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LESSONS FROM THE GREAT LAKES

MAKING SENSE OF THE ECOSYSTEM APPROACH: LESSONS FROM THE GREAT LAKES

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E-mail address: alternat@watserv1.uwaterloo.ca

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Cover: Arthur George Tansley 1871-1955. Photo courtesy of Hunt Institute for Botanical Documentation, Carnegie Mellon University, Pittsburgh, PA.

EDITORIAL

The end of the world as we know it

I can tell you that James Kay and Eric Schneider don't look like subversives. So far as I know they don't behave much like subversives either. But the way they think, and encourage the rest of us to think, is a different matter altogether. If we go along with them it will mean the end of the world as we know it.

Kay and Schneider begin with the unspectacular observation that ecosystems are complex. They then proceed to show how this entails accepting what the theorists of complex systems call surprise, catastrophe and chaos. Some of this is colourful language. But the essence of the story is that we face a world of uncertainties where there are "no black and white answers, no linear causes and effects, no definitive mechanisms and no one person to blame." Not even our objectives can be simple. Trying to maintain the stability of an identified sensitive area, for example, is inappropriate if we see the area as a hierarchy of dynamic living systems naturally going through interrelated cycles of birth, growth, death and renewal in ways that we cannot hope to comprehend, let alone model accurately.

Not surprisingly, there are complaints that this ecosystem approach is not helpful, that it doesn't provide the kinds of clear and quantifiable answers needed for decision making in today's world. The complex ecosystem approach does spell trouble for conventional legal approaches to pollution control. It also threatens to undermine entrenched thinking in ecological science and established practices in various areas of environmental management. But that doesn't mean that the ecosystem approach is what should be rejected.

Viewed on the larger screen, the ecosystem complexity argument is just another version of the lesson that has been presented in many ways for at least a hundred years. It is the lesson that the world is a rich, intricate and surprising place where simple rules have limited application and totalitarian approaches are likely to be destructive, if not wholly evil.

The modern era rose on the foundation of two simple ideas – that nature is knowable and manageable, and that humans are essentially economic beings. If nature is an assemblage of things that obey immutable laws, we can uncover and use these laws to our advantage. And if people are similarly law-bound by their character as economic individuals, they too can be managed (or served, if you prefer) by those with the appropriate knowledge.

These, like all assumed truths, were thought to be universal. Certainty on the specifics, where it was not already at hand, was thought to be just around the corner, waiting to be uncovered through proper thinking and proper application of the correct analytical method.

As we entered the 20th century, there appeared to be grounds for such assumptions. Technology was ascendant and campaigns for dominion occupied scientists and engineers as well as imperial nations. Even social revolutionaries of various stripes claimed the certain backing of science for the inevitable achievement of the desired end.

To be sure, different groups espoused conflicting truths. But underlying all the competing convictions was the shared assumption that lies at the core of modernism – that a proper answer is something single, complete and final.

The 20th century has done its best to dispel this notion. Nearly a hundred years ago, Einstein and others cut through the underpinnings of certainty in physics, the field that had seemed to enjoy the most solid foundation in ascertained fact. Trust in economic truths was shaken in 1929, and much of the following period was devoted to bitter lessons about the evils of totalitarian political faiths. Over the past few decades, environmental disasters, great and small, ought to have taught us something about the complexities of ecological systems and their unanticipated responses to human interventions.

Despite all this we are still tempted today to deny complexity and seek the single truths. We say the most elegant response is the simplest, that the best mind is a razor for cutting through the messy layers of detail and context to reach the essentials. Even environmentalists who consider themselves subversives will act as if there is somewhere the one accurate analysis of environmental crimes and the one proper strategy in response. Some even claim to know what it is.

Perhaps what we are seeing here is fear of the abyss. If not certainty, then chaos. If not the one answer, then the void. This is understandable in a world where many people face increasing insecurity. But it is also unfortunate. The new world of complexity and mystery is richer, more intricate and amazing, than the old world of mechanical parts and manageable resources. And since we are a part of it, we too become richer, more intricate and amazing. Respecting our place in such a world may require us to be more modest, thoughtful and appreciative. But this is not a bad thing. On the contrary it is, as Kay and Schneider suggest, something to be embraced. ❑

Robert Gibson

– Robert Gibson

Visions of Nature and Society

A History of the Ecosystem Concept

Stephen Bocking

In recent decades the ecosystem concept has guided ecological research while informing discussion of environmental issues ranging from land-use planning to Great Lakes water quality. Generally, the concept signifies the study of living species and their physical environment as an integrated whole. In environmental management, its significance is understood to lie in a comprehensive, holistic, integrated approach.

Since its origin nearly 60 years ago, however, the ecosystem concept has had other meanings, reflecting a variety of themes.[1] In its evolution, it has reflected not only ecologists' interpretations of the natural world, but their views of themselves, human society, and their role in society.

The history of the ecosystem concept, therefore, is not only of academic interest. It is widely accepted that science contributes to our decisions about the environment, suggesting options, and providing some basis for choosing among them. It is necessary, then, in evaluating these scientific contributions, to be aware of how they are themselves shaped by their own history, and by the concerns and priorities of society.

British origins

Some of these themes can be seen in the origin of the term itself. Arthur Tansley, a British ecologist, coined it in 1935 to describe his view of the organization of nature.[2] The plants and fauna at any location, he argued, together with soil and climate, form an interacting ecosystem, tending to equilibrium, resisting, to some extent, disintegrative forces.

In part, Tansley's concept reflected ecological traditions around him. Ecologists in Britain, more so than elsewhere, had considered the interaction between plants and soil, and the influence of grazing and other activities of animals on plants. Tansley intended the ecosystem concept to integrate this work into a single unified perspective. The American ecologist Frederick Clements had a part in this, reflected in Tansley's assumption that plant communities exhibit a predictable process of ecological succession, culminating in a state of dynamic equilibrium. Clements had developed a conception of the plant community as an organism, which follows a sequence of stages as it develops into a mature state.[3] While Tansley appreciated Clements as an ally in shifting ecology from description to the study of dynamic processes, he nevertheless sharply disagreed with Clements on this point. "Organism", Tansley believed, was a term best reserved for individual plants and animals, and complex ecological communities should be interpreted as, in principle, physical systems. The universe, in Tansley's view, was a vast number of overlapping physical systems, each tending towards a state of maturity characterized by equilibrium. The ecosystem was one of many such systems, and the one of special interest to ecologists. As the "basic unit of nature" for ecologists, the ecosystem asserted the unity of ecology, while distinguishing it from the study of both individual organisms and inorganic systems.[4]

The ecosystem concept in America

Seven years after Tansley coined the term, a young American ecologist established what many consider the foundation of ecosystem research. Raymond Lindeman's paper, "The Trophic-Dynamic Aspect of Ecology," appeared in 1942, a few months after his death at the age of 27.[5] In it, he discussed concepts long of interest to ecologists, including succession and the significance of feeding (or trophic relationships) to the structure of ecological communities, as elaborated by the British ecologist Charles Elton.[6] What was novel was how he integrated these concepts. Energy, he explained, was the common denominator that could relate successional changes to the productivity of trophic levels (green plants, herbivores and predators, for example). In effect, he showed how to relate long-term change in ecosystems to short-term events such as food consumption, respiration and other aspects of the flow and transformation of energy.

Lindeman's perspective was especially significant because it redefined nature for ecologists. They had generally viewed nature in terms of the behaviour and interactions of species against the backdrop of an abiotic environment. Succession, for example, was the replacement of one species assemblage by another; the study of food relations within a community began with the identification of certain species as predators, others as prey. Lindeman suggested instead that an ecosystem be viewed in terms of functional components: trophic levels, not species, were central to ecological analysis. By reducing the complexity of food chains and ecological change to energy flow, he made ecosystems amenable to quantitative physicochemical analysis. Establishing a common basis for plant and animal studies in the movement and transformation of energy was also a step towards a single unified ecology, and a step away from the view of ecology, held by Tansley, Elton, and others, of ecology as "scientific natural history" grounded in appreciation of the uniqueness of each species.

By emphasizing the functional roles of ecosystem components, Lindeman also undermined the distinction between living and nonliving components. Consider, he suggested, a dying pond weed, covered with periphytes. Was it alive or dead? Even after death, the plant retained a function as a source of nutrients. With rapid transfer of nutrients between living and nonliving ecosystem components, the distinction between them, Lindeman argued, was arbitrary.

Lindeman wrote his paper while a postdoctoral student with G. Evelyn Hutchinson of Yale University. Hutchinson had been considering similar themes in his own research, including the relationship between succession and trophic structure. Like Tansley, he would not follow Clements in his view of the community as an organism, and yet he found the analogy suggestive, noting that "if the community

British ecologist Arthur Tansley coined the word "ecosystem" in 1935. He argued that plants and fauna at any location, together with soil and climate form an interacting ecosystem, tending to equilibrium, resisting to some extent, disintegrative forces.

