Ecosystems, Science and Sustainability

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Abstract:

The dynamics of ecosystems and human systems need to be addressed in the context of Post-Normal Science grounded in complex systems thinking. We portray these systems as Self-Organizing Holarchic Open (SOHO) systems and interpret their behaviours and structures with reference to non-equilibrium thermodynamics; holons, propensities, and canons; and information and attractors. Given the phenomena exhibited by SOHO systems, conventional science approaches to modelling and forecasting are inappropriate, as are prevailing explanations in terms of linear causality and stochastic properties. Instead, narratives in the form of scenarios to depict morphogenetic causal loops, autocatalysis, and multiple possible pathways for development need to be considered. These narratives are used to examine the issues of human preferences and choices concerning the preferred attributes of particular SOHO systems. They provide a basis for adaptive management, monitoring and appropriate structures for governance. A heuristic framework to guide reasoning in this vein is presented, and reiterative steps for applying it are identified. This provides a coherent conceptual basis, in the workings of both natural systems and decision systems, for the practice of Post-Normal Science.

1. Introduction

A new understanding of complex systems, and in particular ecosystems, is emerging [Holling 1986; Kay and Schneider 1994; Kay 1984; Kay 1997; Schneider and Kay 1994]. The hierarchical nature of these systems requires that they be studied from different types of perspectives and at different scales of examination. There is no correct perspective. Rather understanding requires a diversity of perspectives. Ecosystems are self-organizing. Accordingly their dynamics are largely a function of positive and negative feedback loops. This precludes linear causal mechanical explanations of ecosystem dynamics. Furthermore, emergence and surprise are normal phenomena in systems dominated by feedback loops. Inherent uncertainty and limited predictability are inescapable consequences of these system phenomena. Self-organizing systems organize about attractors. Even when the environmental situation changes, the system's feedback loops tend to maintain its current state. However, when ecosystem change does occur, it tends to be very rapid and even catastrophic. When precisely the change will occur, and what state the system will change to, are often not predictable. Often, in a given situation, there are several possible ecological states (attractors), that are equivalent. Which state the ecosystem currently occupies is a function of its history. There is not a "correct" preferred state for the ecosystem.

This understanding of ecological systems as self-organizing complex systems, suggest that explanations of their behaviour, in terms of linear causality and stochastic properties will be non sequitur and that conventional science approaches of modelling and forecasting will likely be futile [Holling 1986; Kay and Schneider 1994; Kay 1984; Schneider and Kay 1994]. Elsewhere [Kay and others 1999] an approach for dealing with these realities of ecosystems has been discussed in the context of informing resource and land use decision makers and planners. This approach is different from "traditional" ecosystem approaches that are interdisciplinary in nature, but focus on forecasting and a single type of entity such as a watershed or forest community. Instead this approach is in the mode of post normal science and is grounded in complex systems theory. At its heart is the portrayal of ecological systems as Self-organizing Hierarchical Open systems (SOHO systems).

In this approach scientists take on the role of narrators. The task of the narrator is to scope out the array of attractors available to the SOHO system, the potential flips between them, and the underlying morphogenetic causal structure of the organization in the domain of the attractors. This is reported as a narrative of possible futures for the SOHO. The role of the scientists is then to inform the decision makers, through the narratives, about the ecological options, the tradeoffs and uncertainties involved, and various strategies for influencing what happens on a landscape.

At the core of these narrative descriptions of ecosystems as self-organizing holarchic open systems is the conceptualization of these systems as dissipative systems. Dissipative system descriptions are in terms of how the system makes use of available energy (and other resources) to self-organize. Such a description is inherently thermodynamic in nature and as such the second law of thermodynamics plays a central role. Other papers [Kay and Regier 1999; Kay 2000; Regier and Kay 1996] explore the role of the second law of thermodynamics in building narratives of ecosystem self-organization. These papers discuss the characterization of ecosystem attractors in terms of the their sources of exergy. This provides a theoretical basis for the formulation of narratives and in particular for the formulation of a conceptual model of ecosystems as self-organizing holarchic open systems.

The description of an ecosystem in terms of this SOHO conceptual model, and its associated narratives, provides the basis for an adaptive ecosystem approach to sustainability. The elements of a Self-organizing Holarchic Open Systems description of ecosystems and an adaptive ecosystem approach to sustainability are sketched out below.

2. Hierarchy

There is growing comprehension that sustainability issues cannot be discussed in isolation. They must always be examined within their broader context. Every system is a component of another system and is, itself, made up of systems. So, a wetland must be understood in the context of the subwatershed it is a part of, and in terms of the processes and species which make it up. The body of thinking which deals with these issues is called Hierarchy Theory [Ahl 1996; Allen and others 1993; Allen and Hoekstra 1992; Allen and Starr 1982]. Its central tenant is that sustainability issues can only be understood in terms of systems embedded in systems which are also embedded in systems or, in the vernacular of hierarchy theorists, as *nested holons*.

