Would Industrial Ecology Exist without Sustainability in the Background?

John R. Ehrenfeld

Keywords

adaptive management
analogy
complexity
industrial ecology
metaphor
sustainability

Summary

Industrial ecology rests historically—even in a short lifetime of 15 years or so—on the metaphorical power of natural ecosystems. Its evolution parallels the rise of concerns over unsustainability, that is, the threats to our world's ability to support human life, as well as the emergence of sustainability as a normative goal on a global scale. This article examines the relationships between industrial ecology and sustainability and argues that, in its historical relationship to classical ecology models, the field lacks power to address the full range of goals of sustainability, however defined. The classical ecosystem analogy omits aspects of human social and cultural life central to sustainability. But by moving beyond this model to more recent ecosystem models based on complexity theory, the field can expand its purview to address sustainability more broadly and powerfully. Complexity models of living systems can also ground alternative normative models for sustainability as an emergent property rather than the output of a mechanistic economic model for society's workings.

Address correspondence to:
John Ehrenfeld
International Society for Industrial Ecology
24 Percy Road
Lexington, MA 02421 USA
<john.Ehrenfeld@alum.mit.edu>

Volume 11, Number 1

Let me begin with a question.[1] Does industrial ecology as a field or discipline exist only within the context of sustainability in the background? With reference to one of the most widely quoted definitions of the field, the answer would probably be, "no, sustainability is not essential." Early in the life of the field, Robert White, then President of the U.S. National Academy of Engineering, defined industrial ecology as

> the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use and transformation of resources. (White 1994, v)

Nothing in White's definition suggests any normative context for this field. But in the next sentence, he goes on to say, "The *objective* [my emphasis added] of industrial ecology is to understand better how we can integrate environmental concerns into our economic activities." By appending this statement of purpose, he added a normative dimension, joining the ongoing debate as to whether industrial ecology is a positive (i.e., descriptive) scientific endeavor or is a quest for solutions to a set of societal problems that demand attention as something that must or should be done.

In an early issue of the *Journal of Industrial Ecology*, Allenby (1999a, 3) argued, "Industrial ecology should not become a normative tool." The justification for this statement lay in the next sentence in the article: "Selective use of data, imposition of ideological absolutes on complex real-world systems and simply bad science should not be a part of industrial ecology." The implication, noted by Boons and Roome (2001), is that normatively driven endeavors suffer from shoddy workmanship. I would agree with Allenby with respect to the latter claim, but, as I will argue below, not with the former. Boons and Roome (2001, 49) urged "researchers in the field of industrial ecology to reflect upon its normative aspects." This article continues and expands upon their work.

Virtually every contemporary engineering field rests on (objective) science as its underlying structure for investigation and design but is applied to solving problems with normative objectives. Biotechnology is an example of such a field. It combines knowledge from molecular biology and chemical engineering to create solutions for problems involving human health, agriculture, and industry. The normative character springs from the implicit claim that it is good to be healthy.

In the case of industrial ecology, its normative claim has been connected to the health of the environment. If the body of the world we live within and rely on for our subsistence is not healthy, then the well-being of our species becomes threatened, and the good life we seek may become unattainable. One might argue that, unlike most conventional applied fields, the normative came to industrial ecology before the science arrived; that is, concerns about environmental degradation were present at the very origins of the field. Compared to biotechnology, the normative context is more complicated for industrial ecology because we usually define social well-being as having aspects beyond mere biological functions (health) and include economic and social measures as well. The inclusion of such socioeconomic dimensions in well-being limits the span of applicability of industrial ecology, as it is currently constituted as a field, to biophysical aspects of well-being.

Like any modern field of engineering, industrial ecology strives to put a solid science-based foundation under itself. Biotechnology builds on biology; chemical engineering is grounded in chemistry and physics. The primary source for industrial ecology, as the name suggests, is ecology, although it also draws on other sciences, including thermodynamics, physics, and chemistry. Robert Frosch, one of the intellectual founders of the field, made the connection to ecology in his introductory comments at one of the very first public gatherings bringing together an audience intrigued by the concept.

> The idea of an industrial ecology is based on a straightforward analogy with natural ecological systems. In nature an ecological system operates through a web of connections in which organisms live and consume each other and each other's wastes. The system has evolved so that the characteristic of communities of living organisms seems to be that nothing that contains available energy or

> useful material will be lost. There will evolve some organism that will manage to make its living by dealing with any waste product that provides available energy or useful material. Ecologists talk of a food web: an interconnection of uses of both organisms and their wastes. In the industrial context we may think of this as being use of products and waste products. The system structure of a natural ecology and the structure of an industrial system, or economic system, are extremely similar. (Frosch 1992, 800)

The notion of similarity or analogy in scientific or technical fields suggests that mathematical or lawlike formulas that describe behavior in one system can be used similarly in another for descriptive or design objectives. Many, however, have pointed out the limitations of analogies. For example, Ruth (1996) criticized evolutionary economics as relying too much on mere analogies and failing to build theory from first principles.

