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The Sustainability Spectrum and the Sciences of Sustainability

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ABSTRACT
Understanding sustainability requires integrating multiple perspectives and investigative methods to explain multidimensional concepts. However, the traditional approach to research and education is organized along disciplinary lines that tend to exclude awareness of contributions in one field that may inform problems in another. This presents a serious obstacle to advancing an understanding of sustainability, which is focused on the *interactions* between industrial and ecological systems, rather than examining each system independently. This paper offers a broad description of different perspectives with regard to sustainability including security, reliability, resilience and renewal, and briefly describes the emerging sciences essential to understanding sustainability: ecological economics, industrial ecology, ecosystem health, and sustainable decision making, policy and design. In the latter, the challenges have yet to find an academic locus. Nonetheless, it is in this area that knowledge of sustainability science must be applied and it is consequently most proximate to business leaders, policy makers and designers. Copyright © 2008 John Wiley & Sons, Ltd and ERP Environment.

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Introduction

ALTHOUGH ORIGINALLY FORMULATED AS THE CONCEPT OF *SUSTAINABLE DEVELOPMENT*, WHICH CONNOTES long-term gains in economic well-being through careful stewardship of environmental resources, the term *sustainability* has gained currency among business leaders, students, scholars, policy makers and designers during the last decade. Since the late 1980s there has been a flurry of interest in corporate environmental strategy and policy, including improving and measuring the environmental performance of industrial systems (see, e.g., Seager *et al.*, 2007b) and progressing from reactive to proactive approaches to management of environmental risks (see, e.g., Hunt and Auster, 1990). To a great extent, the concept of sustainability has emerged as the culmination of a trend towards coupling environmental, social and business interests. Nevertheless, it has also become clear that the meaning of sustainability is not consistent among different groups, which begs the question of whether people with widely disparate views could ever agree on a single vision of sustainability or how to realize that vision (Mebratu, 1998).

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Figure 1 illustrates many different ways of thinking about sustainability, characterizes different aspects of sustainability thinking in industrial systems and contrasts these to analogous aspects in ecological systems. On the left-hand side of the spectrum, sustainability is expressed simply as longevity. Simply stated, the longer a certain state can be maintained, the more sustainable it must be. This view is dominated by preservation of the status quo and consequently can be characterized as a *security* mindset. However, enhanced security often comes at the expense of productivity. Moving to the right in the sustainability spectrum is a *reliability* perspective that emphasizes optimization of functionality to a greater extent than security. From a reliability perspective, a greater tolerance for risk of small losses may enhance overall system performance. For example, predation of some grazing animals (such as old or sick individuals) may ensure an adequate supply of food for the remaining herd during lean months. Further to the right, the concept of sustainability becomes more dynamic and the *resilience* perspective becomes increasingly important (Holling, 1996). In this view, adaptation and recovery are essential (Allenby and Fink, 2005). At the right-most extreme is a view of sustainability that incorporates the concept of *panarchy*, in which systems undergo periodic intervals of rapid change and reorganization, resulting in new and unique system states (Holling, 2001). In this view, sustainability is realized in the progression of a system through multiple states, rather than preservation of the status quo. Between security and renewal extremes, the concepts of static versus dynamic sustainability are balanced to different degrees.

The challenge to business strategists, policy makers, university leaders, workers and consumers is to understand which view of sustainability is appropriate for what particular problem. Every organization must perform functions across the entire sustainability spectrum, including release and reorganization of resources into new models of

