
The Ecosystem Approach

Complexity, Uncertainty, and Managing for Sustainability

Edited by David Waltner-Toews, James J. Kay, and Nina-Marie E. Lister

COLUMBIA UNIVERSITY PRESS



NEW YORK

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Columbia University Press
Publishers Since 1893
New York Chichester, West Sussex

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Library of Congress Cataloging-in-Publication Data

The ecosystem approach : complexity, uncertainty, and managing for sustainability /
David Waltner-Toews, James J. Kay, and Nina-Marie Lister, editors
p. cm. — (Complexity in ecological systems series)
Includes bibliographical references and index.

ISBN 978-0-231-13250-3 (cloth : alk. paper) / ISBN 978-0-231-13251-0 (pbk. : alk. paper)
ISBN 978-0-231-50720-2 (ebook)

1. Ecological integrity 2. Ecosystem management I. Waltner-Toews, David,
1948– II. Kay, James J. III. Lister, Nina-Marie E. IV. Title V. Series.

QH541.15.E245E38 2008
333.72—dc22

2008014964



Columbia University Press books are printed on permanent and durable acid-free paper.
This book is printed on paper with recycled content.
Printed in the United States of America

c 10 9 8 7 6 5 4 3 2 1
p 10 9 8 7 6 5 4 3 2 1

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An Introduction to Systems Thinking

James J. Kay

The Nature of the Beast

Environmental issues and sustainability have thwarted our society's scientific approach to dealing with the world. One need only contemplate global climate change to experience the frustration and confusion. In this book, we are using the term complexity as a concept that covers problematic situations that have eluded traditional scientific solutions. Complex situations involve uncertainty and surprise. They give the impression that there is no right way of looking at them and no right answer to the problems they raise. The problem is really the singularity of our concept of the "right answer." Complexity defies linear logic as it brings with it self-organization and feedback loops, wherein the effect is its own cause. Circular relationships between cause and effect require nonlinear logic, explanations in terms of morphogenetic causal loops where form is determined by and determines its own plans. In essence, complexity is characterized by situations where several different coherent future scenarios are possible, each of which may be desirable, all of which have an inherent irreducible uncertainty as to the likelihood for their actually coming about.

The differences between the above scenarios require a number of different perspectives at different scales of investigation. Understanding complex situations thus invokes alternative perspectives, which can be perplexing. Yet there is no avoiding our environmental concerns, and so we must take up the challenge of complexity. While not a panacea, systems thinking seems to offer some insights and approaches for dealing with complexity. As such, it holds the promise of helping us chart the course to sustainability.

Systems thinking is about patterns of relationships and how these translate into emergent behaviors. This section explores the notion of systems and its application to ecosystem thinking. Systems thinking provides us with a window on the world that informs our understanding of nature and our relationship to it. It provides us with a way of framing our investigations and a language for discussing our

understanding. Translating systems thinking into action is what systems approaches are about. In this section the focus will be on systems thinking as it applies to biophysical systems.

Making Sense of Nonlinearity: Self-Organization

One of the puzzling observations about issues of sustainability is that everything seems to happen at once. Teasing apart causal links using conventional scientific techniques doesn't appear to help us answer the important questions. Systems thinking can help us by providing a language and conceptual tools for talking about the richness that comes with complexity.

Underlying systems thinking is the premise that systems behave as a whole and that such behavior cannot be explained solely in terms that simply aggregate the individual elements. This premise is, of course, the antithesis of prevalent reductionist thinking. Take, for example, evapotranspiration in a wetland. If one measures the evapotranspiration for the plants that make up the wetland when they are isolated in pots and add this to the evaporation for open pans of water (the classical experiment), one gets a higher value than the evapotranspiration of the plants and the open water when they are together in a wetland. One perspective on this is that when the plants transpire, they increase the humidity of the local atmosphere, thus decreasing the evaporation from the open water. Then again, does increased open water decrease plant evapotranspiration? The nonlinear causality in the loops typical of such systems makes distinguishing causal order impossible. Furthermore, this emergent property of wetlands cannot be deduced from more intensely studying their individual elements in isolation. Yet the dominant reductionist approaches are so entrenched that I have personally dealt with senior scholars who cannot accept that the evapotranspiration of a wetland is not simply the sum of the evapotranspiration of its component parts. There is a certain myopia in the dominant reductionist approaches, and it hinders our ability to deal with situations where emergence (i.e., the whole is more than the sum of the parts) is an important feature. Systems thinking is well suited to understanding such situations that require considerations of the whole as an emergent with its own properties.