Courtesy of Hunt Institute for Botanical Documentation, Carnegie Mellon University, Pittsburgh, PA

Courtesy of Hunt Institute for Botanical Documentation, Carnegie Mellon University, Pittsburgh, PA

American ecologist Frederick Clements developed a conception of the plant community as an organism, which follows a sequence of stages as it develops into a mature state. Tansley, while interpreting communities as "systems", nevertheless sharply disagreed on this point, believing that "organism" was a term best reserved for individual plants and animals.

is an organism, it should be possible to study its metabolism."[7]

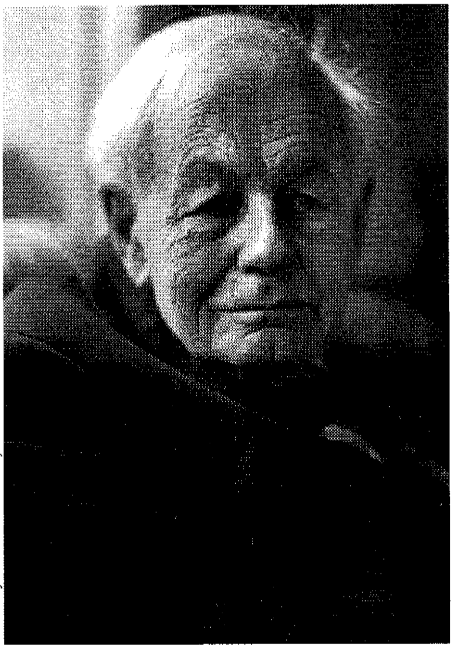
Hutchinson outlined his views in a 1946 paper, "Circular Causal Systems in Ecology." In it, he described the movement and accumulation of carbon in the biosphere, and phosphorus in lakes. Organisms, he noted, influenced the movement of these elements, and in turn, their productivity was influenced by the availability of these substances. He also developed mathematical equations depicting the growth and interactions of populations. Underlying both phenomena – the movement of elements, and the behaviour of populations – were circular causal paths, or feedback loops, damping oscillations and maintaining equilibrium, thereby ensuring the persistence of the system.[8]

Hutchinson had derived the feedback concept from recent wartime developments in the study and management of complex systems. Operations researchers had demonstrated how complex technology, such as missile systems, could employ feedback loops to ensure optimum performance. After the war, the study of self-regulation through feedback, or cybernetics, was transferred to peacetime research, particularly through a series of Macy Foundation conferences held between 1946 and 1953.[9]

One of Hutchinson's students was Howard T. Odum. In 1950 he completed his dissertation on the biogeochemistry of strontium. The stability of its global distribution, he concluded, exemplified the self-regulation of the "strontium ecosystem".[10] In subsequent research, Odum measured energy flow between trophic levels in Silver Springs, a series of mineral springs in Florida.[11] He drew energy flow diagrams, and then used a symbolic language to convert these into electrical circuit diagrams. Reducing ecosystem complexities to flows of energy, Odum believed, would permit discovery of general ecosystem principles. In 1955 he proposed the "maximum power principle," which stated that those ecosystems or other forms persist "which can command the greatest useful energy per unit time (power output)."[12] The practical implication, Odum believed, was that optimum social and ecological organization implied maximum use of energy.

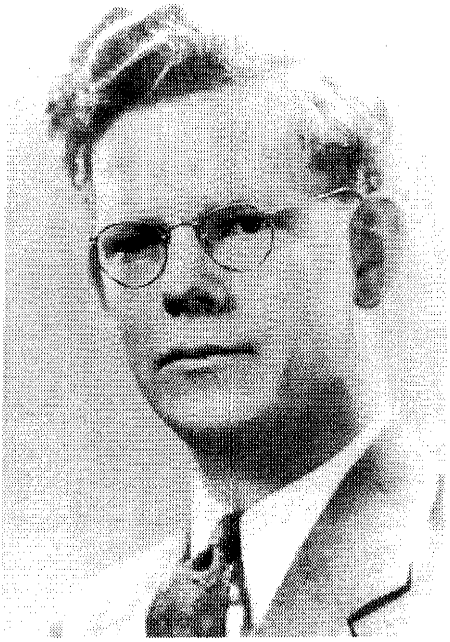
Howard Odum's older brother, Eugene, was also an ecosystem ecologist, but with a somewhat different perspective. While Howard drew analogies between ecosystems and physical systems, Eugene related the order and stability of the ecosystem to physiological mechanisms of homeostasis. Eugene was also probably more influential among ecologists. At his Institute of Ecology at the University of Georgia, and in three editions of his textbook, *Fundamentals of Ecology*, Eugene Odum alerted ecologists to the potential of ecosystem ecology.[13] The result was a small, but growing number of ecosystem studies during the 1950s.

By 1960, then, a growing number of ecologists interpreted nature in terms of ecosystems – as large as the biosphere, as small as a pond. Within the ecosystem, energy and nutrients are exchanged, con-



Courtesy of Yale University Office of Public Affairs

G.E. Hutchinson (above) developed mathematical equations depicting the growth and interactions of populations. Raymond Lindeman (below), while a post-doctoral student with Hutchinson at Yale, established what many consider the foundation of ecosystem research. By reducing the complexity of food chains and ecological change to energy flow, he made ecosystems amenable to quantitative physicochemical analysis.



Résumé

A. TANSLEY fut le premier en 1935 à formuler le concept d'écosystème. Par la suite, plusieurs écologistes, dont R. Lindeman, G.E. Hutchinson, H.T et E.P Odum, ont réutilisé le terme "écosystème" pour parler de l'étude de la nature en termes d'éléments intégrés, caractérisés par des flux d'énergie et des cycles alimentaires, et dont l'équilibre est préservé grâce à un mécanisme d'autorégulation cybernétique. Pendant les années '50 et '60, l'importance du financement injecté par la Commission de l'energie atomique des États-Unis ainsi que le Programme international de biologie on permis à l'écologie écosystèmique d'évoluer rapidement: on visait alors, entre autres à unifier l'écologie et à jeter les bases d'une gestion compréhensive de l'environnement, à l'aide de modèles informatisés. Des approches alternatives ont également vu le jour, comme la modification expérimentale d'écosystèmes entiers. Au Canada, et ce, jusqu'au début des années '70, l'écologie écosystèmique accusait du retard par rapport aux développements américains, reflétant peut-être ainsi les différences entre les deux pays en ce qui avait trait aux priorités des agences de recherche et de gestion des ressources. Depuis, l'écologie écosystèmique a eu fort à faire pour maintenir sa pertinence dans les milieux des affaires environnementales et de la recherche écologique. Aujourd'hui, d'autres approches, plus récentes, comme celle de l'intégrité écosystèmique, et les stratégies incorporant à la science des préoccupations sociales et politiques, nous montrent de nouvelles avenues. Ce regard sur l'évolution du concept d'écosystème nous démontre comment ce concept soi-disant scientifique, a éventuellement englobé diverses perceptions qu'ont les écologistes de la nature de notre société, et du rôle qu'ils y jouent.

sumed and transformed, and feedback loops ensure that, within limits, the system will remain at equilibrium. Such an interpretation had several implications.

One was a shift in ecological metaphor. Clements and other ecologists had viewed ecological communities as organisms, interpreting them in terms of the unique complexity of living entities. Tansley, while interpreting communities (somewhat vaguely) as "systems", nevertheless continued to focus on species acting within their physical environment. Hutchinson and his students eliminated the barrier between living and non-living systems. Both types of systems exhibited similar mechanical principles, tending through self-regulation to remain in equilibrium, and being susceptible to human manipulation that would ensure optimum behaviour. Both, in other words, were cybernetic. Nature became less an organism than a machine.

Some scientists found this image of nature as a machine, susceptible to manipulation, compelling. In the 1930s the Technocracy movement had offered a vision of a stable and efficient future society, managed by technocrats free from the distorting interests of economics and politics. After the war, the perceived contribution of large-scale industrial and scientific organization to victory, the war's demonstration of the hazards of societal instability, and the promise of cybernetics engendered a fresh burst of "technocratic optimism".[14]

Ecology was not excluded from this enthusiasm. Howard Odum, in outlining his theory of energy flows within ecosystems, promoted, as I have noted, its potential as a basis for technocratic management. Human-nature ecosystems, as he argued in *Environment, Power and Society*, could be designed and managed to ensure optimum efficiency and well-being.

Some ecologists shared this view. Many others, however, did not see in ecosystem ecology a basis for "ecological engineering" and large-scale intervention in nature. These ecologists thought that better understanding of ecosystems would provide a basis for their protection, not their control. Eugene Odum's research on coastal salt marshes, for example, helped build support for their preservation.[15] This compatibility of ecosystem ecology with seemingly contradictory objectives has been a continuing theme in the history of the concept.

Big science and big ecology

Large-scale funding stimulated the development of ecosystem ecology in the postwar era. From the early 1950s until 1974, the Atomic Energy Commission (AEC) was the largest supporter of ecosystem research in the United States. At the Oak Ridge National Laboratory in Tennessee, for example, ecologists used computerized simulation models to predict the movement of radionuclides within ecosystems. Oak Ridge eventually became one of the largest ecosystem research programmes in the United States.[16]

The AEC had several motives in supporting ecosystem ecology. It provided a quantitative, physicochemical perspective on nature that physical scientists at the commission could respect. Ecosystem ecologists also promoted the use of AEC-developed research tools, such as radionuclides. Their study of the behaviour of radionuclides in the environment provided a basis for detecting radiation exposures caused by nuclear reactors and weapons tests. Often, ecosystem ecologists defined nature explicitly or implicitly, as analogous to the complex engineered systems that were the AEC's primary concern. Overall, ecosystem ecologists were perceived as contributors to the AEC ideal of establishing a technological, nuclear-powered basis for American society.

Courtesy of the Institute of Ecology at the University of Georgia

Eugene Odum (above) related the order and stability of the ecosystem to physiological mechanisms of homeostasis, alerting ecologists to the potential of ecosystem ecology. Howard T. Odum (below) believed that reducing ecosystem complexities to flows of energy would permit discovery of general ecosystem principles – optimum social and ecological organization implied maximum use of available energy.