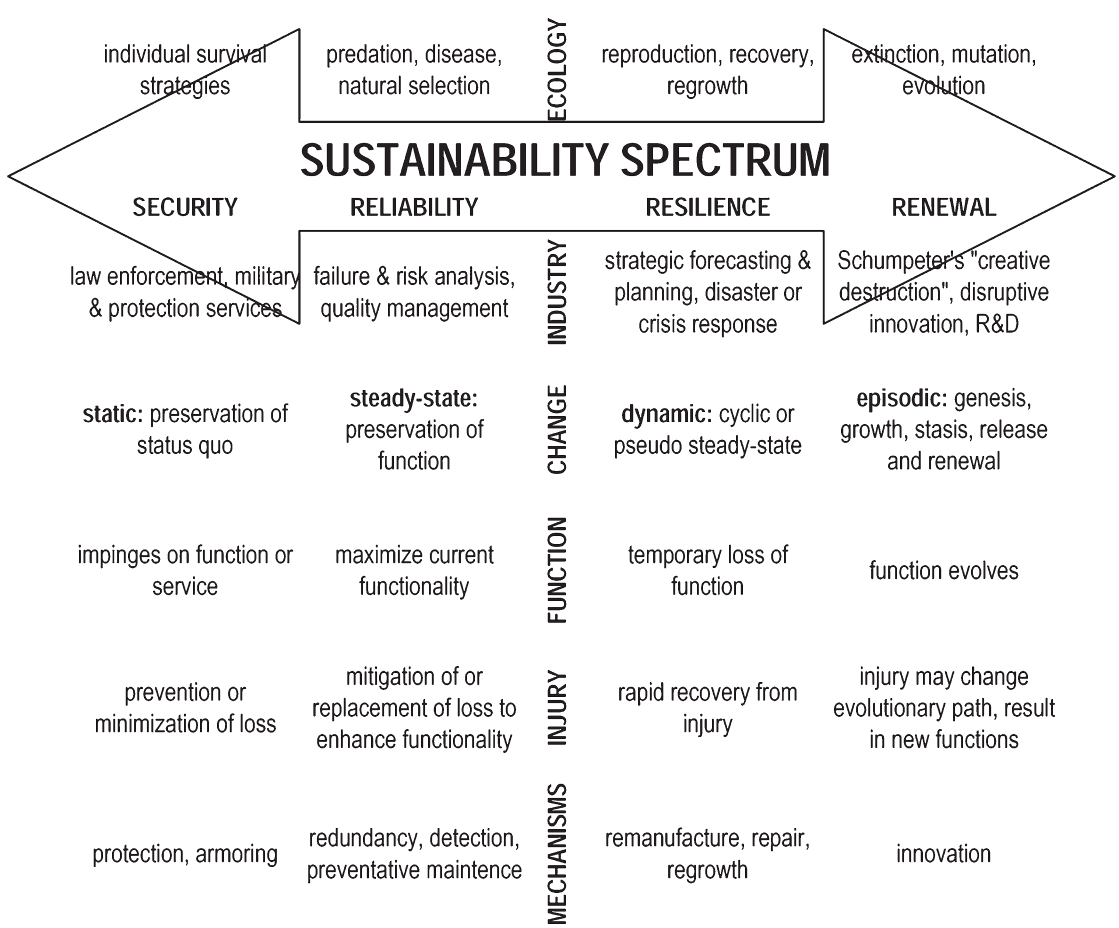

Figure 1. Comparing different views of sustainability between static, steady-state, dynamic and episodic approaches

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operation (the right-hand edge). However, most institutions are adept only on the left-hand side, which is characterized as 'resistance to change' , or at best 'change at the margins' (Handmer and Dovers, 1996). To gain a better understanding of industrial systems at the right-most extreme, it is necessary to study ecological systems for several reasons.

