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The future of systems ecology

Deborah M. Gordon[1]

CENTRAL QUESTION

What is the future of systems ecology in a rapidly changing world?

ANSWER

Systems ecology can contribute by focusing on ecological systems in transformation and by extending systems thinking across biological scales.

FIELD MAP COORDINATES

Emergence; Energy, matter, and information; Persistence and fragility; Transformation; Scaling.

A systems approach begins with a focus on relations and the perspective that the function at one locus of a system depends on what is happening around it. This has been fundamental to biology from the beginning. In 1802, Lamarck called the study of life “biology,” spurred by the insight that the inorganic world, including soil and rocks, is related through decomposition to the organic [1]. Beginning in 1807, Humboldt published many books explaining his vision of nature as an interconnected web. Then, in 1866, Haeckel gave a name to Humboldt’s view of nature: “ecology,” after the Greek *oikos*, meaning household, the study of the relations of organisms with their environment [2].

In the mid-twentieth century, “systems theory” took up some of the ecological ideas of the previous century. The operation of a factory, a weapons system, a body, a person, a set of interacting species, or an ecosystem could all be viewed as dynamic relations among hierarchical levels. It brought together the natural and social sciences, including biology, psychology, and social theory, with fields related to the control of human and mechanical systems: cybernetics, engineering, weapons-systems production, and the management of organizations and industry.

The goal of systems theory was to describe the dynamic flow of materials, energy, or information at one level in relation to the higher or outer level around it. For weapons systems in cybernetics, this was the key to command and control; in social science, one starting point was Durkheim’s view of social forces that constrain the individual [3]. Von Bertalanffy introduced the perspective of systems theory in biology to explain development and metabolism; his diagrams show changes in the flow of nutrients [4] that look much like the diagrams in Forrester’s introduction to operations research, showing the flow of production in a factory [5], which in turn resemble those showing the flow of nutrients across a food web [6].

Odum helped establish systems ecology, beginning in the 1960s, by extending ecology to include processes that had been considered outside the scope of organisms, such as the flow of nutrients, water, and air, in the explanation of local processes [7]. As Evans, Norris, and Benton [8, p. 164] put it: “The aim of this approach was to measure as many aspects of the ecological system as feasible and then search for relationships and link data together using the abilities created by the computing power that was then becoming increasingly available.” This grew into a focus on predictive models, alongside the flourishing of theory in community ecology.

I see two ways that a new systems ecology journal in 2026 can foster new directions. The first, outlined in the Founding Editorial [9], is to encourage new perspectives on the ecology of a world in the throes of rapid anthropogenic change. When systems ecology began in the mid-twentieth century, ecologists were seeking to understand a stable world. Like much of mid-twentieth-century ecology, Charles Elton’s pioneering work in community ecology emphasized the persistence and regulation of ecological systems. Ecological processes were seen as homeostatic. Initial theoretical work in community ecology devoted much attention to explaining stability and coexistence and identifying equilibrium states for dynamic processes.

The ecology of the twenty-first century is situated in a world of drastic anthropogenic change. The loss of biodiversity, transformation of habitat, and climate change are all accelerating [10, 11]. Instead of asking what maintains stability, we are now asking what might persist. It seems increasingly futile to evaluate any ecological process without taking these rapid changes into account. Systems ecology's broader orientation can contribute valuable tools for understanding ecological and evolutionary processes in relation to anthropogenic change.

Moving from a focus on stability to investigating transformation collides with another theme of systems theory as it was originally formulated. Drawing on analogies between factories and machines and natural systems, efficiency and optimality were viewed as the expected outcomes of natural laws governing relations within systems. As theoretical work in biology attracted the interest of physicists, systems theory became a starting point in the search for a general theory of complex systems based on universal laws.

We are not seeing optimal processes that maintain the status quo. The flow of resources and information in natural systems does not look like Odum's electric circuits or Forrester's productive factories. As von Bertalanffy pointed out from the beginning, living systems are open systems. Systems ecology will have to become messier and let go of its origins in control.