The design challenge driving industrial ecology during its early life has generally been some form of dematerialization. The field emerged around the time that the need to reduce the amount of "stuff" being taken from and added back to the environment had become quite apparent to many in the scientific community and also to the more general public, as reflected in the IPAT identity (Ehrlich and Holdren 1972; Chertow 2000), and later through various forms of Factor X books, clubs, and other forms of public dissemination (von Weizsäcker et al. 1997). Compared to economic systems, ecosystems use energy and materials more effectively through cyclic rather than once-through patterns of consumption to support the organisms that constitute such communities. Frosch and others, such as Robert Ayres, argued directly or implied that restructuring industrial economies to mimic the largely closed-material-loop networks of ecosystems would move modern economies in that direction. Ayres (1994) spoke of "industrial metabolism," explicitly invoking a term used by biologists to describe energy and material flows in living organisms and later applied to ecological communities.

Another analogy to ecosystems arose with the popularization of the term *industrial symbiosis*, describing close-knit industrial complexes in which the individual enterprises interchange their wastes and by-products with others in the complex. This aspect of industrial ecology grew after the "discovery" of the symbiotic industrial community in Kalundborg, Denmark. An article about Kalundborg appeared the very first issue of the *Journal of Industrial Ecology* (Ehrenfeld and Gertler 1997). The term is drawn directly from ecology, where it is often used to describe interspecies interactions with positive consequences to all involved.[2] Its opposite, predation and competition, produces negative impacts on one or both of the species involved. Perhaps as a consequence of the prevalent notion of competition as a cornerstone of the free market system, the popular view of ecosystem systems is that they are dominated by negative interactions. This view vastly understates the critical role of positive mutualisms in stabilizing ecosystems.

Much, if not virtually all, of research on and applications of industrial ecology has fallen into two topical areas, focusing, respectively, on (1) the flows of energy and materials (metabolism) and (2) structural relationships and systems (symbiosis). In the case of item (1), much of the work has been devoted to environmental impact assessment, often comparing alternatives. I did an informal survey of papers appearing in the *Journal of Industrial Ecology*, the *Journal of Cleaner Production*, and *Progress in Industrial Ecology* and found that only a few percent of all the papers were not derived from or reasonably related to either the metabolism or symbiosis analogy. The metabolism analogy has helped spawn the development of tools and methods for tracking the flow of materials along product life cycles, through whole economies, or along the paths of a single substance. These tools have been used in the design of product systems, or parts thereof, with lower environmental impact toward the objective of reduced material consumption. Life-cycle management, the name given to the design of the entire product system, is largely an outgrowth of applications of life-cycle assessment and of increased knowledge of places where avoidable effects show up in the overall cycle. To a lesser degree, these tools have been used in the analysis of policy instruments designed to induce dematerialization. Industrial symbiosis, more recently also called eco-industrial networks or eco-industrial development, is the second topic of ecological origin that has captured a significant proportion of the effort within the field. Again, judging from the papers being published in the major outlets available to workers in the field, industrial symbiosis seems to be growing relative to the earlier dominance of the metabolism analogy.

Metaphor has played an important role in the development of industrial ecology, but not without controversy. It is important to understand the difference between metaphor and analogy, as each one pushes the field in a different direction (Ehrenfeld 2003). Much of the published work that has followed from Ayres's or Frosch's early writings springs from the analogy of flows (metabolism) or certain interaction types (symbiosis). The analogy relates structure and process that already exist in the two systems. Much of the work that has been done in the field might be labeled as objective analysis, with White's normative goal far in the background. I use the phrase *objective analysis* intentionally here to avoid evoking the notion of scientific research, as little or none of what passes for research in industrial ecology fits the conventional sense of scientific endeavor.[3] Many have picked up this body of work as a foundation for their normative claims and prescriptions aiming at reducing energy and material consumption.

The design of recycling policies and actual systems has been influenced by input from the industrial ecology community. The introduction of material flow accounting into national economic statistical databases is adding to the body of information that shapes economic policy and planning. Many examples of products and product systems that employ life-cycle assessment information in their design are now evident. Industrial ecology has perhaps made its largest impact in this arena. The design of office copying equipment by Xerox and Océ approaches the goal of closing the material cycle, with well over 90% of the materials remanufacturable or recyclable. Xerox produced their version using a design slogan, "Zero to landfill," which clearly reflects the ecosystem analogy, whether the connection was deliberate or not (Hawken et al. 1999, 138).

Industrial ecology's foundations in classic ecosystem models and theory can be taken beyond metabolism or symbiosis, but not by analogy.[4] Analogies rely on similarities between phenomena that already exist: the metabolism of ecological food webs is like the flow of materials in an industrial economy. My own normative vision for industrial ecology is based on the metaphor of ecosystems as flourishing or sustainable. Metaphor differs from analogy in that it can be generative, producing new visions of the world as it might be. Analogy is basically an analytic expression of similarity and is useful in engineering and problem solving.