- Both industrial and ecological systems may be described as thermodynamic processes that exploit low-entropy resources to self-organize complex networks, structures and embodied information. Through thermodynamic analogy, understanding systems-level phenomena in ecological systems may lead to critical insights regarding industrial systems (Ehrenfeld, 2003).
- The history of industrial systems is extremely brief, and understanding the long-term implications of present industrial activities can be problematic. The longer-term history of ecological systems may provide clues to the range of possibilities accessible to industrial systems (e.g. extinction, mutation, specialization or response to crisis). Also, the progression of ecological systems through four common stages of exploitation, conservation, release and reorganization on multiple trophic and spatial scales may provide a tool for forecasting trajectories for industrial system components (see, e.g., Gunderson and Holling, 2002). For example, as the exploitation (of natural resources) phase of the industrial revolution matures, the interconnectedness between different components of industrial systems can be expected to increase (as in the information revolution).
- Ecological and industrial systems interact and influence each other. The stressors placed on one by the other inevitably feed back to return stress to the original system of interest (see, e.g., Fiksel, 2006). For example, global climate change originates in industrial systems as carbon dioxide (and equivalent) emissions. The result may be a rapid release and reorganization of ecological systems, such as the migration of emergent diseases (see, e.g., McMichael *et al.*, 2003b). These return stress to the industrial system, which may undergo a new rapid release and reorganization in response.
- Industrial systems rely on ecological systems to perform essential services, such as food production, pollution attenuation and energy capture (Cairns, 1996). However, these services are extremely difficult to value from an industrial (i.e. economic) perspective alone (Farber *et al.*, 2002). For example, increased demand for transportation fuels creates incentives for greater biofuel production. Expanding biofuel production requires increased land and water inputs – but also creates increased demand for transportation services (for trucking of fuels and wastes). Increased transportation demands results in greater pollution of the land and water resources that are required for biofuel production. Degradation of the ecosystem services that provide clean water and fertile land could undermine the transportation fuel production infrastructure dependent upon these systems. Consequently, understanding the sustainability of ecological systems is essential to understanding the sustainability of industrial systems.

Reconciling different views of sustainability is a particularly vexing problem to those who assert that sustainability can not be achieved in isolation by a subset of the populace or planet. From this perspective, sustainability requires collaboration (see, e.g., Hartman *et al.*, 1999) – which is difficult to foster without an understanding of different views, motivations or aspirations. Therefore, the challenge is to create a concept of sustainability that is meaningful without being so specific so as to be exclusive. Admittedly, this pluralistic thinking can be counter to the disciplinary development of scientific or professional jargon that emphasizes specificity, discrete classification and economy of expression. For over a hundred years, the development of science has paralleled the development of the industrial revolution, with its specialization, division of labor and (to a lesser extent in academia) returns to scale. The overwhelmingly dominant approach has been reductionist, which requires isolation of system components for independent investigation. In science, as in industry, the specialization of intellectual labor presumably leads to a more efficient allocation of resources. Where new needs have arisen, such as in computer science or bioengineering, these have typically been fulfilled by creating new disciplines or departments that differentiate the education and research experience – not to mention the knowledge base – from the antecedents that previously defined a common intellectual foundation for progenitors of the new discipline. However, the disciplinary paradigm of science is now being challenged by its own creation – namely, the information revolution. (See Ayres and Williams, 2004, for a brief history of the digital economy.) As the cost of storing, sending and using information has collapsed, so have political, geographic, economic, cultural and intellectual boundaries (Roome, 2001). While it is true that labor still does not move freely across international borders, at the very least money, goods, some

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services and intellectual property move more freely than ever. Consequently, the scarce intellectual resource at present may be the ability to conduct *integrative*, rather than reductionist investigations. This may be especially appropriate for an understanding of sustainability, which is inarguably a global challenge. In fact, it is the very multiplicity of sustainability that challenges the tradition of disciplinary science and frustrates efforts to formulate a sustainability research or education agenda within a disciplinary structure in the modern university that 'is increasingly at odds with the reality of the world of invention and engineering design' (Coates, 2000).