Courtesy of Yale University Press

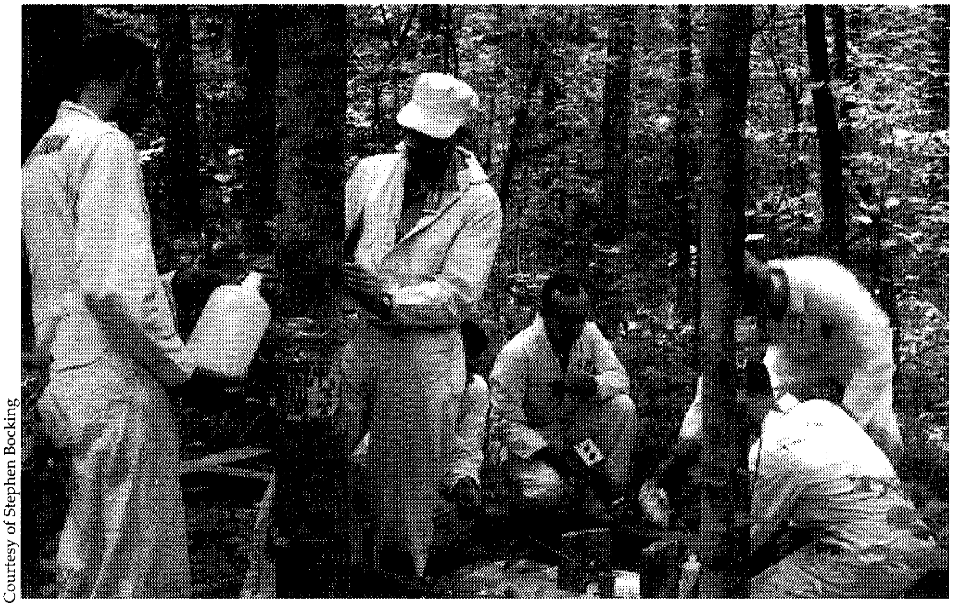
This pattern of consistency between ecosystem ecology and technological and political priorities continued into the late 1960s, when the American government allocated approximately $40 million for ecosystem studies under the auspices of the International Biological Program (IBP). With increasing public concern about the environment, ecosystem ecology, it was believed, could provide the scientific basis for a co-ordinated response to this concern.

Thus, the ecosystem concept conformed to an emerging view of the appropriate role of government. Many influential individuals had come to believe that government should protect the broader public interest by developing a stronger role in resource allocation and regulation, guided by comprehensive, rational decision making.[17] This view was consistent with, but less extreme, and probably more widely held, than the technocratic perspective described above. Because ecosystem ecology was seen as consistent with this view, it received greater funding, and became more prominent in discussions about environmental problems and the role of science in resolving them.

Through AEC and IBP support, ecosystem ecology became known as "big ecology": large, hierarchically structured research teams based on corporate or military models of organization, focused on the study of entire ecosystems, with the objective of developing computer models able to simulate and predict ecosystem behaviour.[18]

Big ecology, however, was not the only possible approach to ecosystem study, even in the US. An alternative perspective was developed at the Hubbard Brook Ecosystem Study in New Hampshire. Beginning in 1963, F. Herbert Bormann and Gene Likens, with colleagues and students, began studying the biogeochemistry of a forest ecosystem. Instead of attempting to capture the complexity of an ecosystem by computer simulation of its internal processes, they focused on the relationship of an ecosystem to its surroundings by measuring the flow of nutrients into and out of forest watersheds. The varying capability of the watershed to retain nutrients, they argued, could provide insights into ecosystem functions. Further insights were derived from ecosystem experiments, in which they deforested an entire watershed, measured its subsequent export of nutrients, and used the results to assess its capability to maintain stability.[19]

Watershed manipulation was not itself a new idea. The novel aspect of Hubbard Brook was its contribution of experimental results to a growing theoretical debate



Courtesy of Stephen Bocking

Ecologists at the Oak Ridge National Laboratory experimented with the use of radioactive elements, simulation models and other tools for ecosystem study. In this 1962 photo (left to right) William Cate Jerry Olson, Hubert Waller, Stanley Auerbach, Dac Crossley and John Witherspoon tag a tulip poplar forest by individually inoculating each tree with Cesium-137.

about the stability of ecosystems and their mechanisms of response to disturbance. Experimental ecosystem studies have since begun at numerous locations, including the Experimental Lakes Area (ELA) in Northern Ontario.[20]

The establishment of the ELA in the late 1960s reflects the relatively recent development of ecosystem ecology in Canada. With a few exceptions, such as the small tradition of holistic study of lakes epitomized by the work of Donald Rawson, Canadian ecologists had rarely explicitly addressed ecosystem-level theoretical concerns.[21] The relative lack of Canadian ecosystem ecology reflected, in part, the absence of agencies willing to support it on a large scale. Instead, most Canadian ecological research has been tied more or less closely to immediate resource management concerns. At the University of Toronto, for example, long the major centre for aquatic ecology in Ontario, research developed in close association with provincial fisheries research, and emphasized the study of specific fish populations, not entire ecosystems.[22] By the late 1960s, however, various factors, including a greater interest in the comprehensive management of lakes and watersheds, Canadian participation in the IBP, and the inability of other perspectives to provide an adequate basis for management of the Great Lakes, had stimulated ecosystem research.[23]

By 1971, Eugene Odum could note a "dramatic shift" towards ecosystem studies, as it was realized that human activities affect not just individual species but entire ecosystems.[24] Since then, a variety of large-scale ecosystem research programmes have been initiated, of which the largest and most recent is the International Geosphere-Biosphere Program, (the "global change" programme). Three themes are especially apparent in such research. One is a continuing interest in energy flows and biogeochemical cycling of elements. Even toxic substances such as DDT have been found to have biogeochemical cycles.[25] In recent years urban theorists have adapted an ecosystem approach to cities that stresses the flow of energy and materials.[26]

A second theme has been a shift in focus to larger-scale phenomena, most apparent in the global change study.[27] In addition, many scientists studying local phenomena are considering the links between these and changes on larger, even global scales.[28] Accompanying this expanding scale has been new methods, such as remote sensing, able to gather data over large areas.

A third theme has been the revision of perspectives on the dynamics of ecological systems. Nature is no longer an orderly system in equilibrium; it is instead a patchwork, characterized by pervasive disturbance and instability; constancy has been replaced by change, chaos and nonequilibrium conditions.[29]

This research has reflected scientists' view of their roles in environmental affairs. One role was to anticipate emerging environmental problems – such as the impact of CFCs on stratospheric ozone – of which the larger community was unaware. A second was provision of a general, theoretical basis for the eventual solution of environmental problems. Genuine solutions, many ecologists argued, could be achieved only through a fundamental understanding of ecological systems.

Eclipse of the ecosystem

Even as ecosystem ecologists sought distinctive roles, they were, to a large extent, eclipsed by other developments in environmental affairs. Since the early 1970s, confidence in ecosystem ecology's central role in ecological research and environmental policy has declined. In part, this reflects the discovery that the construction of realistic ecosystem models able to predict impacts of human activities is more difficult than first expected. Some have also criticized the failure of ecologists and other scientists to explain their results in socially relevant ways. For example, studies of carbon dioxide and climate change have been criticized for neglecting socio-economic implications.[30]

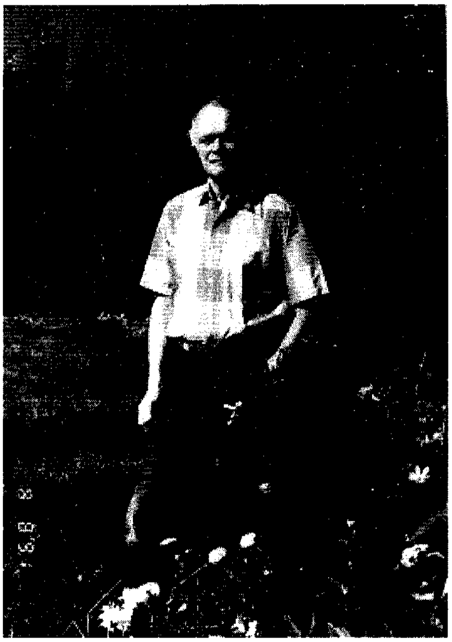
Most importantly, the political context has changed. In the United States, and to some extent in Canada, the belief in comprehensive management, prevalent in the late 1960s, has been replaced by renewed reliance on processes more typical of a pluralistic political system, such as negotiation, compromise and brokerage of competing interests, often conducted in an adversarial environment. Acceptance of a positive role for government in fostering society's interests has been replaced by greater reliance on competition, private initiative, and individual interests. This has implied a shift in the perceived role of science: no longer an alternative to "political" processes – as ecosystem ecology was once envisaged – it instead became a participant, contributing factual, value-free knowledge that would impart an air of objectivity to the resulting decision.[31] Such a role placed a premium on quantifiable, precise predictions, which ecosystem ecologists were not immediately able to provide.

Ecosystem research, certainly, continued to attract some supoort from funding agencies. The Hubbard Brook study for example, has received continual funding since 1963. The contribution of experimental ecosystem studies to improved political perspectives on various issues (forest harvesting and acid rain, in the case of Hubbard Brook; eutrophication and acid rain, in the case of the ELA) also reflects a continuing practical role for ecosystem studies in the provision of information concerning the long-term variability of natural systems, and the long-term impacts of anthropogenic stresses. The eclipse of ecosystem research, however, was nevertheless evident in the near-absence, until the late 1980s, of new research initiatives.