However, the insights of systems thinking still help us understand systems in transition. One of the most important insights is that the relation between organism and environment goes both ways [12]. An example is "niche construction": organisms use the resources in their ecological niches, but they also modify those niches. In turn, this modification influences resource use. Systems regulated through feedback might lead to homeostasis, but they might not. Another fundamental insight is to use the flow of energy and information to characterize the dynamics of ecological relations. The original models of systems thinking were based on principles of energy conservation and a march toward equilibrium. But ecological flows may not settle into stable configurations, and equilibrium seems a quaint fantasy in a world of rapid change.

When the world does not look like our models, it is time to adjust the models. Levins [13] had the last word in a controversy begun in 1966 about whether the models of systems ecology were useful at all. He pointed out that it is not possible to maximize generality, realism, and precision at the same time, but it is possible to increase them all. Anthropogenic change is asking us to increase realism and revise our ideas of generality; what is general is heterogeneity, variation, and transformation [8].

A second new direction in systems ecology is to bring its tools to a wider variety of natural systems. Ecosystem ecology has asked how dynamical relations work across biological scales. This usually moves outward from the local to the regional and global, but we could also include the other direction in systems ecology. Building on von Bertalanffy's perspective on open biological systems, systems biology has flourished within molecular and cell biology. It has become increasingly obvious that understanding molecular and cellular processes requires taking into account the relations among components and their surroundings. Epigenetic processes regulate gene transcription; how a protein folds depends on interactions among sectors of amino acids as well as the primary sequence [14]; cell function depends on physical contact and interactions with other cells [15]; and so on. Because systems biology takes an ecological perspective on the behavior of molecules and cells, it can be viewed as a form of systems ecology.

Understanding the evolution of collective behavior, whether in animals or cells, requires a systems perspective. Collective behavior operates without central control, using interactions among participants. Some forms of collective behavior generate movement patterns, allowing fish schools and bird flocks to move together or groups of cells to migrate, as in the movement of neural crest cells [16]. Other forms of collective behavior regulate activity, such as the allocation of effort to various tasks in an ant colony [17], the transformation of stem and gut cells to maintain organ size [18], or the dynamics of neural networks in brains [19].

Collective behavior, like all aspects of phenotype, evolves in relation to a changing environment. Explaining the evolution of the many diverse forms of collective behavior thus requires an ecological perspective and suggests hypotheses about the fit between the dynamics of collective behavior and those of the environment [20, 21]. Testing these hypotheses and searching for general trends can draw on the methods of systems ecology. For example, collective behavior uses feedback from interactions among individuals, and these interactions create an information network. The feedback regimes that regulate collective behavior may evolve to fit the flow of energy in the environment. One hypothesis is that when the cost of activity is high relative to the gain, the default is likely to be inactivity until interactions associated with gain create positive feedback that stimulates activity. When the cost of activity is low relative to the gain, the default is likely to be continued activity unless interactions associated with high costs create negative feedback. Another hypothesis is that the modularity of the information network regulating behavior through interactions among participants is likely to fit the dynamics of the environment. When resources are patchy or ephemeral in space or time, local information is needed to exploit them, and modular networks can respond more rapidly. When resources are scattered or homogeneous, a more centralized or homogeneous information network can sacrifice speed to be more thorough.

An ecological perspective can inform the study of the collective dynamics that regulate cellular processes. For example, evidence that cancer metastasis depends on the cellular microenvironment [22] reinforced an ecological view of interactions between cancer and healthy cells. This perspective can be traced to Paget's "seed-and-soil" metaphor [23] and was later developed by Fidler [24]. Cancer has also been viewed as an invasive species, with cancer cells acting as invaders within the native environment of the healthy body [25]. A further step is the systems ecology approach: modeling cancer progression as the outcome of an ecological system of interactions among cancer and healthy cells [e.g., 26]. The framework of Adler [27] does this by outlining cancer population dynamics controlled by relationships among cell lineages, including healthy cells and mutations that lead to the evolution of cancer cells, mediated by resources and by growth and antigrowth factors.

A new journal can help facilitate the transformation of systems ecology to fit a changing world and contribute to the use of an ecological perspective throughout biology.

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Deborah M. Gordon conceived and wrote the article.

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AI-use statement

No AI-tools were used in this work.

[1] Department of Biology, Stanford University, Stanford, California, USA. dmgordon@stanford.edu