To balance the need for specificity with the need for inclusivity, *sustainability might best be defined as an ethical concept* that things should be better in the future than they are at present. Like other ethical concepts such as fairness or justice, sustainability is best interpreted conceptually rather than technically (like operational measures of performance such as profitability, efficiency or production). Consequently, sustainability can not be defined without understanding the subjective and normative ideas that support the ethical construct (Shearman, 1990). Nevertheless, both ethical concepts and operational measures are essential to decision making, design and exercising good judgment. Therefore, it would be particularly helpful to have operational definitions of sustainability that are consistent with the ethical framework being brought to bear on any particular decision in business, governance or design (see, e.g., Cairns, 2003). Just as it is possible to describe different situations as 'fair' or 'unfair', it must also be possible to consider the 'sustainability' of any particular scenario, policy, plan or engineering alternative, although interpretation of sustainability may be different for different groups.

The Multiple Sciences of Sustainability

Given the need to integrate knowledge from many different sources, it seems extremely improbable that any one expert or any one scientific discipline could possibly subsume all the knowledge relevant to sustainability in one brain or under one umbrella. Nevertheless, there has been no shortage of scientists and engineers rushing forward with claims of complete and operational definitions of sustainability that (presumably) should be widely adopted by policy makers and engineers everywhere for the inevitable betterment of society (see, e.g., Costanza, 1991; Allenby and Graedel, 1999; Wall and Gong, 2001; Graedel and Klee, 2002). In many cases, experts have focused too narrowly on one or a few dimensions of sustainability while excluding other facets. (Social aspects have been particularly neglected by physical scientists and engineers.) This is also the case with the now well known 'triple-bottom-line' (see, e.g., Dyllick and Hockerts, 2002) principle of business management, which seeks to balance profitability with social and environmental sensitivity. Put simply, even the triple bottom line is too narrow.

More recently, sustainability science has been described as a 'meta-discipline' that transcends and subsumes knowledge from many other fields (see, e.g., Mihelcic *et al.*, 2003). A model that currently represents the reality of academic culture is probably better described as the *sciences* of sustainability – separate academic disciplines that in part address and are motivated by common themes. From this perspective, there are many disciplines that relate to sustainability, although no one field can lay a singular claim. While it may be that any (or *every*) body of knowledge may ultimately be relevant to sustainability, there have emerged several integrative disciplines during the last decade (or so) that are motivated in particular by sustainability and recognized as necessary to achieving or implementing sustainability. The emphasis in each of these areas is on the recognition that the human systems are embedded within natural systems and consequently human growth (e.g., population, resource consumption, habitat alternation, or waste production) is constrained by the capacity limits of natural systems. This contrasts with the view that dominated the industrial (and scientific) revolution: that natural systems are practically boundless and that human well-being is simply a matter of increasing production. Moreover, the sustainability sciences hypothesize that human systems *are already* impinging upon the supportive limits of natural systems and that further human growth could lead to catastrophic collapse of both systems (see, e.g., Ayres, 2007).

Therefore, the locus of study in sustainability science is on *the interaction between human and natural systems* (NRC, 1999; Clark and Dickson, 2003; McMichael *et al.*, 2003a). The essential recognition that ties the sustainability sciences together – and distinguishes them from other fields of study – is that this interface is poorly understood (compared with other areas of science that study ecological or technological systems independently). From this recognition and the underlying hypotheses comes the motivation to create multiple and transdisciplinary

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research agendas. Among the vast opportunities for research, three areas in particular have been well defined: ecological economics, industrial ecology and ecosystem health. Two other areas in which there is less published work are political and social ecology, which both emphasize the central role of human relationships in interactions with natural systems (see, e.g., Peterson, 2000). Lastly, application of sustainability knowledge in decision making, management, policy and design can be recognized as a necessity, but remains in mere nascent stages of development and may even depend upon further progress in other fields to become fully realized.