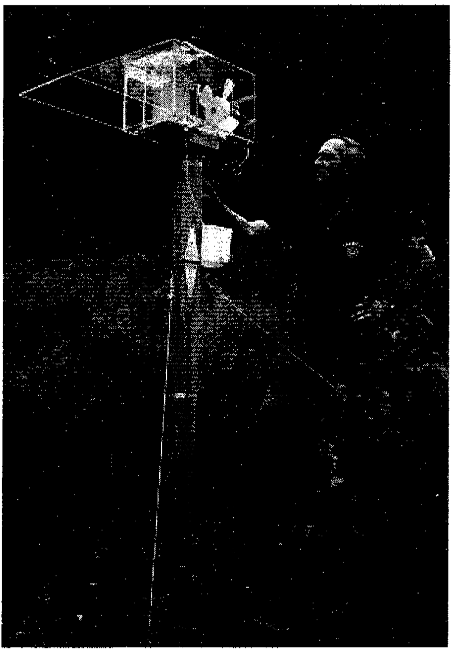
It was also evident in the continuing reluctance of many ecologists to accept the ecosystem concept. Even while Tansley, Hutchinson, the Odums and others developed their ecosystem perspectives, many ecologists resisted, arguing that all properties of nature could be understood in terms of its parts. Ecologists, therefore, should study individuals and populations – their behaviour, interactions, and responses to environmental conditions – not entire systems.[32]

Since the early 1970s, many others have

turned away from ecosystem ecology, to focus instead on other levels of organization: the individual, the population, or the community. Odum's *Fundamentals,* once the most popular college textbook of ecology, has been replaced by others giving considerably less attention to ecosystems.[33] When the IBP ended, many ecosystem ecologists found it difficult to attract continued funding for their research. While the 1960s were marked by a belief in the ecosystem concept as the key to an order underlying the complexity of nature and to a unified theory of ecology, a decade later this sense of unity had nearly vanished. Ecosystem ecology itself is marked by a diversity of approaches; the terms, even the possibility, of their synthesis remains unclear.[34]


Courtesy of Frank Golley and Yale University Press

Beginning in 1963, F. Herbert Bormann (above) and Gene Likens (below), with colleagues and students, began studying the biogeochemistry of a forest ecosystem. They focused on the relationship of an ecosystem to its surroundings by measuring the flow of nutrients into and out of forest watersheds. The varying capability of the forest to retain nutrients, they argued, could provide insights into ecosystem functions.


Courtesy of Gene Likens

Emerging ecosystem concepts: Integrity and home

Two recent developments suggest the possible future evolution of the ecosystem concept. Both reflect efforts to integrate the concept within environmental management. One is ecosystem integrity; the other is the adoption of the ecosystem concept by experts, agencies and interest groups outside the ecological research community.

The concept of ecosystem integrity has emerged since the 1970s. It acknowledges a role for ecological science in mediating the relationship between humans and their environment, and therefore has both theoretical and normative aspects. The objective of the 1978 Great Lakes Water Quality Agreement, for example, was "to restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes Basin Ecosystem." In normative terms, this commitment acknowledges that the Great Lakes ecosystem has intrinsic value and that human society is obliged to live in harmony with it.[35]

A theoretical basis to Great Lakes ecosystem integrity began to emerge 20 years ago, in research demonstrating that a stable fishery depended on healthy fish communities, which serve to some extent as integrators of anthropogenic stresses. These and other conclusions led to a new approach to fisheries management, based on the dual objectives of healthy fish communities, and public participation in their management.[36] Since then, this approach has evolved into a broader commitment to ecosystem integrity.

A variety of theoretical perspectives on ecosystem integrity have emerged. One such perspective views ecosystems as complex systems that develop and maintain some internal organization and identity, and that possess both homeostatic and self-organizational capability. An ecosystem is said to exhibit integrity, if, when subjected to disturbance, it has an organizing, self-correcting capability to recover toward a state that is normal for that system.[37]

Efforts to specify indicators of ecosystem integrity have focused on those that integrate the impact of anthropogenic stresses, and are meaningful to those who must participate in efforts to restore or maintain ecosystem integrity. This reflects the primary political implication of ecosystem integrity: the necessity for broad participation in the environmental policy process.


Courtesy of A.L. Hamilton, International Joint Commission

Between 1930 and 1960 Donald Rawson (above) pioneered the study of limnology in western Canada, developing methods for the holistic study of lake ecosystems.

Henry Regier (below with grandson Nick Betts) of the University of Toronto and his colleagues have used concepts of stress-response and integrity to build an integrated understanding of the behaviour and role of fish communities in the Great Lakes ecosystem.


Courtesy of Henry Regier

Somewhat similar perspectives on the ecosystem concept have emerged as the concept has been adopted by non-ecologists. The Royal Commission on the Future of the Toronto Waterfront, for example, identified five themes inherent in the ecosystem approach:

- the ecosystem as "home",
- everything is connected to everything else,
- sustainability,
- understanding places, and
- integrating processes.[38]

This view, like the concept of ecosystem integrity, implies both a normative and an empirical basis for human activity. It reflects a broader perspective on the place of humans within their environment than had usually been adopted by ecologists alone. According to this view, ecologists do not act as the privileged "ecological engineers", nor as expert participants in an adversarial process that results in government-imposed solutions, as implied by earlier perspectives. Rather, they are seen as contributors to a societal consensus on our comportment toward the environment. Such a consensus can then bolster local environmental stewardship.

Thus, the concept of ecosystem integrity reflects a diminished confidence in the capacity of senior governments to impose solutions to environmental problems. It also reflects the tendency to impose greater responsibility on individuals and communities to find these solutions. Broader acceptance of the concept of ecosystem integrity may hinge as much on the degree to which this responsibility is accepted, as on its theoretical elaboration by ecologists.

Scientific concepts rarely reflect simply an objective understanding of empirical reality. As the history of the ecosystem concept suggests, their evolution reflects not only our changing understanding of nature, but our evolving sense of the role of science, and of our place in the world. In describing nature, we describe ourselves. By understanding this interdependence of visions of nature, science, and society, we can better understand how science might contribute to fostering respect and protection of the environment. ❑

Stephen Bocking received a PhD in 1992 from the University of Toronto, for a study of the history of environmental research. He is currently at the University of British Columbia, where he is completing a book on this topic and conducting a study of environmental research in the Mackenzie River Basin.

Notes

[1] The term "ecosystem" was coined in 1935 and I begin my account there. Somewhat similar concepts, however, predate it, such as the "microcosm" of Stephen Forbes, see "The Lake as a Microcosm," *Bulletin of the Peoria Scientific Association* (1887), pp. 77-87; reprinted in L.A. Real and J.H. Brown, *Foundations of Ecology* (Chicago: University of Chicago Press, 1991), pp. 14-27. See also S.A. Bocking, "Stephen Forbes, Jacob Reighard and the Emergence of Aquatic Ecology in the Great Lakes Region," *Journal of the History of Biology*, 23 (1990), pp. 461-498; J.B. Hagen, *An Entangled Bank: The Origins of Ecosystem Ecology* (New Brunswick, New Jersey: Rutgers University Press, 1992). There is a rich tradition of ecosystem concepts in Europe. For reasons of language and cultural practice, it has largely developed apart from analogous work elsewhere. This account will not consider this tradition, but will instead – in the interest of brevity and clarity – focus on developments in Britain and North America, which have historically been more significant in the shaping of contemporary Canadian views of ecosystems.

[2] A.G. Tansley, "The Use and Abuse of Vegetational Concepts and Terms," *Ecology*, 16 (1935), pp. 284-307.

[3] F.E. Clements, *Plant Succession: An Analysis of the Development of Vegetation* (Washington: Carnegie Institution, 1916).

[4] Tansley, "Use and Abuse" [note 2], p. 299.

[5] R.L. Lindeman, "The Trophic-Dynamic Aspect of Ecology," *Ecology*, 23 (1942), pp. 319-418; see also R.E. Cook, "Raymond Lindeman and the Trophic-Dynamic Concept in Ecology," *Science*, 198 (1977), pp. 22-26.

[6] C. Elton, *Animal Ecology* (London: Sidgwick & Jackson, 1927).

[7] G.E. Hutchinson, "Bio-Ecology," *Ecology*, 21 (1940), pp. 267-268.

[8] G.E. Hutchinson, "Circular Causal Systems in Ecology," *Annals of the New York Academy of Science*, 40 (1948), pp. 221-246.

[9] P.J. Taylor, "Technocratic Optimism, H.T. Odum, and the Partial Transformation of Ecological Metaphor after World War II," *Journal of the History of Biology*, 21 (1988), pp. 215-220.

[10] H.T. Odum, "The Stability of the World Strontium Cycle," *Science*, 114 (1951), pp. 407-411.

[11] H.T. Odum, "Trophic Structure and Productivity of Silver Springs, Florida," *Ecological Monographs*, 27 (1957), pp. 55-112.

[12] H.T. Odum and R.C. Pinkerton, "Time's Speed Regulator: The Optimum Efficiency for Maximum Power Output in Physical and Biological Systems," *American Scientist*, 43 (1955), pp. 331-343.

[13] E.P. Odum, *Fundamentals of Ecology* (Philadelphia: Saunders, 1953, 1st edition; 1959, 2nd edition; 1971, 3rd edition). Some examples of early ecosystem studies include J.M. Teal, "Energy Flow in the Salt Marsh Ecosystem of Georgia," *Ecology*, 43 (1962), pp. 614-624; R. Margalef, "Information Theory in Ecology," *General Systems*, 3 (1958), pp. 36-71; and B.C. Patten, "An Introduction to the Cybernetics of the Ecosystem: The Trophic-Dynamic Aspect," *Ecology*, 40 (1959), pp. 221-231.

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[15] J.V. Siry, *Marshes of the Ocean Shore: Development of an Ecological Ethic* (College Station: Texas A&M University Press, 1984).

[16] S.A. Bocking, "Ecosystems, Ecologists and the Atom: Environmental Research at Oak Ridge National Laboratory," *Journal of the History of Biology*, in press.

[17] S.P. Hays, *Beauty, Health, and Permanence: Environmental Politics in the United States, 1955-1985* (Cambridge: Cambridge University Press, 1985); and L.K. Caldwell, "Environment: A New Focus for Public Policy?" *Public Administration Review*, 23 (1963), pp. 132-139.

[18] E.B. Worthington, *The Evolution of IBP*, (Cambridge: Cambridge University Press, 1975); and W.F. Blair, *Big Biology: The US/IBP* (Stroudsburg, Pennsylvania: Dowden, Hutchinson & Ross, 1975).

[19] F.H. Bormann and G.E. Likens, *Pattern and Process in a Forested Ecosystem* (New York: Springer-Verlag, 1979); on the Hubbard Brook study, see S.A. Bocking, "Environmental Concerns and Ecological Research in Great Britain and the United States, 1950-1980," (Toronto: University of Toronto, PhD Dissertation, 1992), pp. 259-316.

