Michael P. Weinstein
R. Eugene Turner *Editors*

# Sustainability Science

## The Emerging Paradigm and the Urban Environment

Springer

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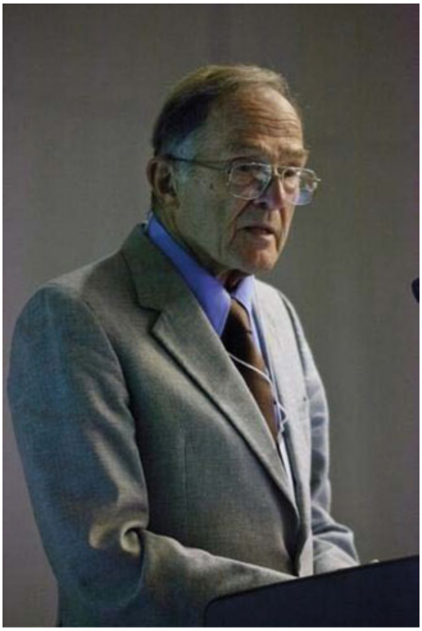

Photo by Mike Peters/Montclair State University

*This book is dedicated to Robert W. Kates,*
*a pioneer in Sustainability Science who*
*inspired a generation of systems thinkers.*

# Preface

Balancing human needs with the ability of ecosystems to provide the goods and services that we all depend on is a fundamental formula for the global sustainability transition (Fig. 1). Equilibrium can be attained either by increasing these goods and services or by reducing our consumption of them, or in today's world, both!

Furthermore, demographic shifts and new patterns of settlement have placed unprecedented pressures on human well-being, ecosystem functions, and the interactions between them. Society has yet to adequately address the challenges of diminishing resources, i.e., by facing challenges that make sustainability more feasible technologically, and simultaneously more difficult politically and economically. First, there has been a dramatic growth in per capita domestic product in many regions of the globe and an increased ability to meet human needs. Second, despite recent successes in decreasing harmful consumption per unit value of product, worldwide consumption of energy and other natural resources in industrialized nations continues to accelerate (Kates and Parris 2003; Brown et al. 2011).

Authorities worldwide have called for the prioritization of uses in order to minimize conflicts, protect resources, and ensure that all uses are compatible with sustainability goals. The public interest is addressed through recommendations to balance long- and short-term strategies with greater decentralization of governance to regional and local levels. Ecosystem-based management has been widely advocated as a central organizing principle for addressing land-use impacts holistically and reconciling multiple use conflicts at different geographic scales. Nevertheless, academicians, governance organizations, decision-makers, and the general public have yet to confront one very real issue:

> Where 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

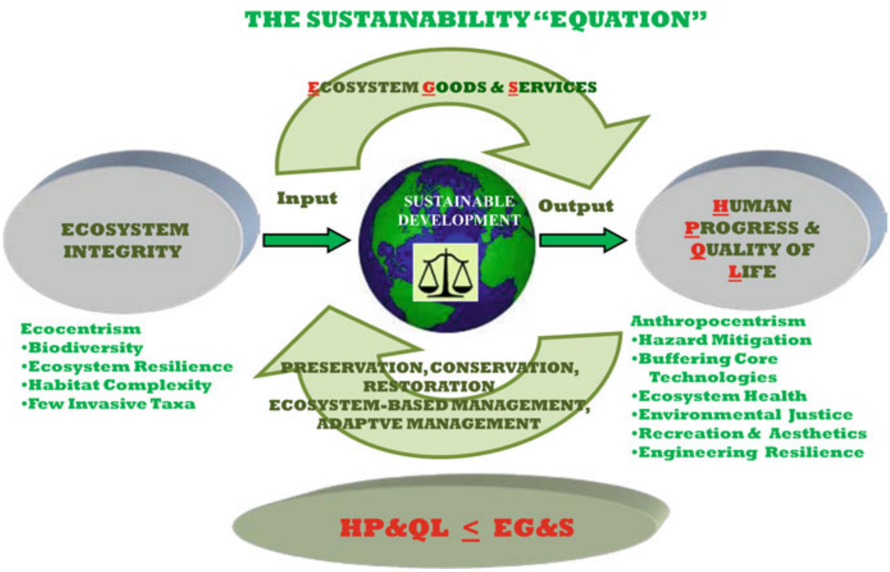


**Fig. 1** The "Sustainability Equation" balancing human needs with ecosystem integrity

Any solution to the emerging conflicts arising on the path to long-term sustainability will, in part, require the integration of the biophysical and social sciences into a new transdisciplinary science that we refer to as "sustainability science,"[1] continued development and refinement of a number of new approaches and concepts including a systems approach to problem-solving, social learning, resolution of the "paradox of the dual mandate,"[2] and enhanced incorporation of human dimensions into resource management.