Ecological economics exists at the boundary of natural ecology and the human marketplace. It is represented by a professional society (www.ecoeco.org), which explicitly states that its purpose is to foster sustainability by promoting understanding between ecologists and economists. However, the intellectual foundations run deeper than simply interdisciplinary collaboration. Ecological economics is distinguished from neoclassical environmental economics by the recognition that human systems impact and are embedded in and dependent upon natural systems. Whereas neoclassical economics borrows mathematical models from physics (specifically, thermodynamics – Mirowski, 1992), ecological economics emphasizes more concepts from biology and systems ecology. Among the important ramifications of this perspective is the treatment of economic growth. In neoclassical models, economic systems tend towards equilibrium (like thermodynamic systems) and the final state is independent of the path. Neoclassical economics is preoccupied with allocation of resources in a manner that is analogous to computation of chemical equilibrium, wherein the abstraction of utility maximization substitutes for free energy (exergy) minimization. Economic growth presumably results from a combination of accumulated savings, capital investment and technological progress. Consequently, in neoclassical economics growth is theoretically exponential and limitless. By contrast, growth in ecological economic models is subject to exogenous limits – such as the carrying capacity of the environment (Ayres, 2007). Because growth is limited, the focus of ecological economics is on the relationships between ecological and economic systems, whereas neoclassical economists are overwhelmingly concerned with economic systems. Rather than growth, ecological economists refocus attention on *development*, in which the quality of life improves despite constant (or declining, if need be) levels of production, material and energy throughput, and without degradation of natural capital (Daly, 1996). In theory this can be achieved by a combination of increased eco-efficiency, environmentally benign energy sources and changing consumption patterns.

Industrial ecology has been defined as the branch of science 'concerned with interrelationships of human industrial systems and their environments' (Seager and Theis, 2002a). Like ecological economics, industrial ecology is represented by a professional society (www.is4ie.org) and seeks to borrow intellectual models from systems ecology and the realization that human industrial systems behave in many ways that are analogous to natural systems. Industrial systems 'metabolize' in the sense that they process and exchange materials and energy. They are evolving, self-organizing and self-propagating. They exhibit symbiotic characteristics, and to some extent industrial processes and products may be viewed from the perspective of a biological life cycle (Ayres, 2004). However, unlike natural systems, industrial systems are primarily sustained by finite and polluting fossil fuels (compared with solar energy through photosynthesis). Consequently they are materially less efficient – but in some ways energetically more efficient – than natural systems. The primary investigative tools of industrial ecology are life cycle assessment, systems analysis and energy and materials flow analysis. The principal motivating hypothesis is that holistic analysis can lead to more sustainable alternatives than piecemeal consideration of different aspects of the industrial system. For example, industrial ecology has shown how geographic collocation of mutualistic industries can allow exchange of waste materials or co-products that reduces the expenses and environmental impacts of each industry (see, e.g., Desrochers, 2001). Consequently, the focus of industrial ecology must ultimately be on relationships, although it has been mostly preoccupied with the fate of materials. There is some question about whether industrial ecology is a descriptive science that seeks to explain systemic relationships, or a prescriptive tool for designing those relationships to better model natural systems. It has been interpreted as both (see, e.g., Ehrenfeld, 2000). However, industrial ecology has yet to incorporate economic principles that describe the incentive structures that may explain *why* industrial relationships exist as they are (Grimes-Casey *et al.*, 2007).

Ecosystem health looks at the whole functioning of an ecosystem (compared with study of individual organisms). The emphasis in ecosystem health is on the linkages between the health of natural and human systems (Rapport *et al.*, 1998). Although the concept of ecosystem health is accessible to many people by analogy with human health, the discipline relies heavily on knowledge in veterinary (rather than human) medicine – partly because ecosystems

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are populated by animals and partly because emergent, contagious human diseases are directly traceable back to vectors that originate in animals.[1] A new journal called *EcoHealth* was founded in 2004 (www.ecohealth.net). It synthesizes three antecedent journals, including *Ecosystem Health*, which ran for several years before suspending publication. Among the hypotheses motivating the field of ecosystem health is the idea that health can be assessed on a system-wide scale and that the health of human systems is dependent upon healthy natural systems. Just as the practice of medicine uses knowledge of biology and chemistry and the practice of engineering uses knowledge of mechanics and thermodynamics, ecosystem health applies knowledge in systems ecology and other fields. Particularly important are the concepts of *vigor* (a measure of total activity), *organization* (a measure of the quantity, quality and diversity of interactions between different components of a system) and *resilience* (a measure of the capacity of a system to recover from injury or perturbation – Costanza and Mageau, 1999).[2]