An important emergent property of the whole is self-organization. We shall discuss this in more detail in a later chapter. However, it is important for us to introduce the notion here because self-organization is the phenomenon that gives us a sense that a system has an "identity" of its own. A simple example is a school of fish or a herd of wildebeest. The school as a whole seems to move of its own accord. Understanding or modeling this movement comes from understanding the relationship that is maintained between individual fish and wildebeest rather than from independent behavior of the individual itself. Self-organization is about how coherent patterns of relationships are internally structured and develop over time. How these relationships develop over time leads to a number of surprising and counterintuitive phenomena.

One of the manifestations of self-organization, which gives us a sense of a "whole" is the way in which systems deal with disturbance and, indeed, often incorporate disturbance as an important element of their dynamics. DeAngelis (1986) gives an example of this from southeastern Australia. The dominant trees are sclerophyllous eucalyptus, but the undergrowth consists of lush mesophytic vegetation. Normally, these circumstances would give rise to a temperate rain forest. However, these systems are subject to frequent fire, which would not occur if the mesophytic vegetation dominated. Fire increases soil leaching and sclerophylls are better adapted to poorer soils than mesophylls. Thus the dominance by sclerophyllous forest depends on fire and the occurrence of fire depends on the dominance by sclerophyllous forest. So fire has been incorporated as an integral element to the existence of the sclerophyllous dominant forest.

In a sense, the self-organization is a happenstance outcome of fire and the vegetation meeting. The components of the vegetation are significantly already evolved before the components of the new stable configuration ever came together. While the organisms in the forest are coded by DNA, the self-organization supersedes all that. There may be some microevolution that causes the components to line up in detail as they stabilize the emergent vegetation type. However, as with all self-organization, it comes down to flux and process; there is no plan or script for how the situation plays out.

This example also illustrates the importance of feedbacks and morphogenetic causal loops in understanding self-organization. In this case the feedback loop is that fires increase soil leaching, which increases the sclerophylls at the expense of the mesophylls, thus increasing the amount of forest fire. This would quickly get out of control, except that the mesophytic undergrowth limits the amount of fire, and so the whole system is in balance. It is such a balanced network of nonlinear causality that is referred to as a morphogenetic causal loop. The morphogenetic causal loop of sclerophyllous dominance, fire, and soil infertility obstructs the development of temperate rain forests and preserves the status quo.

The nonlinear causality of such systems gets us into trouble as environmental managers. An example is forest fire in temperate forests of North America. Forests are adapted to fire and are organized in such a way that normal fires cause only small areas of damage. The fire releases nutrients and makes openings for seedlings, promoting reproduction. Normal forest fires rejuvenate forests, keep the fuel level down, and prevent larger, more damaging fires and pest outbreaks. Suppressing forest fires prevents the rejuvenation process, allows fuel to accumulate and sets the stage for conflagrations, like the one that occurred in Yellowstone in 1988. Even in hindsight, researchers remain ambivalent about the Yellowstone fire, as there was in place a management regime that encouraged fire suppression. Later research indicated that there are huge fires every 400 years or so, of which the 1988 fire may be argued as an example. Suppressing forest fires usually makes forests less healthy! Indeed, anyone who depends on linear causal models as the basis for their management decisions will find the world a perplexing place.

Self-organizing systems have in their repertoire of behaviors a way of dealing with disturbance through their buffering capacity. In essence, one can substantially change the environmental context for such a system up to a point (a threshold or tipping point) with little apparent effect on the system. However, a slight change beyond the threshold and the system will suddenly change, that is, it reorganizes itself in a very dramatic and often unpredictable way. The effect of acid rain on lakes is an example of this phenomenon. The acidity of the precipitation running into lakes did not suddenly change; rather, it changed incrementally over decades. The pH of the lake water, however, did not change substantially, relatively speaking, over the same period (Stigliani 1988). The lakes maintained their organizational state (low pH) through a series of feedback loops that largely buffered the lake (in a chemical sense) from the environmental change. Eventually, the runoff from precipitation into the lake reached a level of acidity that exceeded the compensatory capacity of these loops. Once this happened, the effectiveness of the system decreased, which, in turn, decreased the capacity of the loops to compensate, which decreased the effectiveness of the system, and then quickly the organization unraveled and the system flipped to a different organizational state, in this case a "dead" acidified lake. The pH of the lakes dropped in a very short time period, less than one summer season. In some instances the change occurred in weeks.