Hierarchy theory requires that a study of complex systems begin by careful consideration of the types of perspectives required and the appropriate scales of investigation. For example, the traditional ecological perspective, which dictates an approach based on studies of population dynamics of individual species, is not helpful in understanding fire dynamics in ecosystems. Rather, understanding of the fire phenomena comes from studies of communities and landscapes over local and regional scales.

The researcher must take care to identify the human sustainability issues at hand and the appropriate perspectives and scales of investigation necessary to deal with these issues in an ecological-economic context. This identification process can only occur in the context of human values and requires bringing a diversity of views to bear on the question at hand.

To do otherwise is to court disaster. For example, research on ecosystems and sustainable food production in some areas of the upper Amazon watershed have historically centered on cattle production and its effects. A community based, hierarchical system analysis of the situation revealed the main food source to be fish with cattle playing an incidental role [Murray and others 2001]. Thus, community health and development initiatives focusing on beef production were sorely misplaced. Another example comes from an early Canadian environmental impact assessment that examined the effects of development on reproduction of caribou herds. Later, it was noted that the most serious effect of development was on the food source of the caribou, but this was not studied as part of the impact assessment. The study focus was on the reproductive habitat of a single species, and ignored the (much more relevant) broader food chain.

Hierarchy theory challenges scientists to abandon their normal approach of searching for the single correct model for dealing with a problem. Instead, we must develop a manner of investigation that uses a diversity of different perspectives and models, which brings different players to the table, and which synthesises the different perspectives together into understanding.

3. Self-organization and attractors:

Ecosystems actually have multiple possible operating states or attractors, and may shift or diverge suddenly from any one of them [Holling 1986; Kay and Regier 1999; Kay 1991; Kay 2000; Ludwig and others 1997]. For example, a portion of a natural area in Southern Canada is a *closed soft maple swamp* in a wetland community. However, the amount and duration of the flows of water can radically alter this operating state. Drying events, such as an extended drought, could change the operating state to an *upland forest community* or *grassland* with their associated vegetation structures. If extended periods of flooding do occur, high water levels would shift the operating state to a *marsh ecosystem*. The shift happens because red and silver maple are tolerant to flooded conditions within 30% to 40% of the growing season. If flooding events are greater than this threshold, the forest trees die and give way to more water tolerant herbaceous marsh vegetation. The feedback mechanism which maintains the swamp state is evapotranspiration (i.e. water pumping) by the trees. Too much water overwhelms the pumping capability of the trees and not enough shuts it down. The point of this example is that the current ecosystem state is a function of its physical environment and the accidents of its history. A single dry or wet season can change, for decades, what has been on the landscape.

Each of the three ecosystem states in this example is as ecologically healthy and appropriate as the others. There is not a "right" community for this landscape. Each is equally right. Thus, scientists cannot tell decision makers or policy makers which of these three states is ecologically better. Scientists can only provide information about the different tradeoffs each state represents. A decision regarding which of these three states to promote is necessarily a value decision. In fact, since water flow is the key influence which determines the organizational state of this portion of the natural area, decisions, about which ecosystem state to promote, hinge on what kind of land use and development is allowed on the lands adjacent to the natural area - clearly a political decision.

A similar example comes from the management of the same natural area [Lister and Kay 2000]. Currently, the aquatic ecosystem consists of a fast-moving, highly oxygenated cold-water stream in which brook trout thrive. However, another state, which is normally incompatible with the survival of brook trout, is emerging: a slow-moving, low-oxygen, warm-water stream interrupted by ponds and small wetlands. In this case, beaver and muskrat are dominant species that shape and maintain the habitat and its constituent communities. The current ecosystem trajectory is tending towards this state due to several factors, including an invading population of beaver and purple loosestrife. The beaver dam the stream, thus providing more habitat for beaver and the purple loosestrife choke out the other species in the wetland. Both factors slow the water flow, increase water temperature and decrease dissolved oxygen. The emergence of this attractor was a surprise to the local managers of the natural area. However, mangers operating at the much larger scale of the drainage basin (of which this natural area is part) were not surprised as they have followed the beaver migration into the area for years.

The group responsible for the natural area would like to maintain both the trout stream and the beaver and their ponds. However, this may not be feasible since the two ecosystem states are usually mutually exclusive. A difficult choice may have to be made to favour one over the other. The irony is that ecosystem managers may have to trap beaver (Canada's national animal) and keep them out of the natural area in order to preserve a "pristine state" which will likely require intensive human management to maintain.