Sustainable decision making, policy and design is the least well formed of these four areas and the focus of a larger portion of this paper. While the other areas are largely scientific, which is to say that they are descriptive and focused on the interface between human and natural systems (thus the emphasis on systems ecology), sustainable decision making, policy and design are more *prescriptive* and may place greater emphasis on the human domain. It is within this area that knowledge gained from the other areas must be applied. It is not necessarily clear how this can be done. Sustainable decision making, policy and design present a new research agenda of their own.

Sustainable Decision Making

Fostering sustainability inevitably involves shared resources, multiple perspectives and group decision-making processes. The complexity of both industrial and ecological systems and the uncertainty associated with estimates of risks, costs, benefits and the objectives of different stakeholder groups make sustainable decision-making a particularly challenging problem. Expert analysis is required to understand cause and effect relationships, apply new technologies and assess alternatives. Human and social factors (such as trust) play critical roles in both the decision and implementation processes (Anex and Focht, 2002; Beierle and Cayford, 2002). In consideration of potentially conflicting value systems or objectives, it may be naive to assume that there is any available solution to a particular problem that will be preferred by all stakeholders or public groups. Therefore, an integrated analytic-deliberative approach is called for that both utilizes technical expertise and fosters deliberative discourse (SAB, 2000; National Research Council, 1996).

As an alternative to drawing artificial and unworkable distinctions between the activity of technical analysis and public deliberation, as in traditional regulatory decision making (Stahl *et al.*, 2002; SAB, 2000), the point of analytic deliberation is to integrate these two activities in every step of the decision-making process. Although deliberative processes are essential to science and all scientific study requires what the National Research Council has called 'methodological policy judgments' (NRC, 1983), the expertise to carry out analytic-deliberative group decision making exists in different scientific disciplines (such as economics, operations research, political science and others) that may have little experience in collaborative work and rarely are prepared to remain current with advances outside their specialized disciplines (O'Riordan, 2004). Although research in the analytic fields (such as risk analysis, benefit–cost analysis and life cycle assessment) and research in the deliberative fields (such as public participation, value elicitation and facilitation) have progressed individually, *synthesis* of these diverse areas has lagged. Typical deliberative decision-making processes are not necessarily *structured* (in comparison to analytical

[1] Recent examples are abundant. For example, West Nile virus (like many viruses) originates and is spread by birds, but can be carried to humans by mosquitoes that feed on both infected birds and humans. Lyme disease is carried from infected wildlife (such as deer) by ticks. Some diseases, such as AIDS or SARS, originate in animals and mutate to a form that is transferable to *and* contagious between humans. Asian bird flu, which has devastated domestic poultry populations in southeast Asia and is responsible for the deaths of some poultry workers, is predicted to cause a major worldwide health crisis if it eventually mutates to a form that is contagious between humans. Pearl (2004) discusses irresponsible wildlife trade as a potentially dangerous pathway exposing humans to exotic diseases.

[2] The field of environmental psychology, which boasts a journal of its own, is concerned with the relationship between behavior and a broadly defined environment, including natural and built environments (see, e.g., Bechtel and Churchman, 2002). The concept of environmental psychology predates sustainability and has not typically been closely connected with ecosystem health. Nonetheless, the potential for integration of mental health and ecosystem health seems obvious.