The linguistic nature of metaphor is to take a quality from one place and bring it into another by invoking an image of what is meaningful in one place and carrying it into another where it is absent. Lakoff and Johnson (1980, 5) offer a useful insight on metaphor: "The essence of metaphor is understanding and experiencing one kind of thing in terms of another" (emphasis in the original). "Sustainability is nature at work" and "flourishing is natural" are metaphors that I believe are at the heart of industrial ecology.[5] When I think of sustainability, I think of flourishing, not merely some improved form of development. In my own work I define sustainability as "the possibility that human and other forms of life will flourish on the planet forever" (Ehrenfeld 2004, 4). The normative imperative of sustainability springs from its absence in the world today. A myriad of signs point to diminishment of both the human potential and the resilience of the natural system from which we have evolved.

The power of this metaphorical way of speaking is in the vision it evokes as a call to action, not in the literal truth of the sentence. "Forever" suggests a stable, long-term perspective consistent with the longest horizon imaginable, as does the Native American concept of taking the seventh generation into account. Nor does the inclusion of "other forms of life" mean every species on Earth. Couching this definition in terms of a "possibility" accepts the randomness of evolution. Flourishing does not preclude extinction, especially for species, other than humans, that have little capability to change the world to survive. To enumerate the time frame and the species in quantitative terms would be to vitiate the definition, in the same way that sustainable development is powerless to create a vision of a qualitatively different future. Further, turning the definition into a technical specification channels

Table 1 Paradigmatic parameters derived from the ecosystem metaphor

Modernist paradigm	*Sustainability paradigm*
Reductionist	Interconnected
Simplicity	Complexity
Determinacy	Indeterminacy
Atomistic	Holistic
Mechanistic	Organic
Anthropocentric	Biocentric
Individualistic	Communitarian
Quantitative	Qualitative
Disenchantment	Enchantment
Competition	Cooperation
Geo-political boundaries	Natural boundaries
Linear, predictable	Nonlinear, unpredictable
Equilibrium	Steady-state

responsibility for action to corresponding technical experts and away from everyday actors.

Natural systems flourish: the etymological root of flourish is flower[ing]. Nature gives us concepts of lasting qualities, reproduction, regeneration, and many other terms that connote what is meant by sustainability, even if a precise definition is elusive. Once the metaphorical connection is made, it follows that one may ask what is it about natural systems that brings forth flourishing? The early explorers of the field saw metabolism and symbiosis as features that seemed worth emulating, as both were already features of industrial economies. In some of my own work early on, I spoke of other ecosystem features that also seemed to be good candidates for transplantation (Ehrenfeld 1994). My frame was paradigmatic, that is, addressing the underlying cultural structure of modern societies, arguing that many characteristics of the modernist paradigm were opposed to similar features of natural systems, and that sustainability was more likely to come forth if those elements could be replaced with corresponding concepts taken from nature.

For example, the central notion of independence so characteristic of liberal polities runs counter to the concept of interdependence that grounds virtually all ecological models. In table 1 I have listed some parameters of the dominant modernist cultural paradigm with an opposing set derived from the ecosystem metaphor.[6]

In addition to these parametric aspects of a sustainability paradigm, one can point to many systemic properties that might be considered as signs of sustainability: flourishing, stability, resilience, integrity, and adaptive capability.[7] Health, in general, is a system property that cannot be simply related (that is, by means of a set of nomological—lawlike—statements) to the separate elements of the system. Health and disease are not opposites, as disease can generally be tied to the dysfunction of specific parts of the system whereas health is a property of the whole system. The same disparity is true of unsustainability and sustainability. Unsustainability, that is, the presence of dysfunction in the natural and social worlds, is not merely the opposite face of sustainability. Reducing unsustainability, the objective that is the driving force behind dematerialization, eco-efficiency, and other strategies associated with sustainable development, will not automatically produce sustainability. Although the syntax suggests that these two states are opposites, they are categorically distinct. Unsustainability has conventionally become defined as the presence of pathological or dysfunctional processes and conditions inside of the biospheric system. Sustainability, as flourishing, is an emergent property of the whole [complex] system. Sustainable development as a concept is flawed because it fails to recognize the systemic source of the problems it purportedly aims to address. To the extent that industrial ecology is similarly limited to eco-efficient solutions through application of the metabolic and symbiotic analogies, it can at best only reduce unsustainability.

Allenby (1999b, p. 40) has referred to industrial ecology as the "science of sustainability." I argue that this designation is incorrect on several counts. First, industrial ecology, as it has been conceived and practiced to date, does not conform to the classic definition of a science. If industrial ecology were to be the science of sustainability, it would be necessary to create a laboratory in which sustainability could be studied and develop the tools through which the facts of sustainability could be acquired. The outside world, if appropriately bounded, is the laboratory for many sciences, such as geology. Sustainability, however, is a property of the world at large, so vast and diffuse, and always changing in ways that cannot be maintained such that the conditions needed for scientific investigations cannot be established.