Again, our linear thinking can get us in trouble when we make decisions regarding such systems. When Steve Carpenter began to work with human management of lacustrine systems, he was at first surprised by the flips of behavior he saw because there are not that many examples of them in basic science applied to lake systems. However, after a series of examples in managed systems, Carpenter is now surprised if he does not find such discrete jumps in the state of the system. Carpenter et al. (1999) report this as a common phenomenon. For quite a while our interaction with the system appears not to have any (deleterious) effect. As we increase what we are doing to the system, nothing appears to happen. Then suddenly, with little warning, a small change in our behavior causes the system to change dramatically, and too late we realize that we were impacting the system. The ability of systems to buffer themselves from external influences and to incorporate external disturbance as an integral part of their patterns of organization is part of what gives us our sense of them as a whole, a whole that is adapted to the situation that it is in.

The acid rain-lake interaction is also an example of important self-organizing phenomenon. Complex systems self-organize through feedback loops, and their openness predisposes them to dramatic reorganizations at critical points of instability (Nicolis and Prigogine 1977) (e.g., the dramatic "death" of an acidified lake, which is a flip to a plankton-dominated ecology). These instabilities and the resulting jumps or abrupt changes in the system are caused by self-amplified internal fluctuations mediated especially through positive feedback loops. These give rise to the spontaneous emergence of new structures and forms of behavior. Amplification is thus a source of new organization and complexity in the system. At the

points at which these new structures emerge, the system may branch off into one of a number of quite different organizational states, often referred to as attractors. The existence of multiple stable states, multiple possibilities necessarily implies indeterminacy, as which path is taken depends on the system's history and various external conditions that can never be completely predicted (Nicolis and Prigogine 1989), thus the unpredictable nature of complex systems.

It is one thing to recognize such complexity in multiple case studies, but how do we use this information to help us make decisions about sustainability? In the 1930s, von Bertalanffy (1968) noted that open self-organizing systems exhibited common attributes regardless of the disciplinary domain of study. He called this property of systems "isomorphism" (Blauberg et al. 1977: chap. 2). The existence of isomorphisms allows us to make generalizations about open self-organizing systems, that is, to build a general theory about their behavior and characteristics. This is one of the premises and the impetus behind the development of von Bertalanffy's general systems theory as well as more recent advances in systems thinking. By furnishing us with a typology and description of the patterns of relationships that can occur, both within the system and between the system and its environment, and the types of behaviors that can emerge, systems thinking provides us with a language, questions, and techniques for thinking through the self-organizing aspects of systems.

A Brief History of Systems Theory

The origin of the modern systems movement is generally attributed to von Bertalanffy's work in evolutionary biology. He began his work in the 1920s, and his first major presentation was a series of lectures at the University of Chicago (1937–1938). However, his work became more widely known in the late 1940s after his arrival in Canada. His commonly known publications date back to the 1960s. Von Bertalanffy's general systems theory was one of the first schools of thought that provided alternative models and modes of inquiry to the reductionist methods of disciplinary science. General systems thinking emphasizes connectedness, context, and feedback. Research questions identify and explain interactions, relationships, and patterns. The essential properties of the parts of a system can only be understood from the organization of the whole, as they arise from the configuration of ordered relationships that are specific to that particular system (von Bertalanffy 1968). Understanding comes from looking at how the parts operate together rather than from teasing them apart.

The next major contribution is generally attributed to Wiener (1948), who developed the field of cybernetics. While "systems thinking" originated in fields associated with natural systems, those researching mechanical and human systems quickly adopted them. Early adopters of the systems ideas included Margaret Mead (see von Foerster 1952), Gerard (physiology), Rapoport (mathematical biology; Rapoport and Horvath 1959), and Boulding (1956). Churchman (1968) and Beer (1959) linked systems concepts into operations research and organizational

cybernetics. In recent years, primarily through the work of Senge (1990) and Checkland (1981), systems concepts have been integrated into the management sciences.

Complex systems thinking is the grandchild of von Bertalanffy's general systems theory. It emerged in the wake of the new science of the 1970s: catastrophe theory, chaos theory, nonequilibrium thermodynamics and self-organization theory, Jaynesian information theory, complexity theory, etc. A number of authors have focused specifically on self-organizing systems (di Castri 1987; Jantsch 1980; Kay 1984; Nicolis and Prigogine 1977, 1989; Peacocke 1983; Wicken 1987).

Systems theory was first developed by von Bertalanffy in response to his sense that reductionist science was not sufficient to deal with biological systems. During the Second World War the development of systems theory was spurred on by the logistics (command and control) problems of assembly, delivery, and support of large numbers of men and machines to specific locations at specific times (e.g., amphibious assaults, bomber raids). The problems of tracking multiple moving targets also motivated much thinking about cybernetics and systems organization. During this time, aircraft also began to fly so fast that human response times became a major safety issue, thus motivating the development of ergonomics. The cold war had a similar impetus on systems thinking and approaches, the problem being the organization behind the operation and control of strategic bombers and intercontinental ballistic missiles (ICBMs). Similarly, the race to the moon of the 1960s motivated the development of systems. Much of the work on systems, over the years, was carried out in the Soviet Union, and this association led to ideological issues during the Reagan years, which saw the systems movement fall into disfavor in America.