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processes) with regard to whom should be included, whether the goal of the processes should be focused on dispute resolution, consensus-building or understanding (e.g. of contrasting views) and which types of analytical support tool are most appropriate (see, e.g., Gregory and Keeney, 1994). A more structured approach that is capable of integrating analytical techniques and facilitating public discourse will produce better processes, result in better decisions and greater understanding between those involved and (it has been argued) is essential to understanding and achieving sustainability (Kasemir *et al.*, 2003; Cash *et al.*, 2003; Bäckstrand, 2003).

Sustainable decision making is particularly relevant for business leaders considering the implications of strategy (such as product introduction or defining customer relationships) on up- and downstream stakeholders. In the old model of produce–consume–dispose, decisions at the production stage could be made with little regard for the impacts upon suppliers, consumers or disposers. Agents could be relied upon to act unilaterally in their own narrowly defined best interest (such as profit or consumer surplus maximization). However, industrial ecology demonstrates that every decision has the potential to constrain decisions or change incentives at other product life-cycle stages. For example, consumer disposal decisions may impact the availability of recycled materials for suppliers, just as manufacturing decisions may constrain consumer choices with regard to disposal. Integration of the entire product chain requires understanding of the interactions between decision makers. Therefore, business decision makers must master both analysis (such as life cycle assessment, risk assessment and economic analysis) and deliberation (such as negotiation with suppliers or understanding customer views). While this may be an extension of normal business practices – for example, consumer products manufacturers routinely run customer focus-group and marketing studies – sustainable decision making emphasizes the importance of finding collaborative solutions that are superior to the alternatives available when acting alone.

Sustainable Policy

Policies related to sustainability are dispersed through many different government agencies including environmental protection (which typically includes environmental aspects such as chemical pollution and ecological aspects such as endangered species habitat protection), economic development, energy policy, defense, education, housing, or human health and welfare. Sustainable policy can not be relegated to the exclusive purview of any single government agency. It requires coordination among all agencies. Nevertheless, there is a pressing need within agencies to move significantly beyond bureaucratic or interest group driven decision-making processes focused on end-of-pipe, end-of-life, or legacy and catastrophe management (such as management of abandoned contaminated sites, chemical spills or periodic disease outbreaks) to proactive and systemic approaches to policy making. Principles of industrial ecology, ecological economics and ecosystem health are certainly making inroads into agency thinking. The USEPA has, in its recent multi-year strategic plan, declared that the 'ultimate goal' of the agency is to move the nation from linear, extract–consume–dispose thinking to the life-cycle thinking advocated by industrial ecology (USEPA, 2003, p. 60). However, the goals of the agency stretch beyond the current scientific tools or policy mechanisms required to achieve them. Implementing life-cycle policies is more complicated than the common practice of point of use or point of discharge limits – or even total maximum daily pollutant loadings. In a typical industrial life cycle, changes in the constraints or conditions at any single point in the material chain will influence others actors in the life cycle, and perhaps even create unintended consequences. For example, the Montreal Protocol is widely acclaimed as an example of international environmental cooperation that has successfully reduced stratospheric chlorine levels by prohibiting manufacture and discharge of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) in developed countries (Newchurch *et al.*, 2003). In fact, the Montreal Protocol has been perceived as so successful that it remains the model for the Kyoto Protocol, which places limits on greenhouse gas emissions (such as methane and carbon dioxide). However, the Montreal Protocol suffers from a lack of life-cycle thinking, as subsequent research has shown that the complete ban on even extremely low ozone-depleting substance manufacture results in energy consumption and global warming penalties in the use phase of equipment that could take advantage of these compounds such as HCFC-123 (Seager and Theis, 2002b, 2002c). This could be a fatal flaw in the strategy of modeling climate regulation after ozone protection. As complex as the role of chlorine in stratospheric ozone chemistry is, climate regulation is far more complicated. Whereas CFCs and HCFCs are entirely anthropogenic, the most important climate active gases have natural sources and sinks as well as industrial. Therefore, in climate regulation, life-cycle thinking is unavoidable – for example, when

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considering how natural carbon sequestration (or release) processes should be counted towards or against Kyoto Protocol emission targets. To regulate with both natural and industrial life cycles in mind will require expansion of the stakeholders involved in any particular policy decision, broadening of the alternatives considered feasible and new policy-making processes and instruments that are designed to incorporate the increased number of considerations.