Second, I argue that, at this point in its evolution, industrial ecology is not dealing with sustainability at all. White's objectives fall far short of sustainability. The classic ecological model does not include equity and economy, two of the three aspects of the standard definition of sustainable development. Humans with the capacity for design and choice do not fit the mathematical and structural underpinnings of conventional ecosystem models [see Odum (1971, 510–516)]. The economic and equity objectives of sustainable development lie outside of industrial ecology seen as focused on metabolic and symbiosis analogies. Emergence, the appearance of phenomena characteristic of the whole system, such as resilience or sustainability, is not a part of standard ecological theory [for example, Odum (1971)]. Emergence is not the same as evolution, although certain emergent properties may not become evident until a system has evolved beyond a certain point. The limited ability of the ecological analogy to portray emergence can be transcended if classical ecological theory is replaced by the more recent interpretation of ecosystems as complex self-organizing, hierarchical, open systems. The work of the late James Kay and his collaborators is central to both the development of the complexity theory of ecosystems and its relationship to industrial ecology (Kay 1991; Kay 2002; Kay et al. 1999; Schneider and Kay 1994).

Following Lakoff and Johnson (1980), I note that sustainability is itself a metaphor reflecting our observations of nature. Then it follows that the human economy and social world might—only a possibility—become sustainable if more of what is to seen to constitute our understanding of natural systems were to be brought into the design of our human systems. In table 1, I counterposed a set of notions taken from descriptions of ecosystems against a corresponding set found in the dominant modernist cultural paradigm. We have no guarantee that sustainability-as-flourishing would appear even if our culture were to reflect these natural characteristics. It seems clear, however, that many of the woes of today's world can be attributed to the failings of our limited view of this world. The reductionism of science always leaves something out and scientists struggle to cope with what are clearly highly interconnected systems. The basically linear models used to describe most of life fail to reflect the indeterminacy and unpredictability of nonlinear behavior. We do not distinguish between complicated and complex systems. Unlike complexity, which cannot be described by a finite set of nomological relationships, complicated systems can, in theory, be reduced to just such a set. The scientific necessity of making the world coming under the microscope of the scientist small and simple enough to afford reproducibility and consistency hides the very set of phenomena, including complexity itself, that need to be understood.

We can go some considerable distance extending the current set of metabolic and symbiotic analogies in industrial ecology without straying far from the classic model. Interconnectedness and community, for example, are fundamental features of ecosystems. In the modern world, particularly in the United States, independence, seen increasingly as a form of hyperindividualism, trumps community and relationships.

This article was first prepared for a seminar with the theme of industrial ecology as a response to threats from nature. First, let me say that I think this topic is misconceived. It is not nature that poses threats; it is the human species that threatens nature. Without intention, there can be no threat. Threat is an assessment of an intentional act by another that holds out the possibility that one's world will change in a way that brings negative consequences. But nature never does anything intentionally. It just changes as conditions change. And it changes, according to complexity theory, in unpredictable ways, moving, if sufficiently perturbed, from one attractor to another. *Attractor* is a technical term describing a quasi-stable, interrelated set of behavioral patterns. Another way of saying this is that living systems tend to find an attractive neighborhood (attractor) in which the components move around until something happens that causes the neighborhood to change. The metaphorical sense of this last sentence has shown up in reality many times when ethnic neighborhoods have changed following the influx of a few families of a different color, religion, or nationality.

One might say that our species owes its very existence to such changes in nature, which created the conditions out of which life emerged. What, then, has happened so that we say that nature poses a threat, even if that statement is valid only metaphorically? Human cultures have evolved over long periods, punctuated with disruptions due to natural and human causes. Historians trace this evolution as a process of civilization, the construction of more and more sophisticated, complex social structures than those that preceded them. Perhaps out of what seems to be an inherent arrogance of our species or maybe only a sign of modernity, we view this evolution as positive (in a normative, rather than a descriptive sense) and progressive and see anything that might interfere with the continuing march as a threat. In this context, the emergence of sustainability over the past decade or so is a public recognition that the possibility of a serious setback has reached the public consciousness.

The public's concern has grown over the past several decades from an early focus on environmental upsets to a more general sense that both nature and human societies are not healthy. This new focus is quite distinct from earlier environmental concerns, which tended to be quite specific and focused on distinct elements of the natural world: air pollution, global warming, ozone depletion, loss of habitat, and so on. A sense now exists that the problems are more systemic and affect the health, an emergent property of complex systems, of both humans and nature. This shift—from treating sustainable development as the solution of specific problems related to parts of the social structure to seeing sustainability as the quest for flourishing—calls for a fundamentally different way of thinking about the sources of trouble and about approaches for addressing the "causes." I use quotation marks around "causes" because in complex systems the notion of cause and effect as mechanically related is no longer always valid.

This shift also offers the evolving field of industrial ecology an opportunity to become the science of sustainability its early proponents heralded—but not a conventional positive science. A postnormal science in the model of Funtowicz and Ravetz (1993, 1994) is a better fit given the normative origins of the field and the complex world to be addressed. In their model of the new science, values cannot be left in the background when it comes to design of social and technological structures within complex systems (also see Boons and Roome, 2001). Given that no one can claim the privilege of knowing the truth in a complex system, decisions involving the public must be made under conditions where values and assumptions are explicit.