However, with the publicity in America surrounding the Santa Fe Institute and its association with successful business management, systems thinking is once again being pursued. Currently, systems thinking is playing a major role in dealing with environmental issues, organization of global corporations, and computer networks. It is interesting to note that systems approaches have played a central role in some of the most technically and organizationally challenging activities of humans over the past half century. It is unfortunate that the impetus for the development of systems thinking and approaches has often been the problems posed by the most detestable of human activities—the waging of war. For more complete discussion of the development of systems thinking, I suggest Blaubeurg et al. (1977) and Flood and Jackson (1991).

Questioning Reality from a Systems Viewpoint

One well-known statement associated with systems thinking is that “everything is connected to everything else.” This is an overstatement as the connections between things can be quite weak. In the systems we study, most potential connections are set to zero. So what does the adage mean to say? It is not that everything is connected, though technically true, but rather that we should expect unsuspected and

surprising connections to be important with some regularity. Because there are so many potential ways that things may surprise us, there are several dialects of systems approaches that can be useful. Systems theories, particularly those associated with nonlinearity and complexity, are not suitable for all classes of problems.

Many problems or investigations can be completed successfully using the Newtonian worldview. Many of the discussions within the systems community focus on defining the contexts and problems best suited to the various approaches and worldviews. Weinberg (1975), following on the work of Weaver (1948), proposed the partitioning of problem situations based on their complexity and level of randomness.

Organized (not random), simple situations, with small numbers of interactions, are designated “small-number” problems. Two masses orbiting each other, the trajectory of propelled objects, and simple pendulums are examples. The behavior of these entities can be explained by Newtonian science and mechanistic explanation. This is because the interactions and relationships between objects in these situations are tightly constrained and can be written as simple solvable equations.

Highly unorganized complex situations, dominated by large numbers of random interactions and aggregate behavior, are designated “large-number” problems. Gas molecules in a room and large groups of people are examples. They can be adequately described by statistics and statistical mechanics. Averages mean something because there are large numbers of unconstrained (i.e., random) interactions between objects.

The remaining middle ground, with intermediate numbers of interactions and organized complexity with only a degree of unpredictability, are designated “middle-number” problems. Interactions between objects are loosely constrained and in sufficient number such that averages are not helpful and equations that can be written to describe the interactions are not uniquely solvable.

Human organizations, three masses orbiting each other, double pendulums, and ecosystems are all examples of situations where behavior cannot be explained by Newtonian mechanics or linear cause-and-effect explanations nor described in a useful way by statistical means. In middle number situations, prediction is not possible, but one can still get an answer to a slightly different question. Systems thinking is most applicable in situations where simple prediction fails. One must change the context to get an answer to the original question to one that is still useful. This idea of partitioning problem situations based on complexity, organization, and degree of constraint is key to understanding the domain of applicability of systems thinking. In middle number systems the constraints are ambiguous. As systems thinking changes the context by bounding the system in some new way, some reliable constraints come to the fore. There is a certain freedom in finding those helpful constraints, and it is the nature of the interactions between objects in a situation that determines which tools are appropriate.

The problem is that, because normal scientific concepts work for some classes of problems, we seem to think that they must be valid for all classes of problem.

We tend not to think through the connections that might lead us to a more systemic view. Environmental management projects, ranging from dams to agricultural development, have often resulted in unanticipated, usually negative, impacts. For example, large dams were seen as a panacea in development, but few thought through the ecological change they would cause. The Aswan dam on the Nile disrupted the annual flooding of the Nile, which provided the nutrients for the downstream agriculture. In order to maintain this agriculture, fertilizer has to be produced to replace the nutrients once provided by the flooding. The energy required to produce the fertilizer exceeds the energy produced by the dam, thus nullifying the energy-producing benefits of the dam. According to *The World Commission on Dams* (2000), many ecosystem impacts of large dams were unanticipated, even as late as the 1990s.