There is a growing awareness that the intractability of environmental problems can be explained in part by the social context in which they arise. When perceptions of a problem vary broadly, and when there is uncertainty in the scientific assumptions and outcomes that underlie the process, then a consensus is difficult to achieve. Under such circumstances, tensions can arise among stakeholders (Fig. 2), even

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[1] There are many definitions of sustainability science; the National Academy of Sciences through its Proceedings offer the following: "…an emerging field of [transdisciplinary] research dealing with the interactions between natural and social systems … how those interactions affect the challenge of sustainability: meeting the needs of present and future generations while substantially reducing poverty and conserving the planet's life support systems."

[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 and van Eeten 2001; Berkes 2006).

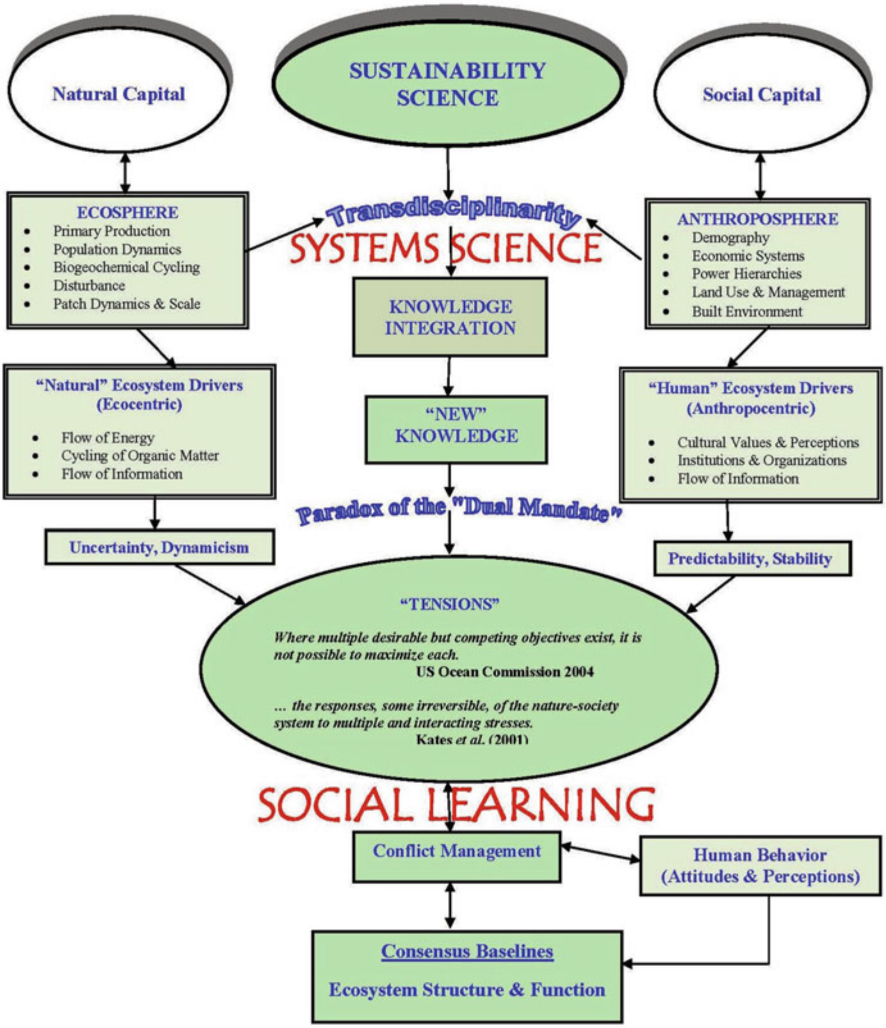


**Fig. 2** (modified from Weinstein 2009) A conceptual framework for achieving the sustainability transition through the integration of the natural and social sciences in a transdisciplinary, systems approach to managing natural and social capital. Developing "new knowledge", changing human behavior and perceptions through a lens of social learning, and achieving consensus on how to effectively manage ecosystems for sustainability will be consummated through the emerging discipline of Sustainability Science and Conflict Management. Resolution of the "paradox of the dual mandate"—reconciling 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—will be a key component of any future success