In making this choice, the values of various stakeholders and community members will play an essential role in the decision making process. The role of the scientists will be to inform decision makers about the ecological options, the tradeoffs and uncertainties involved, and various strategies for influencing what happens on this landscape. However, scientists cannot inform us about the "correct" way to proceed, nor can they predict with complete certainty what will happen in the situation. So, the role of science in decision making for sustainability changes from problem solver (in the sense of providing a solution for the situation) to the role of facilitating understanding about the bio-physical realities of the situation. In this manner, both experts and stakeholders contribute to the resolution of the situation.

4. Narratives

By their nature, ecosystem dynamics cannot be captured in a single model. This is because multiple descriptions are required to deal with complexity, and self-organizing phenomena cannot be explained in terms of a linear mechanistic casual description. Describing the complexity of ecological systems poses a considerable challenge to science. Consider the case of shallow lakes, such as Lake Erie in North America. Two different attractors for shallow lakes have been identified [Carpenter and Cottingham 1997; Kay and Regier 1999; Regier and Kay 1996; Scheffer 1998]. In the **benthic** state, the ecosystem is characterized by high water clarity and lake bottom vegetation. As nutrient loading increases turbidity of the water, the ecosystem crosses a catastrophe threshold and flips into a hypertrophic, turbid, phytoplankton ecosystem, i.e., a **pelagic** state. Lakes exist that regularly flip between the two attractors. At least three quite different descriptions of such a lake will be needed, one for the pelagic state, one for the benthic, and one for the intermediate stage as the system flips between attractors.

The nature of these descriptions is also quite different. The description is in terms of the feedback loops that tend to maintain the ecosystem in its current state [DeAngelis and others 1986; Ulanowicz 1997]. Of particular importance are those feedback loops which buffer the system from changes in external influences. In the case of shallow lakes, the benthic ecosystem has elaborate feedback schemes, operating at different spatial and temporal scales, to limit the phosphorous in the water column The pelagic state has elaborate schemes to accomplish just the opposite. Describing the "flip" from one attractor to the other involves accounting for how environmental influences (acting at different spatial and temporal scales) disable one feedback system while enabling another [Kay and Regier 1999]. Such a description takes the form of a multilayer narrative which recounts the ecosystem's operation from different perspectives and scales [Kay and Regier 1999; Kay and others 1999]. While individual elements may consist of traditional scientific models and descriptions, synthesising these elements together into a narrative transcends normal scientific descriptions, to invoke a more complete picture of the system.

5. The role of scientists

In post normal science, the scientist's role in decision making shifts from inferring what will happen, that is making predictions which are the basis of decisions, to providing decision makers and the community with an appreciation, through narrative descriptions, of how the future might unfold. As noted earlier, these narratives consist of several scenarios of how the ecological systems in question might evolve. These narratives focus on a qualitative/quantitative understanding that describes:

- the human context for the narrative
- the hierarchical nature of the system;
- the attractors which may be accessible to the system;
- how the system behaves in the neighbourhood of each attractor, potentially in terms of a quantitative simulation model;
- the positive and negative feedbacks and autocatalytic loops and associated gradients which organize the system about an attractor;
- what might enable and disable these loops and hence might promote or discourage the system from being in the neighbourhood of an attractor; and
- what might be likely to precipitate flips between attractors.

These narratives are in the service of informing decision makers and the community about:

- possible future states of organization of the system;
- understanding of conditions under which these states might occur;
- understanding of the tradeoffs which the different states represent;
- appropriate schemes for ensuring the ability to adapt to different situations;
- and perhaps most importantly the appropriate level of confidence that the narrative deserves, this is our degree of uncertainty.

Having painted a picture of the possibilities in the future, it remains for scientists to suggest ways of mitigating and adapting to the inevitable surprises, both surprises in the form of unexpected flips to known attractors and those that involve flips to new attractors which correspond to heretofore unknown manifestations of system organization. Only through learning to do this will science be able to contribute to humanities quest of learning how to live sustainably.