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[23] H.A. Regier, "Ecosystem Integrity in the Great Lakes Basin: An Historical Sketch of Ideas and Actions," *Journal of Aquatic Ecosystem Health*, 1 (1992), pp. 25-37.

[24] Odum, *Fundamentals* [note 13].

[25] See, for example, G.M. Woodwell, "Toxic Substances and Ecological Cycles," *Scientific American*, 216:3 (1967), pp. 24-31.

[26] J. Brugmann and R. Hersh, *Cities as Ecosystems: Opportunities for Local Government* (Toronto: International Council for Local Environmental Initiatives, 1991).

[27] H. Friedman, "The Science of Global Change: An Overview," *Global Change*, T.F. Malone and J.G. Roederer, eds. (Cambridge: Cambridge University Press, 1984), pp. 28-31.

[28] See, for example, G.M. Woodwell, *et al.*, "Global Deforestation: Contribution to Atmospheric Carbon Dioxide," *Science*, 222 (1983), pp. 1081-1086.

[29] W.C. Clark, "Sustainable Development of the Biosphere: Themes for a Research Program," *Sustainable Development of the Biosphere*, W.C. Clark and R.E. Munn, eds. (Cambridge: Cambridge University Press, 1986), pp. 31-38; C.S. Holling, "The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change," *Sustainable Development*, Clark and Munn, eds., pp. 292-317; and D. Worster, "The Ecology of Order and Chaos," *Environmental History Review*, 14:1/2 (1990), pp. 1-18.

[30] A.B. Pittock, "The Carbon Dioxide Debate: Reports from SCOPE and DOE," *Environment*, 29:1 (1987), p. 26.

[31] *Expert Evidence: Interpreting Science in the Law*, R. Smith and B. Wynne, eds. (London: Routledge, 1989), especially S. Jasanoff, "The Problem of Rationality in American Health and Safety Regulation," pp. 151-183. See also *Controversy: The Politics of Technical Decisions*, D. Nelkin, ed. (Newbury Park: Sage, 1992, 3rd edition).

[32] See, for example, S. Kingland, *Modeling Nature: Episodes in the History of Population Ecology* (Chicago: University of Chicago Press, 1985).

[33] See, for example, M. Begon, J.L. Harper, C.R. Townsend, *Ecology: Individuals, Populations, and Communities* (Sunderland: Sinauer Associates, Inc., 1986).

[34] As one example of this diversity, see C.J. Edwards and H.A. Regier, *An Ecosystem Approach to the Integrity of the Great Lakes in Turbulent Times* (Ann Arbor, Michigan: Great Lakes Fishery Commission Special Publication 90-4, 1990).

[35] Great Lakes Research Advisory Board, *The Ecosystem Approach* (Windsor: International Joint Commission, 1978); and Rawson Academy of Aquatic Science, *Towards an Ecosystem Charter for the Great Lakes-St. Lawrence* Rawson Occasional Paper No. 1, 1989.

[36] K.H. Loftus, M.G. Johnson, H.A. Regier, "Federal-Provincial Strategic Planning for Ontario Fisheries: Management Stratey for the 1980s," Journal of the Fisheries Research Board of Canada, 35 (1978), pp. 916-927.

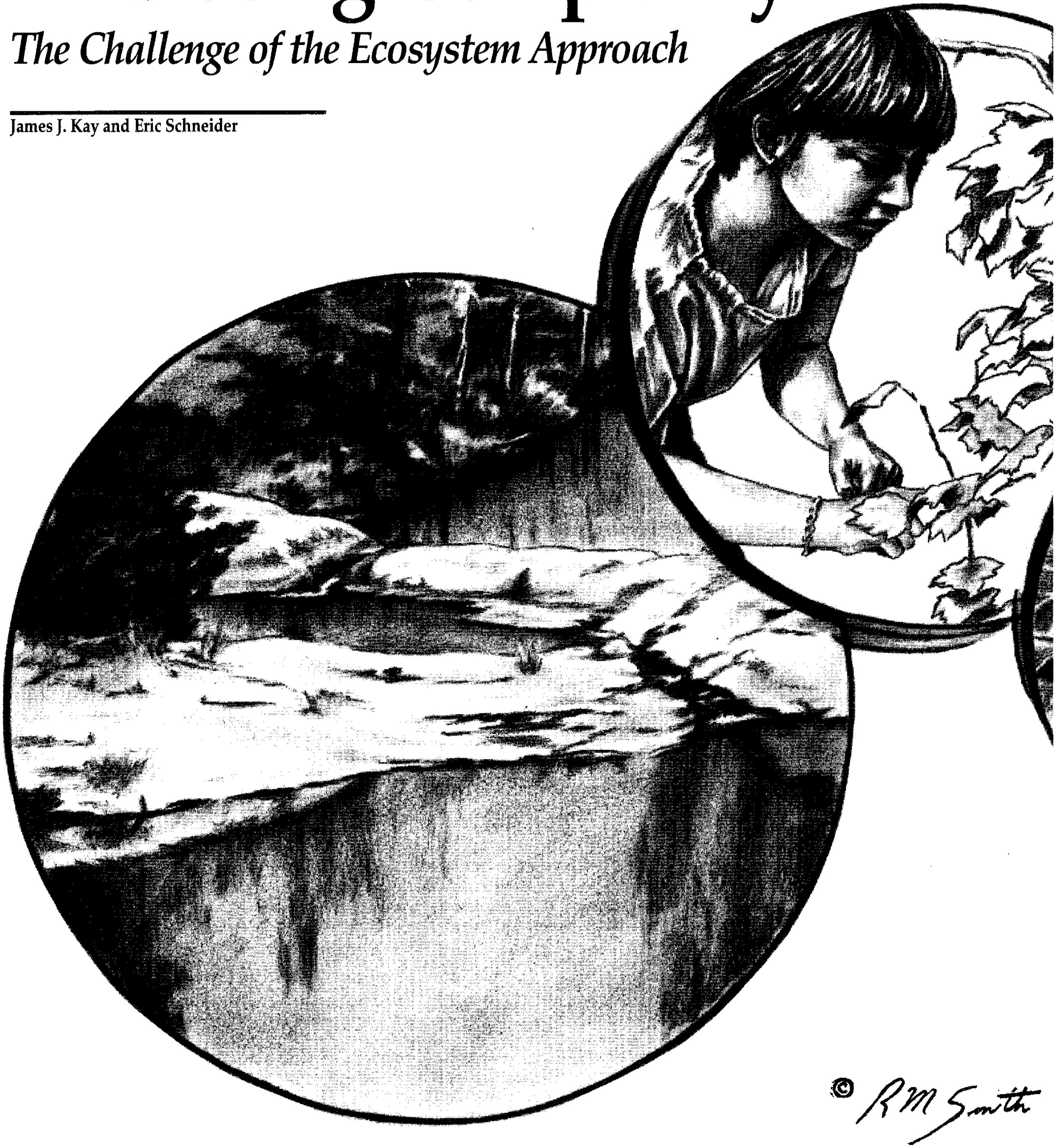
[37] J.J. Kay, "A Nonequilibrium Thermodynamic Framework for Discussing Ecosystem Integrity," Environmental Management, 15 (1991), pp. 483-495. "Ecosystem health," a concept frequently invoked, varies in several respects from the concept of ecosystem integrity. As a metaphor based on human individuals, ecosystem health emphasizes a stable state of well-being, not processes of change, response to stress and self-organization.

[38] Royal Commission on the Future of the Toronto Waterfront, Regeneration: Toronto's Waterfront and the Sustainable City: Final Report, (1992), p. 32.

Embracing Complexity

The Challenge of the Ecosystem Approach

James J. Kay and Eric Schneider



As environmental degradation and change continues, decision makers and managers feel significant pressure to rectify the situation. Scientists, in turn, find themselves under pressure to set out simple and clear rules for proper ecosystem management. The response has been one of frustration. Michael Soule and Laurence Slobodkin both loudly complain that ecology is an intractable science, immature and not very helpful. Kristin Shrader-Frechette and Robert Peters reproach ecologists for not producing simple testable hypotheses.[1] Meanwhile policy makers and managers clamour for a measure of ecosystem integrity whose value in different situations can be predicted by simulation models. The question on everyone's mind is "what does ecosystem science identify as the main, simple, basic, universal laws which will allow quantitative prediction of ecosystem behaviour and what are the resulting rules for ecosystem management?"

All of these demands on ecology are predicated on a vision of science which assumes that it can provide firm knowledge, and that the only way of obtaining this knowledge is the scientific method. The standard scientific method works well with billiard balls and pendulums, and other very simple systems. However, systems theory suggests that ecosystems are inherently complex, that there may be no simple answers, and that our traditional managerial approaches, which presume a world of simple rules, are wrong-headed and likely to be dangerous.

In order for the scientific method to work, an artificial situation of consistent reproducibility must be created. This requires simplification of the situation to the point where it is controllable and predictable. But the very nature of this act removes the complexity that leads to emergence of the new phenomena which makes complex systems interesting. If we are going to deal successfully with our biosphere, we are going to have to change how we do science and management. We will have to learn that we don't manage ecosystems, we manage our interaction with them. Furthermore, the search for simple rules of ecosystem behaviour is futile.

Take for example the diversity-stability hypothesis.[2] This is a classic example of the kind of simple rule people are looking for. Students are taught that diversity in ecosystems is important because it maintains their stability. Yet, we know that to obtain an increase in diversity in ecosystems, we need only stress them.[3] Daniel Goodman long ago dissected and refuted this hypothesis and yet we still see it being promoted as a guideline for management and policy.[4] Why? Because we want simple answers to complex questions.