when all are committed to sustainable development (Weinstein et al. 2007). This understanding of the social character of environmental problems has focused the attention of researchers, stakeholders, and policy-makers on the important role of governance, participation, and collaborative decision-making in better managing, if not solving, environmental problems. The human dimensions of natural resource management incorporate the ways people affect, value, utilize, and benefit from ecosystems (Salz and Loomis 2005). While ecological considerations are essential, the successful implementation of sustainable management depends on, and is driven by, societal values. We need a better understanding of the human-induced causes and social drivers of environmental change and how human behavior can be made to coincide with environmental and social priorities.

Although political, economic, and social systems make up the human dimensions of natural resource management, natural resource values originate in only the social system (Kennedy and Thomas 1995; Ayensu et al. 2003). These values are manifested as environmental laws, national and local budgets, volunteerism, voting behavior, and management decisions and largely determine the fate of the natural systems that sustain societies. Implicit in the human dimensions approach is not whether ecosystems will persist—they will—but rather what trade-offs will be struck and what kinds of ecosystems will be desired by individual social groups, based on their demographics, cultural identity, and existing and expected resource requirements. The present scenario is one in which issues tend to be treated in isolation, instead of being considered as part of an integrated system, and broad-scale decisions are generally avoided. Accordingly, policy-makers may too easily avoid the trade-offs and there are therefore many conflicts and few solutions.

## Difficult Choices

Most citizens now recognize that natural resources are not inexhaustible, and an international call for fundamental shifts in governance, political will, and resource management is underway. The challenges we face in the move towards global sustainability are substantial and often underappreciated:

1. The complexity of natural systems precludes a reductionist experimental approach to management. Moreover, the scale of large ecosystems make controlled and replicated experiments virtually impossible. Consequently, our "imperfect science" and the effects of natural variability and uncertainty lead to an inability to reach consensus and accurately predict the environmental consequences of our actions. We are often left with a wide range of opinions on the issues (Ludwig et al. 1993).
2. With acquired wealth comes political and social power that is often used to promote further unlimited exploitation of natural resources (Ludwig et al. 1993).
3. Traditional demography and economics do not incorporate sufficient appreciation of environmental principles. Furthermore, ecologists tend to disregard human influence and instead concentrate on ecosystem function and dynamics. Numerous authors have suggested that the failure to agree on a collective vision of how to attain sustainability lies in the limitations and disconnects among disciplines (Kaufman and Cleveland 1995; Holling 2000; Clark and Dickson 2003; McMichael et al. 2003; Naveh 2005).

4. Anthropocentrism and the “we versus them” mentality stemming from the “arrogance of humanism” is a concept that expresses humankind’s faith in its technology to manage nature so that all can prosper (Ehrenfeld 1981). In anthropocentric terms, humans have the “right” to control the natural world for the benefit of humanity. Even a cursory examination of the published literature reveals the sometimes large divide between ecocentrists and anthropocentrists, scholars and practitioners, functionalists and compositionalists (Callicott et al. 1999), environmental organizations and industry, commercial and recreational fishermen, public and government, etc. (Weinstein and Reed 2005). Thus, the ultimate compromises and sacrifices required—a distasteful concept to many, and possibly the root cause of the “we versus them” mentality that pervades sustainability management—will be necessary to accommodate human needs. Thomas Friedman (2007) stated this idea succinctly: “if you think we can deal with these huge problems without asking [the American] people to do anything hard, you’re a fool or a fraud.” Successfully balancing the demands of competing uses is perhaps the greatest challenge we face.

In the end, the successful transition to sustainability rests on a complex infrastructure that translates science-based information into public policy. This, in turn, elicits effective responses from society at large (Baird 2005). It is the performance and long-term capacity of this diverse array of entities (including scientific and educational institutions) from global to local scales that will ultimately determine the tempo and mode of the transition. Our fate rests in societal action involving all stakeholders, consensus building, and accepting the compromises and sacrifices that will ensure environmental and social justice for all. We hope that this book will contribute towards those goals, and quickly!