In deciding whether or not we are dealing with a simple, complicated, or complex problem, we need to ask what needs to be considered and what can be ignored. How far upstream and downstream from the dam must one think about the problem? And at what level of detail? These questions combine to ask what scale of analysis is appropriate? Need we be worried about individual farms or agriculture in general? This raises one of the fundamental conundrums of systems thinking and dealing with complexity. It is a given property of systems that everything is connected (at least weakly) to everything else. However, no scientist can look at everything at once. So any analyst must make decisions about what to include and what to leave out of the system to be studied. Scale, extent, and type of study must be selected, as discussed by Allen (chapter 3). Decisions on scale and type, while done in a systematic and consistent way, are necessarily subjective, reflecting the viewpoint of the analyst about which connections are important to the study at hand and which can be ignored. So, because of their very nature, the notion of an objective scientific observer is not applicable to the study of self-organizing systems, because the new level of emergence forces changes in the decisions as to how to bound the system.

Furthermore, this conundrum begs the question: Who gets to decide what is important and what is not? Whose values are used and why? These questions must be answered at the beginning of a system's investigation and are clearly political in nature. The inability, in principle, to have a unique objective systems description of a situation immediately moves systems thinking and systems approaches out of the domain of traditional scientific approaches and into the realm of post-normal science. Post-normal science applies when the stakes are high, the time is short, there is much intrinsic uncertainty, and values are in conflict. Post-normal science puts front and center the issue of who gets to decide, and it develops a stagecraft for finding better, not correct, answers to that question.

Systems thinking provides us with a heuristic tool and common language for framing situations and exploring self-organizing phenomena. It provides us with guidance about how to decide what is important to look at, and not look at, and how to describe a situation. It helps us to understand the self-organizing possibilities in a situation and thus to map out potential future scenarios. It provides a basis

for synthesizing our understanding of a situation into narratives about how the future might unfold and the trade-offs that exist between choosing different paths. It also helps us understand what it is we don't understand.

Conclusions

In summary, then, the complexity of problems offered by asking questions about sustainability offers a major challenge to systems thinkers. Addressing sustainability means finding a way to deal with this complexity. It has become clear that systems explanations of social-ecological complexity require different types of perspectives and at different scales of examination. There is no single correct perspective. Rather, a diversity of perspectives is required for understanding. Such systems are self-organizing; their dynamics are largely a function of positive and negative feedback loops. Linear causal mechanical explanations of dynamics are insufficient to understand them. Emergence and surprise are normal phenomena in systems dominated by feedback loops. Inherent uncertainty and limited predictability are inescapable consequences of these system phenomena. Such systems organize about attractors. Even when the environmental situation changes, the system's feedback loops tend to maintain their current state. However, when change does occur, it can be very rapid and even catastrophic. Precisely when the change will occur and to what state the system will change are often not predictable. Frequently, in a given situation, there are several possible states (attractors) that are equivalent. Which state the system currently occupies is a function of its history. There is not a "correct" preferred state for the system.

This enhanced understanding of systems, as complex systems, forms the backdrop for navigating a path to sustainability. Moving toward sustainability involves long enough timelines for the actors and the context of the ecosystem to change. These insights into buffering capacity of self-organizing phenomena address that long timeline. By contrast, the conventional science approaches of modeling and forecasting are often so inflexible as to be inappropriate, as are prevailing explanations in terms of linear causality and homeostatic properties that underpin ecosystem management of the traditional sort. The new understanding of complexity leads to an approach that is different from traditional ecosystem approaches. The conventional approaches may be interdisciplinary and participatory in nature, but they focus on analysis, forecasting, and a single type of entity such as a watershed or forest community. Complex systems approaches go beyond interdisciplinary to transdisciplinary, which invokes emergence between the disciplines over merely working between them. The new approaches remain participatory but go on to be adaptive and multiscale in their focus. In short, the new approach is in the mode of post-normal science (Funtowicz and Ravetz 1992, 1993). At its heart is the portrayal of ecological systems as self-organizing. They are also seen as requiring multiple levels of organization and indeed link the twinned hierarchies of social and biophysical systems in a given place. Accordingly, the new approach has coined a neologism, generally accepted practitioners in this new endeavor. They

are called self-organizing hierarchical open (SOHO) systems and will be discussed in some depth in chapter 4.

Having explored the rationale underlying systems thinking and its application to the problem of sustainability, it is time to turn our attention to some of the basic concepts, tools, techniques, principles, and considerations of systems thinking. Looking at a problem situation through the lens of systems thinking involves three phases. The first involves framing the situation by generating a systems description or map of what is involved and the important relationships that are used to define the system. In the second phase a description of the dynamics of the situation is developed. The third phase involves synthesizing the understanding gained from the first two phases into narratives about how the situation might or could unfold in the future. The discussion that follows in the next few chapters is not by any means a complete review of systems thinking. Rather, it is meant to establish some of the important aspects and point the reader to more detailed sources. Enough will be said to give the reader a basis for starting to apply systems thinking to the problem of sustainability.

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