The diversity-stability hypothesis illustrates this nicely. Examination of what is meant by diversity and stability quickly leads us into the quagmire of complexity. Is diversity to be measured by number of species? the relative abundance of species? their richness? Which species do you include? big ones that are easy to count? all the micro-organisms in the soil? Very quickly it turns out that there is no one correct way to measure diversity, and in the end, it is an observer-dependent phenomenon, dependent on which species the researcher decides to include.

The notion of stability is even more slippery.[5] The traditional approach developed by M. Lyapunov focuses on some numerical state function and whether that function has a constant value which the system tends towards and returns to when disturbed. But what state function should we measure? population numbers? biomass? productivity?... The list is endless and the problem doesn't end there. We may choose a function to represent the ecosystem and its stability, but we are now discovering that these functions are not stable.[6] Instead ecosystems are dynamic and constantly changing. Stability gives way to the notion of a shifting steady mosaic.[7] Thus, the diversity-stability hypothesis evaporates because the basic concepts of diver sity and stability are just too simple to describe the complex reality of ecological phenomena.

The same is true of the notion of "succession", the idea that an ecosystem develops through a series of dominant vegetation types and ultimately reaches a climax community. Robert McIntosh has documented the ongoing debate about succession and identifies six major schools of thought in the US alone.[8] The thinking ranges from succession as an orderly pattern of development, which is reproduced time and time again, to succession as a myth, that is there is nothing but random assemblages of species with no underlying patterns. There is nothing approaching consensus about succession in the ecology community. In fact, ecologists bemoan that there is not one single "law" of the science of ecology. Why? Because we are asking the wrong questions.

There is a group of thinkers who argue that to deal with ecology requires an "ecosystem approach", an approach based on the notions of complex systems theory, the grandchild of Ludwig von Bertalanffy's general systems theory.[9] It is a fundamentally different approach to knowing about the world, and it is, not surprisingly, complex itself. Any effort to study complex systems must look at them in the context of *space, time, energy* and *information*. We shall probe, in turn, each of these aspects of ecosystems as complex systems.

The sky is falling

Part of our trouble is that our conventional notion of science is based on understanding the temporal and sometimes spatial dynamics of systems in the context of their inertia (mass). We see the world as billiard balls from a Newtonian perspective. Ball A strikes ball B causing it to move. All activities of a system can be explained by mechanisms, in terms of the interactions of components, usually in a linear way. Component interactions are sufficient to explain all. So science focuses on establishing which components are responsible for what.[10]

At the turn of the century, several insights changed how scientists look at the physical world. In terms of space and time, it was realized that there is not a preferred observer and that the relationship between observers, at least in four dimensions, is not linear. Space and time are curved. Furthermore, energy is quantized, mass is a form of energy, and we always lose information about things.[11] The world is running down. The sky is falling.

These insights did not affect how we looked at the world on a day-to-day basis. Its direct impact has been on the development of things "nuclear" and things "solid state" (e.g. computer chips). As for the world running down, we already knew that. So scientific inquiry continued to follow the "scientific method", attempting to explain everything through mechanistic interactions of components. The logical extremes have been the elementary particles of physics, the selfish gene of biology, and "Newtonian ecology".

However, the minute one leaves the physical sciences there is a paradox, a paradox whose resolution ultimately requires us to abandon the hypothesis that the reductionist, mechanistic, scientific method is sufficient for understanding the world. The paradox is that the second law of thermodynamics maintains that the world is running down, but the biological world is not running down. Quite the opposite is happening; life is proliferating. The sky is *not* falling! The same can be said of the systems studied by the social sciences.

A revolution in science has occurred in the last two decades that is as profound as the one which occurred between 1890 and 1910 with the work of Ludwig Boltzmann, Albert Einstein, Josiah Gibbs, Max Planck, *et al.* The revolution of the turn of the century was about how we view the microscopic world. It did not change how we look at our world, day-to-day. The current revolution is about how we look at the macro world and it will profoundly affect our day-to-day living, our institutions and our decision making, including decisions on judicial matters.

It is fitting that one cannot put this new set of insights down on paper in a nice linear way. The revolution emerges from the synergism of new insights in several fields. Since the prevalent worldview is largely about mechanistic-reductionist predictions about space and time, it seems appropriate to start with the unravelling of this.

Space and time

Catastrophe theory describes the change in systems over time. It predicts that systems will undergo dramatic, sudden changes in a discontinuous way. The classic example is the failure of a structural beam under loading. The choice of the name of the theory is quite unfortunate because it implies abnormal nasty events, when in fact such events are normal and necessary for the continued ordinary functioning of many systems. Your heartbeat is a catastrophic event, as is the emptying of your bladder. Both are necessary for your continuing survival. Both are discontinuous events that occur suddenly.

Furthermore, at the point where a system undergoes a catastrophic change several distinct changes are possible and actually occur – which one is not predictable. For example, dogs (in fact most animals) have a bubble of space around them which is their territory. Enter the space (the catastrophe threshold) and the dog will either retreat or attack, but it is not, a priori, possible to predict with certainty which of the two actions will occur.

The general insight from catastrophe theory is that the world does not always change in a continuous and deterministic way. There are points in any system's development where several possible directions of radical change are open, and it is not possible to predict, with certainty, which one will occur.

Chaos theory takes this one step further by noting that change in any dynamic system is ultimately not predictable, because individually small interactions between components accumulate.[12] This applies even to the balls on a billiard table and the planets in the heavens, those objects whose motion Newtonian mechanics is supposed to predict perfectly. Consequently our ability to forecast and predict is always limited, for example to about five days for weather forecasts, regardless of how sophisticated our computers are and how much information we have.

These two bodies of insight into behav-

Résumé

UNE NOUVELLE COMPRÉHENSION écologique est en train de naître. Cette émergence est fondée sur l'application de la théorie des systèmes complexes issue de la théorie des systèmes généraux de Ludwig von Bertalanffy.

Cette nouvelle approche est radicalement opposée aux principes mécaniques universels newtoniens traditionnels car elle cherche à comprendre l'écosystème comme étant un système dynamique, en constante évolution et à l'intérieur duquel les changements pourraient être autant harmonieux que violents.

Pour mieux comprendre ces comportements, nous serons requis d'étudier les écosystèmes à partir d'un modèle de perspectives hiérarchiques qui sera attentif aux problèmes d'équilibre et de déploiement. Il faudra aussi rendre compte des aspects spatiaux-temporels, thermodynamiques et informatifs des écosystèmes sous étude.

Le défi sera de trouver les moyens d'administrer les activités humaines de façon à ce qu'elles puissent améliorer l'organisation et le développement naturel en cours dans les écosystèmes. Cette gestion devra diriger et faciliter les changements, sans pour autant essayer d'atteindre et de maintenir un état stable et perpétuel dans les écosystèmes.

Tout dépend de notre compréhension des procédés d'organisation autonome des écosystèmes pour que nous soyons capables d'organiser nos actions et parvenir ainsi à une synergie fonctionnelle avec les processus d'organisation des écosystèmes.

iour in space and time eliminate the possibility of precise, a priori, mechanistic, deterministic predictions of the future. Computers cannot substitute for crystal balls, except for very limited classes of problems that occur over short spatial and temporal dimensions.

Thermodynamics and open systems

The next insights concern energy, that is thermodynamics. Ilya Prigogine in his Nobel Prize winning work, showed that spontaneous coherent behaviour and organization (e.g. tornadoes) can occur and are completely consistent with thermodynamics.[13] The key to understanding such phenomena is to realize that one is dealing with open systems with a constant flow of high quality energy. In these circumstances, coherent behaviour appears in systems almost magically. Prigogine showed that this occurs because the system reaches a catastrophe threshold and flips into a new coherent behavioural state. (This is evident for example in the vortex which spontaneously appears when draining water from a bathtub.)

Prigogine's work can be taken one step further to explain the energetics of open systems.[14] An open system with high quality energy pumped into it is moved away from equilibrium. But nature resists movement away from equilibrium.[15] So the open system responds with the spontaneous emergence of organized behaviour that uses the high quality energy to maintain its structure, thus dissipating the ability of the high quality energy to move the system away from equilibrium. As more high quality energy is pumped into a system, more organization emerges to dissipate the energy.[16]

This view of the world is radically different from that of a reductionist view which sees the world's workings in terms of mechanical interactions between components of a system. The emergence of organized behaviour, and even life, is now mandated by thermodynamics. This self-organization is characterized by abrupt changes that occur when a new set of interactions and activities emerge among components and the whole system.

The form of expression this self-organization takes is not predictable in advance because the very process of self-organization is by catastrophic (in the catastrophe theory sense) change; it "flips" into new regimes. As noted earlier, one of the characteristics of catastrophic change is that systems may have several possible behavioural pathways available at a catastrophe threshold. Which pathway is followed is largely an accident of circumstances. A reductionist worldview, which cannot deal with the reality of emergence and self-organization in non-equilibrium systems, cannot offer sufficient explanation of how the world works.

An important observation about systems that exhibit self-organization is that they exist in a situation where they get enough energy, but not too much. If they do not get sufficient energy of high enough quality (beyond a minimum threshold level), organized structures cannot be supported and self-organization does not occur. If too much energy is supplied, chaos ensues in the system, as the energy overwhelms the dissipative ability of the organized structures and they fall apart. So self-organizing systems exist in a middle ground of enough, but not too much.

Furthermore, these systems do not maximize or minimize their functioning. Rather their functioning represents an optimum, a trade-off among all the forces acting on them. If there is too much development of any one type of structure, the system becomes overextended and brittle. If a structure is not sufficiently developed to take full advantage of the available energy and resources, then some other more optimal (i.e. better adapted) structure will displace it. In sum, these systems represent a fine balancing act. Inevitably then, human management strategies that focus on maximizing or minimizing some aspect of these systems will always fail. Only management strategies which maintain a balance will succeed.

Ecologists bemoan that there is not one single "law" of the science of ecology. Why? Because we are asking the wrong questions.