This book is organized into five thematic sections and an Epilogue; a summary of which precedes each compilation of chapters: Part I. Managing the Earth’s Life Support Systems: The Emergence of Sustainability Science and Transdisciplinarity; Part II. Balancing Ecology and Economy: Natural Capital and Quality of Life; Part III. From Science to Policy: Managing the Commons, Social Learning, and Social Responsibility; Part IV. The Ecology of Cities; Part V. Restoring and Rehabilitating Ecosystems: Return from the Precipice; and Epilogue: The Challenge of Sustainability—Lessons from an Evolutionary Perspective. Key topics address emerging research and policy in (a) sustainability science, (b) the ecology *of* cities, (c) landscape ecology—scale, spatial patterns, organizational levels, and ecological processes, and (d) related topics in resource exploitation and management, ecosystem health and habitat restoration, the valuation of natural and social capital, habitat and biodiversity conservation, social learning, ecosystem-based management, and integrated watershed-coastal zone management.

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# Contents

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# Part I
# Managing the Earth's Life Support Systems: The Emergence of Sustainability Science and Transdisciplinarity

By focusing on the science–policy interface through a "systems" lens, 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). The underlying principles of this nascent field suggest, moreover, that a sustainable biosphere is not only necessary but economically feasible, socially just, and ecologically sound. It targets the need to break down artificial and outdated disciplinary gaps between the natural and social sciences through the creation of new transdisciplinary knowledge and its practical application to decision-making. New applications of "use inspired" science that incorporate different perspectives of society become more relevant and, in turn, contribute to more transparent and democratic processes of governance (Gibbons et al. 1994; Nowotny et al. 2001).

Conflict mitigation, consensus building, and trade-offs in the form of sacrifice and compromise will become the norm for sustainable management of coupled human-environment systems because growing demands on resources can no longer be met by access to unexploited sources. An integrated systems approach is required, taking into account conflicting goals and interlinkages among environmental issues (Ayensu et al. 2003; Naveh 2005), as well as the geographic scales of both the issues and political jurisdictions. Success will depend on the ability to create new paradigms that will resolve the growing tensions among the involved communities. More effort at the interface between science and society is needed in order to make the transition from the centralized, top-down approach of government institutions to more decentralized, regional, and local approaches to resource management (Bruckmeier 2005).

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# From the Unity of Nature to Sustainability Science: Ideas and Practice

**Robert W. Kates**

**Abstract** The ideas of sustainability science are at least two centuries old, but only a decade in practice. This introductory paper reviews some of the key concepts underlying sustainability science beginning with Alexander von Humboldt and the unity of nature, discusses the basic foundation of the science, and illuminates the three major tasks of sustainability science: fundamental research on use-directed problems; nurturing the next generation of sustainability scientists; and moving knowledge into action.

**Keywords** Sustainability science • New knowledge • Use-directed research • Student learning

## Ideas of Sustainability Science

I have selected some of the major ideas that contributed to the development of sustainability science from a much larger set, beginning first with Alexander von Humboldt's dream of understanding the unity of nature. This was followed by George Perkins Marsh's vision of nature as modified by human action. Then much later, the International Union for the Conservation of Nature (IUCN) linked nature and human development, which led to the World Commission on Environment and Development, and culminated in the US National Academy of Science (NAS) report of *Our Common Journey* and the call for a sustainability science.

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## *The Unity of Nature*

Let me begin with Alexander von Humboldt's dream. Humboldt, then 29 years old, set out his dream in a letter to friends in 1799 as he awaited his sailing from Spain to Venezuela and the beginning of a 5-year exploration of the Orinoco River and the Andes mountains: "In a few hours we sail round Cape Finisterre. I shall collect plants and fossils and make astronomic observations. But that's not the main purpose of my expedition—I shall try to find out how the forces of nature interact upon one another and how the geographic environment influences plant and animal life, In other words, I must find out about the unity of nature." (Alexander von Humboldt; as quoted in Nicolson 1995).

He would pursue that goal until the final posthumous publication of Volume 5 of the *Kosmos* in 1862. But his dream was not to be shared widely, for by then the Academy had discovered another more powerful approach to understanding nature, but not its unity. To pursue this new approach of reductionism, specialization increased, disciplines were born, and graduate degrees were invented.