By incorporating notions from the complex theory of ecological systems, industrial ecology can move beyond the limits of the metabolism and symbiosis analogies (Spiegelman 2003). Two scholars working in the natural sciences, in particular, have pointed the way. I mentioned Kay earlier. Much of his work was focused on ecological system theory, in particular introducing the notions of nonequilibrium thermodynamics and complex system theory. Kay argues that ecosystem behavior over time cannot be adequately described with the classical equilibrium population models of, for example, Odum (1971). Kay characterized ecosystems as complex adaptive self-organizing hierarchical open systems (SOHO) (Kay, 2002).

Following the pioneering thermodynamic research of Prigogine, this model points to the development of structure in open systems subjected to gradients of energy (or materials) created by outside sources impinging on the systems (Prigogine and Allen 1982; Prigogine and Stengers 1984). This flux incident on the system moves it away from any equilibrium that may have existed prior to the opening up of the system. Prigogine noted that, as the system is moved away from equilibrium, structure emerges to stabilize the system, opposing further departure from equilibrium and dissipating the gradient imposed by the external flux. If the flux remains constant, the system will settle into a steady state far from equilibrium. In a large system such as an ecosystem, this process can manifest itself at different scales forming a set of nested structures—hence the hierarchical descriptor.

If the flux is increased, more structure will appear, again to restrain the departure from the equilibrium state and dissipate the flux, until the system may become overwhelmed, at which point the existing structure cannot dissipate the flux and the system collapses into a chaotic state.

New, different structures may then arise, but not necessarily, as the system may simply fall apart. As noted above, each new steady state organizes itself about an attractor, while maintaining its basic structure. The ability to maintain the basic structure is called resilience or adaptive capacity.

Kay (2002, 76) then claims that "natural ecosystems and *societal systems* cannot be understood without understanding them as SOHO systems. Industrial ecology must take into account these considerations of complexity and self-organization (my emphasis added)." And, because of the hierarchical character, different types of processes taking place at very different time and spatial scales, no one discipline or objective is likely to be able to explain what is happening. The emergence of system properties and the unpredictability or surprise involved when a system flips from one attractor to another cannot be ignored even by classical scientists who would like to believe that their nomological models still apply. Industrial ecology has been multidisciplinary from its start, a history that is consistent with Kay's views of what is needed to address complexity, but it will take even more diverse viewpoints to address the challenge of sustainability.

Kay takes a very different stance on the definition of industrial ecology from White, explicitly giving it a normative foundation related to ecological integrity and to sustainable livelihoods. His definition is worth mentioning:

> Industrial ecology is taken to be the activity of designing and managing human production-consumption systems, so that they interact with natural systems, to form an integrated (eco)system, which has ecological integrity and provides humans with a sustainable livelihood. (Kay 2002, 82)

Kay argues that integration is the key—with environment standing on a higher plane. White takes the opposite stance, putting economy above environment, leaving us to learn how to integrate environmental concerns into it. In Kay's definition, he comes close to the triad (environment, economy, and equity) of the Brundtland definition of sustainable development (WCED 1987). Kay's (2002) first sustainability management principle extends our current sense that ecosystems are being degraded and suggests that the technocratic approach taken to address this condition is insufficient and even wrong-headed, given that the capacities of nature may become shifted to some unfriendly and inhospitable state if we push the system too far. We must *interface* (emphasis in the original) our efforts with nature's structure, not the other way around.

The second scholar whose work is relevant to industrial ecology is C. S. Holling. Holling developed the concept of adaptive management some years ago (Holling 1978). More recently, he and his co-workers have used complex systems theory to describe ecosystem behavior and to give more substance to the concept of adaptive management. Starting from the same basic complex system theory as Kay, they describe ecosystems as a "panarchy," a nested set of self-organizing systems, each exhibiting cyclical behavior (Gunderson and Holling 2002). Holling, like Kay, believes that this model can be applied to human social systems as well as to natural systems (Holling 2001). Each subsystem in a panarchy goes through "adaptive cycles," starting with exploitation (r-growth in classical models of ecosystem development), followed by conservation (k-growth in classical models). He adds two additional stages: release (or creative destruction, as some have called this stage) and reorganization. The latter two stages correspond approximately to the process of restructuring that takes place in the movement of a complex system to a new attractor or to what was the original state. After a fire (release) a forest may return to the origin configuration after going through the r- and k-stages, or it may also develop into a different kind of system with a different set of species or in the extreme case into a barren condition.