Middle number systems and observer dependence

The description of these self-organizing systems is known as the middle number problem. Small number problems involve a very controlled situation with very few components. (e.g. two billiard balls colliding). Such problems are usually well explained by traditional science. Large number problems involve so many objects interacting that they can be described by statistical means (e.g. the air molecules in a room). This is the domain of classical thermodynamics and statistical mechanics. Middle number problems involve many things interacting in ways that are not random (e.g. most real world problems).[17]

This area of inquiry is the domain of system theorists. There are two important lessons to be learned from the study of middle number systems. First, such systems can only be understood from a hierarchical perspective. Neither a reductionist nor a holistic approach is sufficient. One must look at the system (e.g. a wetland or a woodlot) as a whole and as something composed of subsystems and their components. One must also look at the system in the context of its being a subsystem of a bigger system, which in turn is part of a wider environment. So, study of an animal population without reference to the individuals that make it up, the community it belongs to, and the environment it lives in, is not sufficient. This is not to say that population ecology is useless, but on its own, it cannot explain ecological phenomena.

Another property of these middle number systems is that everything is connected (at least weakly) to everything else. An analyst, in identifying the system to be studied, decides what to include and what to leave out. These decisions, about scale and extent and the hierarchical units to be studied, may be done in a systematic and consistent way, but they are necessarily subjective, and to some extent arbitrary. They reflect the viewpoint of the analyst about which connections are important to the study at hand, and which can be ignored. Thus the notion of a pristine objective scientific observer, is not applicable to the study of self-organizing systems.

It is the observer-dependent nature of the study of self-organizing systems which is the most difficult point for traditional reductionist science to understand. Take for example the notion of an ecosystem. Because the world is made of living and non-living stuff with multitudes of interrelationships, any one defined ecosystem is just one package of stuff and relations. To describe one ecosystem is to take one of many possible perspectives on these entities.[18] An ecosystem can refer to what's happening on our eyelashes, in our gut, or in Lake Ontario, or in the boreal forest. Where one draws the boundaries around an ecosystem depends on the scale and extent from which one needs to observe the whole, given the purpose of the study being undertaken. Different people looking at the same stuff are going to define the ecosystem differently, unless they agree on the inevitably subjective criteria for deciding on scale, extent and hierarchy.

The response of traditional science to this is that ecosystems don't exist, since we cannot come up with an observer-independent way of defining them. One consequence of this logic is that ecosystem research is not considered proper "scientific" research by most North American granting agencies and is not a fit topic in American ecological journals. Luckily, Canadian and European journals do not have this problem. Complex systems theory represents a profound change in the paradigm for doing science, so profound that traditional science rejects it out of hand.

The notion of ecosystem is a focal point for the clash between these paradigms of what science is about.

Information: The key to self-organization

The notions of observer dependence and hierarchical context lead us to discuss the last player of the space, time, energy and information quartet. The key question is: What information do systems need to self-organize successfully?

All living systems go through cycles of birth, growth, death and renewal. We are all familiar with death and reproduction at the cellular level, and the birth-growth and death of individuals, but it is only recently that Buzz Holling has made us aware that this cycle occurs at many temporal and spatial scales.[19]

Living systems must function within the context of the system and environment of which they are part. If a living system does not conform with the circumstances of the supersystem it is part of, it will be selected against. This process of selection functions at all levels. The supersystem imposes a set of constraints on the behaviour of the system, be it at the level of the cell, individual, population or community. Living systems that are evolutionarily successful have learned what these constraints are and how to live within them. (This is the painful process the human species is now undergoing, assuming it is not selected against).

But this presents a problem. When a new living system is generating after the demise of an earlier one, it would make the self-organization process much more efficient if it were constrained to variations which have a high probability of success. At the level of cells to species, genes play this role. Genes constrain the self-organization process to those options which have a high probability of success. It is not that genes direct or control the process of development, rather they constrain it to forms which will respect the realities of the supersystem and environment. They are a record of successful self-organization. Genes are not the mechanism of development, the mechanism is self-organization. Genes put boundaries on the process of self-organization.[20]

At higher hierarchical levels other devices constrain the self-organization process. For example, some species will kill their young under certain conditions, and many tree species need specific microclimate conditions to trigger self-organization.[21] In some species, young are taught behaviours and individuals are banished from the group for inappropriate behaviour. Indigenous human cultures have taboos, morals and other cultural mechanisms that constrain behaviours to those which are sustainable in the context of specific ecosystems. Each of these devices acts, at a particular level of organization, as an information database about self-organization strategies that have an historical track record of success. They set out the boundaries of behaviour by self-organizing systems.

Given that living systems go through a constant cycle of birth, growth, death and renewal again, at many temporal and spatial scales, a way of preserving information about what works and what doesn't so as to constrain the self-organization process is crucial for the continuance of life. This is the role of the gene. At a larger scale it is the role of biodiversity.

Biodiversity is the information database for ecosystem organization. The ability of an ecosystem to regenerate, as part of the birth, growth, death and renewal cycle, is a function of the species available for the regeneration process. This, of course, is related to the biodiversity of the larger landscape that the ecosystem is part of. Thus preservation of biodiversity is important because we are in effect preserving the library used for regeneration of landscapes.[22]

The ecosystem approach and integrity: A new perspective

So what are the implications of all this? The first is that we need to look at ecosystems from a hierarchical perspective with careful attention to scale and extent. Second, we must examine the spatial, temporal, thermodynamic and information aspects (dynamics) of these systems. This must be done in the context of behaviour which is both emergent and catastrophic. In other words, we must recognize that ecosystems are dynamic, not deterministic, that they have a degree of unpredictability and that they will exhibit phases of rapid change.

This is not to say that ecosystem behaviour is chaotic or random and haphazard. On the contrary, ecosystem behaviour and

"Hairy Woodpecker" Robert M. Smith

development is like a large musical piece such as a symphony, which is also dynamic and not predictable and yet includes a sense of flow, of connection between what has been played and what is still to come, the repetition of recognizable themes and a general sense of orderly progression. In pieces such as symphonies or suites we know the stages (allegro, adagio, etc.) that the piece will progress through, even though we don't know the details of the piece. The same is true of ecosystems. Some behave in a very ordered way as does a Baroque suite, while others are full of improvisation as in modern jazz. And yet we know the difference between music and random collections of noise.

Ecosystem self-organization unfolds like a symphony. Our challenge is to understand the rules of composition and the limitations and directions they place on the organization process, as well as what makes for the ecological equivalent of a musical masterpiece that stands up to the test of time. However we should not expect to have a science of ecology which allows us to predict the next note.

We must always remember that left alone, living systems are self-organizing, that is they will look after themselves. Our responsibility is to not interfere with this self-organizing process or better yet, to enhance it. Of paramount importance, in this respect, is that we must not destroy the information needed for the regeneration process which is continually ongoing. A damaged ecosystem, left to its own devices, has the capability to regenerate if it has access to the information required for renewal, that is biodiversity; and if the context for the information to be used, that is the biophysical environment, has not been so altered as to make the information meaningless.

Another important thing we need to do is to stop managing ecosystems for some fixed state, whether it be an idealistic pristine climax forest or a corn farm. Ecosystems are not static things, they are dynamic entities made up of self-organizing processes. Management goals that involve maintaining some fixed state in an ecosystem or maximizing some function (biomass, productivity, number of species) or minimizing some other function (pest outbreak) will always lead to disaster at some point, no matter how well meaning they are. We must instead recognize that ecosystems represent a balance, an optimum point of operation, and this balancing is constantly changing to suit a changing environment. And if this isn't radical enough we must bear in mind that all living systems from cells to communities face death and regeneration. This is required by the second law; it is a thermodynamic necessity.

> ***If human activities maintain the integrity of the self-organizing entities that we call life, we will be all right. If they don't, we will be selected out of the systems. We have a simple choice, to be stewards of integrity or disrupters of integrity. There is no middle ground.***

For us, the notion of serving ecological integrity means accepting all of this. If human activities maintain the integrity of the self-organizing entities that we call life, we will be all right. If they don't, we will be selected out of the systems. We have a simple choice, to be stewards of integrity or disrupters of integrity. There is no middle ground.

But what exactly is ecological integrity? For an ecosystem, integrity[23] encompasses three major ecosystem organizational facets.[24] Ecosystem health, the ability to maintain normal operations under normal environmental conditions, is the first requisite for ecosystem integrity. But it alone is not sufficient. To have integrity, an ecosystem must also be able to cope with changes (which can be catastrophic) in environmental conditions; that is, it must be able to cope with stress. As well, an ecosystem which has integrity, must be able to continue the process of self-organization on an ongoing basis. It must be able to continue to evolve, develop and proceed with the birth, growth, death and renewal cycle. It is these latter two facets of ecosystem integrity that differentiate it from the notion of ecosystem health.

This understanding of the behaviour of complex self-organizing systems provides a framework for the investigation of environmentally induced changes in ecosystem organization and integrity.[25] It establishes that ecosystems can respond to changes in the environment in five qualitatively different ways:

- The system can continue to operate as before, even though its operations may be initially and temporarily unsettled.
- The system can operate at a different level using the same structures it originally had (for example, a reduction or increase in species numbers).
- Some new structures can emerge in the system that replace or augment existing structures (for example, new species or paths in the food web).
- A new ecosystem, made up of quite different structures, can emerge.
- The final, and very rare possibility, is that the ecosystem can collapse completely and no regeneration occurs.

This enumeration of possible ecosystem responses to environmental change is far richer than the simple classical notion, which holds that stress temporarily displaces an ecosystem from its climax community, to which it eventually returns. In fact, an ecosystem has no inherent single preferred state for which it should be managed.

While this identifies the ways in which an ecosystem might re-organize in the face of environmental change, it does not indicate which re-organization constitutes a loss of integrity. It could be argued (and often is) that any environmental change that permanently alters the normal operations of an ecosystem affects its integrity. Ecosystem integrity would then be defined as the ability to absorb environmental change without any permanent ecosystem change. Thus the final four distinct ecosystem responses described above would constitute a loss of integrity, even though all but the last option (collapse) are responses in which the ecosystem reorganizes itself to mitigate the environmental change. However, the reorganized ecosystem is usually just as healthy as the original, even though it may be different. There is no scientific reason that an existing ecosystem should be the only one to have integrity in a situation, just because of its primacy.