## *Nature Modified by Human Action*

Beyond the unity of nature, a second great idea was that of a nature modified by human action. George Perkins Marsh, the remarkable Vermonter wrote *Man and Nature* in 1862 and revised it as *Earth Modified by Human Nature* in 1874 (Marsh 1965[1862, 1874]) documenting for the first time, the destructive impacts of human activity on the biosphere. A more detailed examination of human activity took place in 1956 (Thomas 1956) but 30 years later a systematic review moved beyond modification and found the earth transformed (Turner et al. 1990). Along the way, Vernadsky had integrated human knowledge with the biosphere in a "noosphere" (Vernadsky 1998[1926]) and Rachel Carson helped initiate the modern environmental movement with her *Silent Spring* (Carson 1962).

## *Nature Linked to Human Development*

The next great idea about an earth already transformed by human action was to link nature or the environment to development, particularly human development. Thus the idea of sustainable development was born, emerging in the early 1980s from scientific perspectives on the interdependence of society and environment that were fostered by the International Union for the Conservation of Nature and Natural Resources (1980) in the *World Conservation Strategy*. It gained considerable political attention through the publication by the Brundtland led World Commission on Environment and Development (1983–1987) report, *Our Common Future* (World Commission on Environment and Development (WCED) 1987) and the subsequent

United Nations Conference on Environment and Development held in Rio de Janeiro in 1992. There were no scientists on the World Commission and little science present in Rio. Ten years later at the Johannesburg world summit, there was some scientific presence, in part because work on sustainability science had already begun.

## NAS-NRC Board on Sustainable Development 1995–99

Beginning in 1995, I served as vice-chair along with William Clark of Harvard University on the National Academy of Sciences Board on Sustainable Development when we began a 5-year effort to reconnect science and technology to sustainable development. We sought to make the concept of sustainable development both manageable and measurable by focusing on a minimal sustainability transition over two relatively foreseeable generations. Using one of the major social science findings of the time, i.e., the demographic transition, we envisioned a world population of about nine billion in 50 years. To decide what constituted a sustainability transition we chose three normative goals that had emerged at the top of priority-setting negotiations of international conferences and summits: meeting the human needs of the nine billion, preserving the life support systems of the planet, and reducing hunger and poverty. We argued for acting on what we already know and creating a sustainability science for what we needed to know (National Research Council-Board on Sustainable Development [NRC-BSD] 1999).

## Friibergh Workshop on Sustainability Science

But after finishing our report and presenting it to a meeting of the World Academies of Sciences (Interacademy Panel on International Issues 2000) which embraced the notion of a sustainability science, we also realized that there was much to learn on how to do sustainability science. So with assistance from Sweden we convened a small international workshop in Friibergh to identify the core questions and methodologies of sustainability science (Kates et al. 2001). This meeting was followed by a series of regional meetings in Africa, Asia, Latin America, and North America (International Council for Science [ICSU] 2002).

Our discussions at Friibergh and in the subsequent regional meetings revealed profound differences in problems and perspectives between scientists based in developed countries and those in developing countries. Scientists in developed countries focused primarily on global issues, whereas their colleagues in developing countries were concerned primarily with local issues. The two groups were separated by a variety of economic, digital, and capacity divides (Fig. 1). Scientists in the "north" worried about the effects of affluence and consumption, climate changes and its causes, and undertook theory-driven research. Scientists in the "south" worried about the effects of poverty and under-consumption, and the impacts of climate change, and they undertook action-driven research. Scientists in the north