Holling suggests that as systems develop more and more structure during the k-phase, they tend to become rigid and lose resiliency, the ability to maintain organization around the same attractor. In terms of ecosystems, this behavior can be observed in the downward spiral from productive use of savanna cropland to desertification caused initially by overgrazing. As overgrazing degrades the system, it loses the capacity to recover should the grazing stop (Gunderson and Holling 2002, 201). The cod fishery along the northeast coast of North America analogously shows ominous signs of failure to return to the original state even after severe limits on catch have been imposed (Chouinard et al. 2003). Social systems can exhibit similar behavior, as in, for example, Ladakh, a Himalayan enclave where the social structure collapsed following the introduction of a Western-style development strategy (Norberg-Hodge 1991). I mentioned earlier the phenomenon of neighborhoods completely changing ethnic or socioeconomic identity following the arrival of groups foreign to the historic settlement pattern. Even the collapse of the Soviet empire might be another example of this pattern.

For some time, Holling (2001) has argued that adaptive cycles are a fundamental property of living systems and, further, that such systems can adapt to stresses in such a manner that each succession maintains properties deemed to be healthy. He has defined sustainability as "the ability to create, test, and maintain adaptive capacity" and development as "the process of creating, testing, and maintaining opportunity." In his argument, he uses normative terms, such as resilience, wealth, and opportunity, to characterize a particular form of succession where each cycle retains many of the normatively positive properties of the preceding one and perhaps even adds more desirable traits. Putting all this together, Holling suggests that properly managed adaptive cycles constitute sustainable development. Although the words mimic the Brundtland formulation (WCED, 1989), the meaning here is very close to my definition of sustainability as flourishing.

If the field of industrial ecology moves beyond the current inspiration of the metabolism and interspecies interaction analogies of classical ecosystem theory, I believe that its aspirations to become the science of sustainability might actually come to be. But the nature of the research and practice must shift to a much more dynamic, evolutionary stance focusing more on the course of (eco-)industrial development. It must try to identify and understand the factors that maintain stasis around an attractor and also the factors and conditions that lead to the emergence of new structure in those parts of the panarchy comprising the socioeconomic arenas of interest. And finally, an entirely new approach to design and management will be required.

I have built this argument largely on the work in complexity theory of several natural scientists. Social scientists and organizational theorists have also made significant contributions to the understanding of the behavior of complex socioeconomic systems (Simon 1981). Punctuated equilibrium, for example, is a phrase used synonymously with flips and bifurcations to indicate a shift from one steady-state region to another. The term is found in both organizational theory (Tushman and Romanelli 1985) and science (Eldredge and Gould 1972). The work of Kay and others stemming from Prigogine is particularly useful in gaining understanding of the dynamic processes and structure of complex natural systems and addressing the environmental aspects of governance. The work of social scientists and organizational theorists is especially useful in understanding social behavior and in designing governance systems for largely human entities.

Management is, per se, a deterministic notion and needs to be rethought and redefined. Perhaps we should instead use "governance," an alternative, broader term, as in the above paragraph. I continue to use "management" here, however, because this is the way the cited authors refer to the subject. One critical outcome of the work of Kay (2002) or Holling (2001) and their several collaborators is that complex systems require a fundamentally different approach to management than do merely complicated systems. Kay argues that we have no choice but to recognize and accept that our societies and the socioeconomic systems that constitute them are a part of the natural system and that we must integrate ourselves into those systems and not vice versa. Both Holling and Kay go on to speak of adaptive management, that is, carefully monitoring the outcome of the implementation of any manmade design and adjusting social and technological structures to avoid a move into another attractor. This does not mean reducing observations to "scientific" laws and principles. Rather, it means learning and applying broad rules derived from experience. The expectation of success shifts from nomological certainty to a more cautious expectation that the management scheme in play may produce only temporary success. The Greeks called this kind of knowledge prudence; today we often call it common sense.

Designs should be flexible and facilitate adapting to changing conditions. Monitoring and learning from the behavior of the systems is important, but it is critical that learning not be equated with certainty. Wisdom and prudence need to replace technological prediction. The notion of restructuring the industrial establishment has been an objective of many in the industrial ecology community, but the models they have been using have been classical ecosystem theory with virtually no attention paid to complexity.

This way of framing the issue poses a daunting paradoxical challenge to the field of industrial ecology and all others with broad normative intentions. The present world does not seem to work and needs to be changed. But, if we perturb it sufficiently to move to a different regime, we cannot know where the new world will come to rest. This situation often creates paralysis as experts try ever harder to predict the future. My personal sense (it has to be only a sense, given this unpredictability) is that the best route toward sustainability can be mapped by replacing the elements of the modernist social paradigm with a new set mimicking nature, bringing industrial ecology back to its foundation in the biological metaphor. To the extent that the academic community agrees with me, industrial ecology will not only exist, but flourish. We must also replace our current deep-seated hubris and narcissism with humility and even love.

As an epilogue and clue to why I have added love, I point to a biologist whose work could have a profound influence on industrial ecology and on sustainability. Humberto Maturana, a Chilean biologist, and his co-worker Francisco Varela have developed a theory of life and cognition that, more or less, follows the same lines as the self-organizing principle of complexity theory (Maturana and Varela 1988). They argue that living systems are autopoetic, meaning self-reproducing. Further, they claim that life is sustained by altering the structure of an organism coherently with the changing conditions in its environment. As long as the coherence can be maintained, the autopoetic process can continue, but if the organism loses coherence, it dies as it loses structural integrity. As organisms evolve toward more and more complex structures, culminating with the human species, consciousness itself emerges as a system property. This model has profound implications for our modern way of thinking. Maturana and Varela say "Learning is doing and doing is learning," reinforcing the idea of adaptive management (better, governance) and stressing the centrality of experience as producing practical knowledge.

