.g., population dynamics, interspecific interactions, and spatial-temporal variability), effective ecosystem management at the landscape scale, and monitoring programs with the statistical power to detect change against background variability.

Grounded in transdisciplinarity, sustainability science will create the new knowledge required to address the paradox of the dual mandate and the tensions associated with competing uses. Two other ingredients are also essential: (1) social learning manifested as the slow, interactive accumulation of scientific knowledge, technical capacity, management institutions, and public concern over extended periods (generations) and (2) new methodologies that generate semiquantitative models of qualitative data, building upon the lessons of case studies, and extracting “inverse” approaches that work backwards for undesirable consequences to identify pathways that avoid such outcomes (Berkes et al. 2008).

Thus, while ecological considerations and natural capital are essential, the ultimate success of sustainability science rests on social and cultural capital and is therefore a fundamental human trait. We must do a better job of managing ourselves before we can effectively manage the earth and its resources.

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2 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 require predictability and stability to ensure uninterrupted provision of resources for human use. The paradox of the dual mandate arises from the need to reconcile society’s desire to preserve, restore, and rehabilitate natural ecosystems while at the same time ensuring the provision of reliable, predictable, and stable supplies of goods and services at a time of escalating demand (Roe & van Eeten, 2001).
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