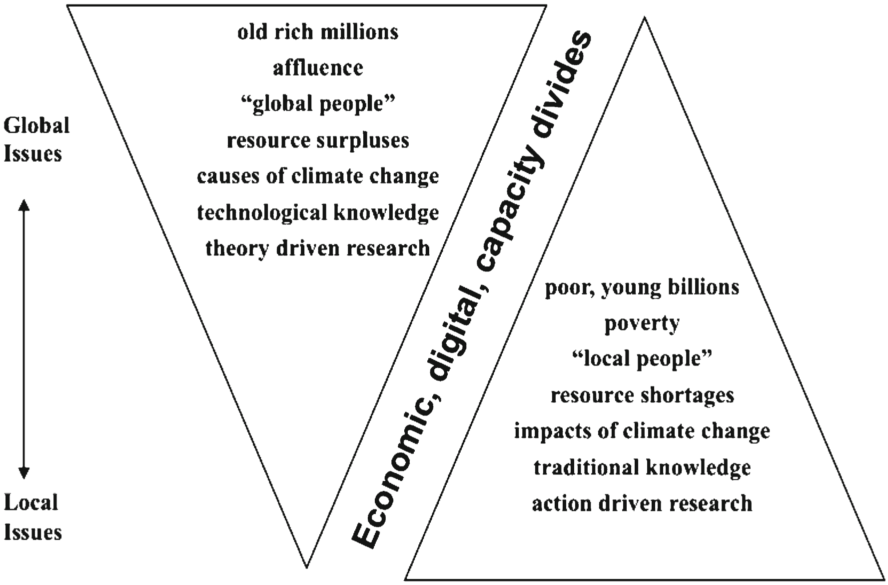


**Fig. 1** Differences in problems and perspectives in developed and developing countries. Scientists based in developed countries focus primarily on global issues, worry about consumption, climate changes and its causes, and undertake theory-driven research with needed tools and funds. Scientists based in developing countries focus primarily on local issues, worry about poverty and under-consumption, the impacts of climate change, and undertake action-driven research, often short of facilities and funding (based on Figure 1 in Kates et al. 2001)

took for granted broadband Internet access and many sources of funding. Scientists in the south tried to cope with interrupted electricity, worked at multiple jobs to support themselves, and had few funding sources.

Such differences notwithstanding, the workshops also reflected broad agreement that science and technology have an enormous potential to make important contributions to a sustainability transition. Realizing that potential, however, will require that serious efforts be made to promote science for sustainability. It will have to be more than the status quo such as simply renaming work we are already doing or claiming that specific work limited to either environmental science or development studies is sustainability science. And sustainability science is not just an extension of existing research agendas (e.g., that of earth systems science) or action agendas (e.g., that of climate change) to include the various goals of sustainability.

## Sustainability Science

The science and technology needed to develop sustainability is essentially integrative of the natural, social, and engineering sciences; seeks to bridge the communities engaged in promoting environmental conservation, human health, and economic development; and brings together the worlds of knowledge and action.

Our discussions also revealed agreement that much of the science and technology developed to support sustainability will be regional and place-based, and focused at intermediate scales where multiple stressors intersect to threaten or degrade human-environment systems. In a sense, sustainable development differs in every place as human needs and life support systems vary, and as hunger and poverty are smaller or larger. It is at these intermediate scales that the complexity of coupled human-environment systems is more readily comprehensible, where innovation and management happen, and where significant transitions toward sustainability may have already begun.

We also agreed in our workshops that sustainability science addresses fundamental questions of scale, nonlinear processes and complexity, and the unity of nature and society. How is the universal related with the particular, the whole with its parts, and the global with the local? How can knowledge of the component parts explain the properties of larger systems, and are such properties knowable? How do the earth, its living biota, and our human species work together?

Thus our global conversations concluded that the science and technology needs for sustainability will have fundamental and applied characteristics. These needs will be addressed with cutting-edge questions regarding nature-society dynamics, while recognizing the need to address sustainability concerns in a problem-solving mode, and to apply what we already know in science-based action programs. Stokes' (1997) quadrant model of scientific research is instructive with his 2×2 view of research contrasting the quest for fundamental understanding with the quest for utility (Fig. 2). His model has a "Neils Bohr" quadrant that is high in fundamental understanding and little immediate utility, and a contrasting "Thomas Edison" quadrant that has pure applied focus. The sustainability science quadrant of use-inspired fundamental research, in contrast, is exemplified by the discoveries of Louis Pasteur.

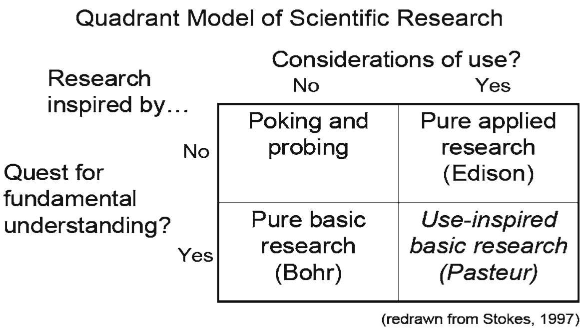


**Fig. 2** Quadrant model of scientific research. Stokes' (1997) two by two view of research contrasts the quest for fundamental understanding with the quest for utility

For a succinct definition of sustainability science, I prefer that of the Proceedings of the National Academy of Sciences (PNAS 2010) as: "…an emerging field of research dealing with the interactions between natural and social systems, and with how those interactions affect the challenge of sustainability: meeting the needs of present and future generations while substantially reducing poverty and conserving the planet's life support systems." Variants of this definition are widely accepted, but as sustainability science spread around the world, different emphases emerged, as in Europe (Jäger 2009; European Commission 2009), Japan (Komiyama et al. 2010), or the US (Clark 2007; Matson 2009).