In this model of consciousness, the cornerstone of our rationalistic way of knowing and acting, reality, is constituted through language rather than simply existing out there waiting to be mirrored in one's mind. Maturana (1988, p. 39) notes explicitly that, "In this context, reality is not an experience, it is an argument in an explanation. Reality is an explanatory proposition that arises in a disagreement as an attempt to recover a lost domain of coordination of actions or to generate a new one." And finally, in his later work, Maturana has developed his theories to incorporate emotion as a fundamental mode of human behavior, with love and caring as the most basic emotional context for social life (Maturana 1988). In his theory, love is not some "thing" that is present or not, but is a biological phenomenon resulting from the evolution of our species as social beings always relating to others. Love emerges as the acceptance of others as legitimate without qualification and shows itself accordingly through caring behaviors. This property, he claims, is so fundamental to human being that when love is absent, we become ill. In a world where love has become a mere thing to be acquired, even through the Internet, it is no wonder that flourishing, and thereby sustainability, is so distant and unapproachable. But the same biological system that is now being stressed is also our strength and hope for the future. I close with a quotation taken from a discussion of Maturana's work that says what I want to in words that are far more expressive than any I could muster:

> The constitutive nature of our biological process of living together is also our great possibility for the future because we all have the natural ability to participate with others in consensual domains (an attribute which Maturana calls intelligence). By the laborious, but rewarding, bootstrap process of our cognition, we will continue our structural dance together and make a history for human society, which will be synthetically

determined, but analytically indeterminable. We cannot know what the future holds, but we can know that everything we do (or say) contributes significantly to it. This awesome responsibility is what we regard as the biological basis of our human ethics. (Fell and Russell 1994)

Notes

1. This article is adapted from a lecture given at the University of Bremen on June 8, 2005. It was peer-reviewed using the *JIE*'s standard procedures.
2. Symbiosis—living together—may also be used to describe other close relationships without mutual benefits, such as parasitism. (See Odum [1971, 213].)
3. I am using the classic concept of "science" as an epistemological method that results in a certain kind of truth. Scientific truth is privileged by the "scientific" method, the fidelity and reproducibility of its application, and by its power to explain phenomena in general. This classical meaning of science has become distorted by the recent emergence of practical fields adding its name, such as management, decision, or risk science.
4. *Editor's note*: For a discussion of the limits of the biological analogy, see the work of Levine (1999, 2003).
5. Lakoff and Johnson (1980, Chapter 6) call this type of metaphor "ontological," relating experience to the material world.
6. I have taken many of these entries from tables developed by Thomas Gladwin, which include these as well as other parameters of what he calls "the unsustainable and the sustainable mind" (Gladwin et al., 1997).
7. Living systems do not always flourish or show these positive characteristics. The normative imperative of sustainability arises from concerns that the world system is, in fact, unhealthy and will continue to deteriorate in the absence of some deliberate change.

References

Allenby, B. 1999a. Culture and industrial ecology. *Journal of Industrial Ecology* 3(1): 2–4.

Allenby, B. R. 1999b. *Industrial ecology: Policy framework and implementation*. Englewood Cliffs, NJ: Prentice Hall.

Ayres, R. U. 1994. Industrial metabolism: Theory and policy. In *Industrial metabolism*, edited by R. U. Ayres and U. E. Simonis. Tokyo: United Nations University Press.

Boons, F. and N. Roome. 2000. Industrial ecology as a cultural phenomenon: On objectivity as a normative position. *Journal of Industrial Ecology* 4(2): 49–55.

Chertow, M. 2000. The IPAT equation and its variants: Changing views of technology and environmental impact. *Journal of Industrial Ecology* 4(4): 13–30.

Chouinard, G. A., A. F. Sinclair, and D. P. Swain. 2003. *Factors implicated in the lack of recovery of southern Gulf of St. Lawrence cod since the early 1990s*. ICES CM 2003/U:04. Copenhagen: International Council for the Exploration of the Sea.

Ehrenfeld, J. R. 1994. Industrial ecology: A strategic framework for product policy and other sustainable practices. Paper presented at Green Goods: 2nd International Conference on Products and Environmental Policy, Stockholm, Sweden, September 26–27, 1994.

Ehrenfeld, J. R. 2003. Putting a spotlight on metaphors and analogies in industrial ecology. *Journal of Industrial Ecology* 7(1): 1–4.

Ehrenfeld, J. R. 2004. Searching for sustainability: No quick fix. *Reflections* 5(8): 1–13.

Ehrenfeld, J. R. and N. Gertler. 1997. Industrial ecology in practice: The evolution of interdependence at Kalundborg. *Journal of Industrial Ecology* 1(1): 67–79.

