Can Industrial Ecology be the "Science of Sustainability"?

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Early in the history of industrial ecology, key thinkers referred to this field as the "science of sustainability." Their definition relates to the context of sustainable development, which foresees continuing growth far into the future without depleting resources needed for future generations. The ambitious implications of this phrase energized many early workers in the field. But in spite of the catchy sound, scholars have not been able to fully ground this claim. The implications of an analogy between the system of material and energy flows in natural ecosystems to that in industrial networks, recognized by Ayres early on and later by Frosch and Gallopoulos, created the context for the claim. Ecosystems show patterns of evolution that have gone from once-through to more sustainable closed-loop modes. The "science" in the definition meant that knowledge important to understanding and designing a more effective path toward sustainable development would be created through the study of the mechanisms of the material and energy interchange of industrial systems using the framework of natural ecosystems.

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The major practical implications of this perspective have come in the development of the central set of tools and methodologies that industrial ecology calls its own, even if some have been drawn from other places. Materials flow analysis, life-cycle assessment, substance flow analysis, and other material and energy flow models are all derived from metabolic aspects of the analogy to natural systems. Recycling in its many forms, such as life-cycle management or industrial symbiosis, also springs from the interchange relationships in ecosystems as practical manifestations of the application of the above set of tools. Critics of the field (e.g., Bey 2001) have argued that an emphasis on metabolism, particularly on producers, has diminished the potential of industrial ecology to fulfill its promise as the science of sustainability. He criticized the omission of consumers as serious. Some early work by Duchin (1998) and others attempted to bring consumers into our arena, but little has been done here. Recently, interest in the consumption side has picked up. It was the subject of a well-attended and provocative session at the last International Society for Industrial Ecology (ISIE) meeting in Ann Arbor, Michigan, and it is the focus of an upcoming special issue of this journal edited by Edgar Hertwich of the Norwegian University of Science and Technology.

Bey (2001) continued his critique to argue that the analytic frame cannot be merely static, as is the case in most work in the field, but should follow the concepts of development and succession, again by analogy to natural ecosystems. At the same time, he recognized limits in the ecological analogy due to a fundamental difference

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between human economic systems and natural ecosystems. His way of avoiding the theoretical problem is to state that industrial ecological analyses need to incorporate the concept of "sufficiency." But here is the rub. Classic system ecology theory, from which the oft-cited type 1, 2, and 3 ecosystem patterns emerge, is predicated on closed systems, except for solar energy inputs, and on linear equilibrium population dynamics. Sufficiency has no meaning in this framework. Growth, measured in the quantity of biomass, is limited by the initial endowment of resources (although the relative population of species can vary).

Economic systems are fundamentally different. They are open to energy and materials. The equilibrium models employed by neoclassical economists allow for endogenous increases in money, the analogue to nutrients in an ecosystem. This problem with the analogy between human economies and natural ecosystems has been pointed out by many scholars in the literature of ecological economics, but only to a limited extent in our own field.[1] Criticism here ranges from cautionary—be careful in applying the analogy—to strong assertions that it is invalid; both warnings call the "science" assertion into question.

Whether attributable to this limitation or merely to intellectual curiosity, articles that depart from the classical system ecological foundation have begun to show up in this journal and in other industrial ecology forums. Spiegelman (2003) provided an introduction to newer theories to explain the behavior of ecological systems based on complex self-organizing systems operating far from equilibrium. A key feature of such systems is that they exhibit nonlinear and unpredictable behavior, flipping from one state to a qualitatively different state. His article is an excellent, but limited, introduction to this literature.

Tucked into his article is a very important sentence with major implications bearing on the relationships of industrial ecology and sustainability. Drawing from work of the noted (biological) ecologist C. S. Holling, Spiegelman (2003, 19) noted that "[r]esilience is a characteristic that defines how far [complex, open] systems may be pushed away from their attractor without causing destabilization." "Attractor" is a term from complex systems theory that might be thought of as a kind of space in which a system exists. As long as it lives in one space, its behavior is more or less predictable, although often not without great uncertainty. But occasionally when perturbed, the system can jump mysteriously from one space to another in which its structure and behavior are distinct from the first. The downward spiral from productive use of savanna cropland to desertification caused initially by overgrazing is a familiar example in the ecological literature. Social systems can exhibit similar behavior, for example in Ladakh, a Himalayan enclave where the social structure collapsed following the introduction of a Western development strategy (Norberg-Hodge 1991). At first glance, this model may not sound like one that fits the normative sense of sustainability. Sustainability and unpredictability seem like antagonistic concepts. Not necessarily so.

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 a manner such that each succession maintains properties deemed to be healthy. He has defined sustainability as "the ability to create, test, and *maintain* adaptive capacity." He further defined development as "the process of creating, testing, and *maintaining opportunity*" (emphasis added). In his argument, he uses normative terms, such as resilience, wealth, and opportunity, to characterize a particular form of succession where each one retains many of the 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. But this is not at all the same sort of sustainable development evoked by the familiar Brundtland definition. To highlight the difference, I have been using a distinctive definition. My framing of sustainability is that it is "the possibility that human and other forms of life will flourish on the planet forever. Flourishing has great metaphorical power."

The significance of a link between ecological dynamics and sustainability is of substantial importance to industrial ecology insofar as it has the potential of tying the normative aspirations of many in the field to a scientific foundation. The science involved is that which Spiegelman described—the whole arena of complex system theory. Although some may consider it risky to look to this still evolving and somewhat controversial field as the underpinning for industrial ecology, it offers possibilities to transcend the obvious limitations of classical systems ecology, neoclassical economics, and all other positivist disciplines. If one chooses to follow the standard concept of sustainable development as the normative goal, then the classical forms of systems ecology, within limits, can continue to underpin research and practice related to material and energy flows. But if one chooses a different normative vision of sustainability as evoking flourishing, resilience, integrity, adaptive capacity, or other similar concepts—all of which happen to be emergent properties of living complex systems—then it seems more likely that complex system theory will, when we learn more about it, support our claims that industrial ecology is indeed the science of sustainability.

Note

1. See, for example, the analyses by Levine (1999, 2003).

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