## Major Tasks of Sustainability Science

There were three major tasks for sustainability science in its first decade; (1) fill the Pasteur quadrant (Fig. 2) and do fundamental research on use-directed problems; (2) nurture the next generation of sustainability scientists; and (3) move new knowledge into action. I will illustrate the progress currently being made for each task with three examples.

### *Fundamental Research on Use-Inspired Problems*

Over this last decade, core fundamental research questions and themes have been identified. Central to these has been the study of coupled human-environment systems. Existing models for many of the components of human-environment systems have been evaluated for their suitability for integrated sustainability assessments. And a growing body of fundamental research on use-inspired problems has been published.

### *Core Research Questions and Themes*

There have been two major efforts to articulate core research questions for sustainability science. At Friibergh, seven core questions were identified and these survived a set of follow-up regional meetings in Africa, Asia, Latin America, and North America (Kates et al. 2001; International Council for Science [ICSU] 2002). Then at the initiative of the US National Science Foundation, a second conference "Towards a Science of Sustainability" was convened in 2009 at the Airlie Center in Warrenton, Virginia. There were twice as many conferees at the Airlie conference as at the original Friibergh workshop, but unlike that workshop, most attendees were from the United States. The conference identified six sets of major thematic research areas (Clark and Levin 2010). These core questions and themes are compared in Table 1. Four of the core questions and research themes were almost identical in both Friibergh and Airlie efforts, but some were expanded in the Airlie version. Three of the Friibergh core questions (in italics) were not specifically singled out at the Airlie Conference, while two new themes (also in italics) were added about the trade-offs between natural and human systems and rigorous evaluation of sustainability trajectories were added.

**Table 1** The Friibergh international workshop of 2000 (Kates et al. 2001) identified seven core research questions for sustainability science. A decade later, the US Airlie House conference, *Towards a Science of Sustainability* (Clark and Levin 2010), selected six major research themes. Those that differ between the efforts are in *italics*. H-E; Human Environment

| Sustainability science research questions and themes | |
|---|---|
| Friibergh 2000 (Kates et al. 2001)<br>Core questions | Airlie House 2009 (Clark and Levin 2010)<br>Major themes |
| Integrative H-E models | H-E theory and models |
| Long-term trends | Long-term trends and transitions |
| Vulnerability or resilience | H-E systems adaptability |
| Incentive structures | Guidance of H-E systems |
| *Limits or boundaries* | *H-E trade-offs* |
| *Monitoring and reporting* | *Evaluation of sustainability trajectories* |
| *Better integrated activities* | |

Research questions are now better defined as a result of these two attempts to articulate the overlapping questions and themes. The view of the participants at the Airlie conference was, however, that major progress has been made only in the two themes concerned with the original core set of research questions identified as “Long-term trends” and “Vulnerability or resilience.” Selected progress has been made on “Limits or boundaries” (primarily about climate), in “Incentive structures” (primarily for common resources or conservation), in “Monitoring and reporting” (primarily from space), and in “Better integrated activities” (primarily from inter-disciplinary efforts). The two new themes on coupled Human-Environment (H-E) system trade-offs and sustainability trajectories seem well justified. The results of both the Airlie and Friibergh meeting were the identification of the basic need for better theory and models to bridge the gap between those expert in modeling approaches but not in H-E systems and those empirical scientists knowledgeable about H-E systems but not modeling complexity. Only in climate modeling has there been a significant improvement in the merger of theory and models.

## *Elaborating Human-Environment (H-E) Systems*

At the heart of sustainability science are the closely coupled human-environment systems that are more easily described with box and arrow models than detailed with numbers and equations. Although I use these all the time, I suspect that box and arrow diagrams are more useful to their authors than to prospective viewers. Nevertheless, I will use two recently described box and arrows diagrams from Dasgupta et al. (forthcoming) to illustrate several points (Figs. 3 and 4). The basic structure of interacting H-E systems has been used for many years (e.g., Burton et al. 1978) although labeled variously as “nature-society,” or “socio-ecological,” as well as “human environment.” There has been much effort over the past decade that