Sustainable Design

Like sustainable decision making and sustainable policy, sustainable design is a prescriptive exercise. It is about understanding the way the world is and works for the purpose of describing how *it should be* in the minds of the designers, and requires an understanding of the sustainability sciences *and* the human values that motivate the design. However, there are important differences, too. Just as sustainable decision making may be the purview of managers, and sustainable policy the purview of regulators, sustainable design is the purview of design professionals, such as engineers, architects, artists and others. It is a creative but also a structured process. (See Fiksel, 2003, for an example of a structured approach to sustainable design.) Like all design processes, sustainable design relies upon knowledge of *technique*, which (particularly in engineering) has come to mean *technology*.

As an agent of change, technological innovation is both threatening and promising. Depending upon how one balances technological optimism and pessimism, technological innovation can be viewed as enabling either unsustainable practices (such as industrial pollution and ecological habitat destruction) or greater human well-being (such as agriculture, industrial production and leisure). Nonetheless, it is certain that the concept of sustainability challenges designers to consider a much broader range of impacts or objectives than narrow definitions of net present value.

What is clear is that technology development for sustainability can not take place in a social vacuum. Whereas traditional technological innovation conjures up the image of a group of laboratory scientists working in relative secrecy and isolation (either for protection of intellectual property rights or national security), the sustainability paradigm calls for broad inclusion of stakeholder and public groups in new technology development and deployment (see, e.g., Seager *et al.*, 2007a). Partly this is because the risks and consequences must be assessed relative to changing human and social values, as is the case with genetically modified organisms (GMOs); partly this is because the benefits of sustainable technologies do not necessarily accrue solely to private parties – they may be, like pollution reduction, distributed among a wide swath of society – and partly this is because there are barriers to sustainable technology adoption (such as technology lock-in or eliciting multiple-stakeholder cooperation) that may require government intervention.

Additionally, new technologies will require methods of *sustainability assessment* that may not exist today. Multiple metrics and indicators must be employed to ascertain the consequences and trade-offs implicit in technology adoptions. There are at least five broad dimensions: economic, environmental, thermodynamic, ecological and socio-political, to which any quantitative metric may relate (Seager, 2004). Further simplification of these categories to a higher level of aggregation may be particularly misleading. Each dimension is distinct from the others and essential to achieving and defining sustainability – but none describes sustainability completely. Higher-level assessment is a multi-criterion problem without a single best answer (see, e.g., Seager *et al.*, 2007b; Kiker *et al.*, 2005; Lahdelma *et al.*, 2000).

Conclusions

Sustainability presents a major challenge to scientists, decision makers, regulators and designers. No single body of knowledge, investigative method or discipline can legitimately claim to capture all of the essential information or perspectives. Therefore, there are many sciences of sustainability, although integration of these into a single 'meta-discipline' is problematic in traditional administrative structures. In particular, three academic areas have identified specific gaps in knowledge at the interface of economic, industrial and human health systems with natural ecology. These are ecological economics, industrial ecology and ecosystem health, respectively. However, research is also needed in a fourth area, here called sustainable decision making, policy and design, where the

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knowledge gained by the science of the other three (and scientific knowledge in general) can be applied. Each of these three processes – decision making, policy and design – requires expert analysis and social deliberation. The greatest challenge is to successfully integrate analysis and deliberation in a structured approach that is amenable and adaptable to multiple objectives and perspectives, such as security, reliability, resilience and renewal. Environmental multi-criterion decision analysis represents one tool to provide a single analytic-deliberative framework with the goal of identifying conflicts or opportunities for compromise between different stakeholder groups.

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