At the other extreme, it could also be argued that any ecosystem that can maintain itself without collapsing has integrity. Utter collapses have been rare, desertification being one of the few examples. This definition would encompass almost all ecosystems, including ones whose organization has changed radically in response to major stress.

Neither of these definitions of integrity is operationally useful. The definition which accepts only temporary change is too restrictive in most situations, and reflects a desire to preserve the world as it is currently.[26] This denies the fundamental dynamic nature of ecosystems and leads to disastrous mismanagement (e.g. the complete suppression of forest fires, which eventually results in catastrophic conflagrations). But the latter definition, which accepts all responses except collapse, does not help managers because it restricts loss of integrity to a situation that rarely occurs and that is clearly undesirable. Hence this definition would be trivial.

In between these two extremes of definition lies a third option, which holds that some changes in ecosystems are undesirable, and therefore represent a loss of integrity. This option promises to be the most useful but it embraces many possibilities and requires difficult choices. In particular it requires the value-laden selection of criteria for determining which changes are desirable and which are not. The science of ecology can, in principle, inform us about the kind of ecosystem response or reorganization to expect in a given situation. It does not provide us with a scientific basis for deciding that one change is better than another, except possibly in the two extreme cases just discussed.[27]

Here again the insight into ecological integrity gained from complex systems theory is that the physical and biological sciences can describe and, even to a limited extent, predict human-induced changes in the biosphere, but they alone cannot determine which changes are acceptable. Ultimately, any evaluation of the ecological acceptability of a human activity, will depend on value judgments about whether the resulting changes in the affected ecosystem are acceptable to the human participants.

It should be noted that it is exactly this conclusion that leads classical scientists to reject this whole mode of reasoning as unscientific, soft and useless except as a parlour game. The complaint most often spoken is that such a treatment of ecology is not defensible in court, because there are no black and white answers, no linear causes and effects, no definitive mechanisms and no one person to blame. In short this treatment does not lead to a scientific conclusion that this behaviour is good and that behaviour is bad.

Scientific judgments about right and wrong seemed possible when we viewed the world as a set of billiard balls, and it is this mechanistic, reductionist worldview that our court system assumes. Unfortunately, this worldview with its approach to governance and law does not recognize, and will not help us deal with, the realities of complex systems. And here we have the crux of the issue. If we are truly to use an ecosystem approach, and we must if we are to have sustainability, it means changing in a fundamental way how we govern ourselves, how we design and operate our decision-making processes and institutions, and how we approach the business of environmental science and management.[28] This is the real challenge presented by an ecosystem approach. ❑

James J. Kay is a professor in Environment and Resource Studies at the University of Waterloo. Eric Schneider was formerly chief scientist of the US National Oceanic and Atmospheric Administration.

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Notes

[1] L.B. Slobodkin, "Intellectual Problems of Applied Ecology," *Bioscience*, 38:5 (1988), pp. 337-342.

[2] The diversity-stability hypothesis arose from Robert MacArthur, "Fluctuations of Animal Populations and a Measure of Community Stability," *Ecology*, 3 (1955), pp. 533-535, in which he proposed that the diversity of a food web was a measure of community stability. G.E. Hutchinson, "Homage to Santa Rosalia Or Why Are There So Many Kinds of Animals?" *American Naturalist*, 93 (1959), pp. 415-427, mistook this paper as a proof that species diversity explains community stability. Ramon Margalef, "On Certain Unifying Principles in Ecology," *American Naturalist*, 97 (1963), pp. 357-374; and Ramon Margalef, *Perspectives on Ecological Theory* (Chicago: University of Chicago Press, 1968) elaborated a theory of ecosystem development which held that species diversity was the cornerstone of the emergence of a stable system. This hypothesis was "codified" as dogma by the Brookhaven Symposium of 1968 in *Diversity and Stability in Ecological Systems*, G.M. Woodwell, H.H. Smith, eds. (Brookhaven National Laboratories Symposium #22, 1969). It is a very pleasing and simple to understand hypothesis based on the notion that "you don't put all your eggs in one basket." In the early 70s a number of empirical counter-examples to this hypothesis were presented. Daniel Goodman, "The Theory of Diversity-Stability Relationships in Ecology," *Quarterly Review of Biology*, 50:3 (1975), pp. 237-366, systematically examined the literature and demonstrated clearly that there was no scientific basis for the diversity-stability hypothesis.

[3] For example, in southwestern Ontario the most diverse ecosystems can be found in the area between urban development and rural lands. For more discussion see P.S. Petraitis, R.E. Latham, and R.A. Niesenbaum, "The Main-

tenance of Species Diversity by Disturbance," *Quarterly Review of Biology,* 64:4 (1989), pp. 393-418.

[4] See P.J. Burton, *et al.,* "The Value of Managing for Biodiversity;" *The Forestry Chronicle,* 68:2 (1992), pp. 225-237, "... the diversity within a biological community confers some measure of stability to that community," p. 229.

[5] J.J. Kay, "A Non-Equilibrium Thermodynamic Framework for Discussing Ecosystem Integrity," *Environmental Management,* 15:4 (1991), pp. 483-495.

[6] C.S. Holling, "The Resilience of Terrestrial Ecosystems: Local Surprise and Global Change, *Sustainable Development in the Biosphere,* W.M. Clark and R.E. Munn, eds. (Cambridge: Cambridge University Press, 1986), pp. 292-320; C.S. Holling, "Cross-scale Morphology, Geometry and Dynamics of Ecosystems," *Ecological Monographs,* 62:4 (1992), pp. 447-502; and Kay, "Non-equilibrium" [note 5].

[7] F. Bormann, G. Likens, *Pattern and Process in a Forested Ecosystem* (New York: Springer-Verlag, 1979).

[8] R.P. McIntosh, "The Relationship between Succession and Recovery Process in Ecosystems," *The Recovery Process in Damaged Ecosystems,* J. Cairns, ed. (Ann Arbor Science, 1980), pp. 11-62.

[9] See for example T.F.H. Allen, T.W. Hoekstra, *Toward a Unified Ecology* (New York: Columbia University Press, 1992).

[10] This way of looking at the world spills over into our judicial system, where we strive to determine who is responsible, and who is guilty. This is based on the assumption that the observed behaviour can be explained by simple linear interactions between the components. Somebody is responsible for something happening.

[11] In the sense that Ludwig Boltzmann spoke of randomization rather than the modern Jaynesian interpretation of information, see E.T. Jaynes, "Where Do We Stand on Maximum Entropy," *The Maximum Entropy Formalism,* R. Levine and M. Tribus, eds. (Cambridge, Massachusetts: MIT Press, 1979), pp. 15-118.

[12] In classical analysis, small interactions between components (such as friction), interaction due to spherical imperfections (billiard balls which aren't perfectly round), etc. are ignored. It turns out that these interactions, after some time, actually determine the system's behaviour as much as anything. But these interactions are essentially noise and unpredictable.

[13] G. Nicolis, I. Prigogine, *Exploring Complexity* (New York: W.H. Freeman, 1989). Prigogine showed that such systems do not violate the second law that entropy must increase, even though they increase order or organization.

[14] E.D. Schneider and J.J. Kay, "Life as a Manifestation of the Second Law of Thermodynamics," *Advances in Mathematics and Computers in Medicine* (1994 in press).

[15] This is the second law of thermodynamics restated for non-equilibrium situations.

[16] More formally, from Schneider and Kay, "Life" [note 14], "the thermodynamic principle which governs the behaviour of self-organizing systems is that, as they are moved away from equilibrium, they will utilize all avenues available to counter applied gradients (high quality energy flows). As an applied gradient increases so does a system's ability to oppose further movement from equilibrium." This seems to be the natural principle behind the emergence of life.

[17] See Gerald M. Weinberg, *An Introduction to General Systems Thinking* (New York: John Wiley and Sons, 1975).

[18] A.W. King, "Considerations of Scale and Hierarchy," *Ecological Integrity and the Management of Ecosystems,* S. Woodley, J.J. Kay, G. Francis, eds. (Delray, Florida: St. Lucie Press, 1993), pp. 19-46. An ecosystem is a collection of interacting biological entities combined with the physical environment in which they live, which is perceived to act as a whole.

[19] Holling, "Resilience" [note 6].

[20] J.J. Kay, "Self-Organization in Living Systems" (PhD thesis, Systems Design Engineering, University of Waterloo, 1984), pp. 85-88.

[21] For example, jack pine cones require heat from a forest fire to open.

[22] N.M. Lister, "Biodiversity: Socio-Cultural and Scientific Perspectives With Reference to Decision Making in the Great Lakes Basin," (unpublished 1994).

[22] Ecosystem integrity is about the integrity of ecosystems versus ecological integrity which refers to the integrity of life at all ecological levels including ecosystems. In what follows the focus is on ecosystem integrity.

[23] Kay, "Non-equilibrium" [note 5]; and J.J. Kay, "On the Nature of Ecological Integrity: Some Closing Comments," *Ecological Integrity,* Woodley, Kay and Francis [note 18], pp.201-212.

[24] Kay, "Non-equilibrium" [note 5].

[25] Of course one may wish to preserve an ecosystem as an example or specimen of a specific type.

[26] To return to the musical composition analogy, the two extreme cases correspond to the playing of the same piece over and over with minor variations or to no music at all. The third option allows for different compositions, but not all compositions. As in music, the question of taste and need plays an important role in deciding which compositions are acceptable.

[28] For an early version of some practical and institutional aspects see H.A. Regier, *A Balanced Science of Renewable Resources* (Seattle: University of Washington Press, 1978).