Ehrlich, P. R. and J. P. Holdren. 1972. One-dimensional ecology. *Bulletin of the Atomic Scientists* 28(5): 16–27.

Eldredge, N. and S. J. Gould. 1972. Punctuated equilibria: An alternative to phyletic gradualism. In *Models in paleobiology*, edited by T. J. M. Schopf. San Francisco: Cooper.

Fell, L. and D. Russell. 1994. An introduction to Maturana's biology. In *Seized by agreement, swamped by understanding*, edited by L. Fell et al. Sydney: Hawkesbury Printing, University of Western Australia. <www.univie.ac.at/constructivism/pub/seized/matsbio.html>. Accessed 9 October 2006.

Frosch, R. 1992. Industrial ecology: A philosophical introduction. *Proceedings of the National Academy of Sciences* 89(February): 800–803.

Funtowitz, S. O. and J. Ravetz. 1993. Science for the post-normal age. *Futures* 25: 739–755.

Funtowitz, S. O. and J. Ravetz. 1994. Embracing complexity, the challenge of the ecosystem approach. *Alternatives* 20(3): 32–38.

Gladwin, T., W. E. Newburry, and E. D. Reiskin. 1997. Why is the northern elite mind biased against community, the environment, and a sustainable future? In *Environment, ethics, and behavior: The psychology of environmental valuation and degradation*, edited by M. H. Bazerman et al. San Francisco: The New Lexington Press.

Gunderson, L. H. and C. S. Holling, eds. 2002. *Panarchy: Understanding transformations in human and natural systems*. Washington, DC: Island Press.

Hawken, P., A. B. Lovins, and L. H. Lovins. 1991. *Natural capitalism*. New York: Little Brown.

Holling, C. S. 2001. Understanding the complexity of economic, ecological, and social systems. *Ecosystems* 4: 390–405.

Holling, C. S., ed. 1978. *Adaptive environmental assessment and management*. New York: Wiley–Interscience.

Kay, J. J. 1991. A non-equilibrium thermodynamic framework for discussing ecosystem integrity. *Environmental Management* 15(4): 483–495.

Kay, J. J. 2002. On complexity theory, exergy, and industrial ecology: Some implications for construction ecology. In *Construction ecology: Nature as a basis for green buildings*, edited by C. J. Kibert et al. London: Spon Press.

Kay, J. J., H. A. Regier, M. Boyle, and G. Francis. 1999. An ecosystem approach for sustainability: Addressing the challenge of complexity. *Futures* 31(7): 721–742.

Lakoff, G. and M. Johnson. 1980. *Metaphors we live by*. Chicago: University of Chicago Press.

Levine, S. H. 1999. Products and ecological models: A population ecology perspective. *Journal of Industrial Ecology* 3(2–3): 47–62.

Levine, S. H. 2003. Comparing products and production in ecological and industrial systems. *Journal of Industrial Ecology* 7(2): 33–42.

Maturana, H. R. 1988. Reality: The search for objectivity, or the quest for a compelling argument. *Irish Journal of Psychology* 9(1): 25–82.

Maturana, H. R. and F. J. Varela. 1988. *The tree of knowledge*. Boston: New Science Library.

Norberg-Hodge, H. 1991. *Ancient futures*. San Francisco: Sierra Club Books.

Odum, E. P. 1971. *Fundamentals of ecology*. Philadelphia: Saunders.

Prigogine, I. and P. Allen. 1982. The challenge of complexity. In *Self-organizing and dissipative structures: Applications in the physical and social sciences*, edited by W. Schieve and P. Allen. Austin, TX: University of Texas Press.

Prigogine, I. and I. Stengers. 1984. *Order out of chaos*. Toronto: Bantam.

Ruth, M. 1996. Evolutionary economics at the crossroads. *Journal of Social and Evolutionary Systems* 19(2): 125–144.

Schneider, E. and J. J. Kay. 1994. Complexity and thermodynamics: Towards a new ecology. *Futures* 24(6): 626–647.

Simon, H. 1981. The sciences of the artificial. Second edition. Cambridge, MA: MIT Press.

Spiegelman, J. 2003. Beyond the food web: Connections to a deeper industrial ecology. *Journal of Industrial Ecology* 17(1): 17–23.

Tushman, M. L. and E. Romanelli. 1985. Organizational evolution: A metamorphosis model of convergence and reorientation. *Research in Organizational Behavior* 7: 171–222.

Von Weizsäcker, E., A. B. Lovins, and L. H. Lovins. 1997. *Factor four: Doubling wealth—Halving resource use*. London: Earthscan Publications.

White, R. M. 1994. Preface. In *The greening of industrial ecosystems*, edited by B. R. Allenby and D. J. Richards. Washington, DC: National Academy Press.

WCED (World Commission on Environment and Development). 1987. *Our common future*. New York: Oxford University Press.

About the Author

John R. Ehrenfeld is executive director of the International Society for Industrial Ecology and co-editor of the *Journal of Industrial Ecology*.