6. An Adaptive Ecosystem Approach

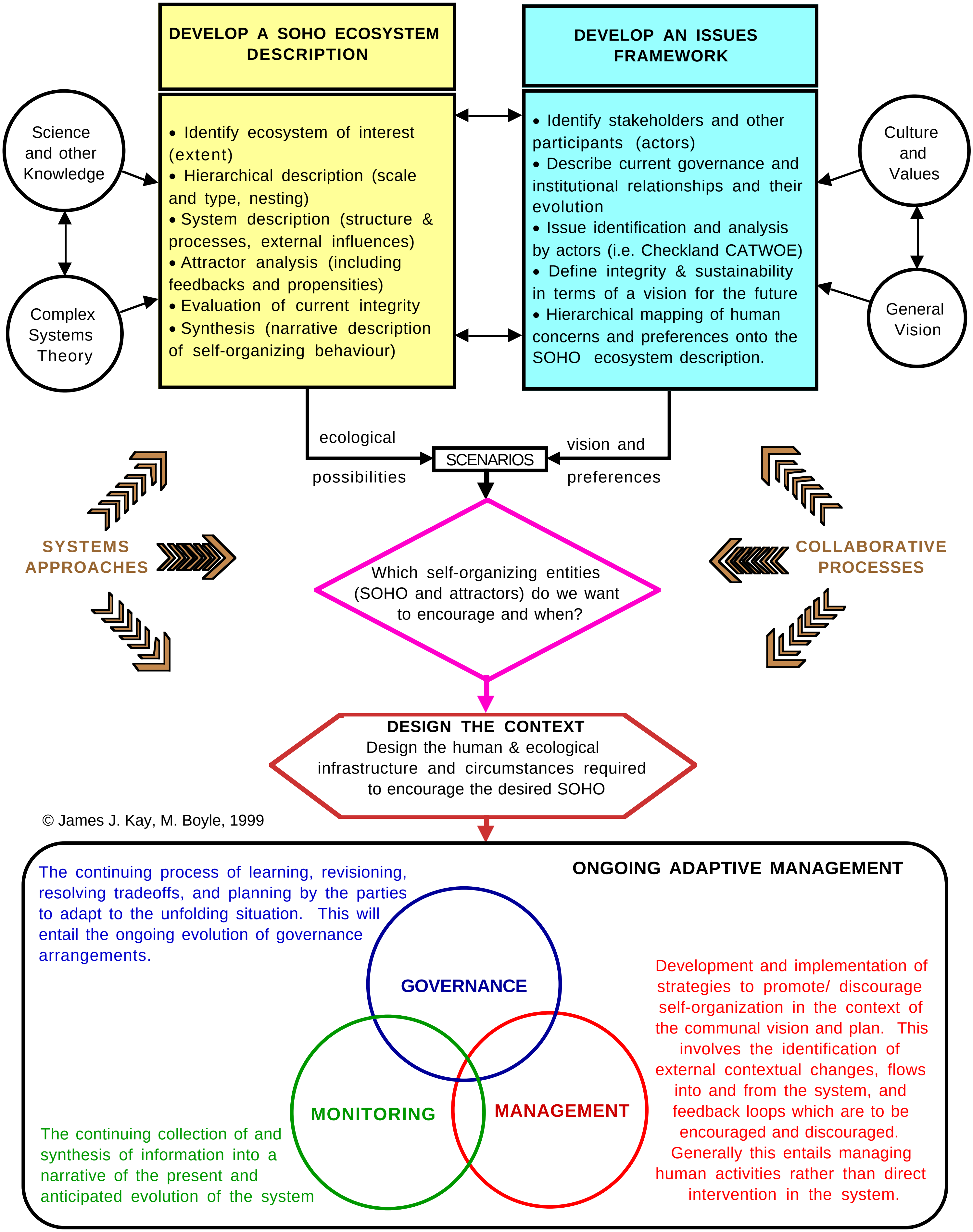
The complexity of situations surrounding the resolution of sustainability issues, necessitates a self-organizing hierarchical open (SOHO) system approach. SOHO systems have the ability to decouple their behaviour from environmental change, to generate novel behaviour, and to self-organize in response to change (in a way that we cannot determine). These properties limit our capacity to predict how such situations will unfold. In principle, in many situations it will not be possible, or even appropriate, to make accurate quantitative models which forecast the future.

The premise of the traditional approach to management (anticipatory management) is that it is possible to predict and anticipate the consequences of decisions. Once all the necessary information is gathered to make a scientific forecast, the “right” decision can be made. Unfortunately, the premise of this approach is not valid for complex systems. Given the limitations imposed by complexity, the focus of management and decision-making strategies must be on maintaining the capacity to adapt to changing environmental conditions. Adaptive management involves a very different agenda than anticipatory management [Gunderson and others 1995; Holling 1978].

At the core of an adaptive ecosystem approach to sustainability and integrity is the premise that a sustainable society maintains itself in the context of the larger ecological system of which it is part. The formulation of a sustainable society involves realizing a vision of how the landscape of human and natural ecosystems should co-evolve as a self-organizing entity. Decision making comes to be understood for what it has always been, finding our way through partially undiscovered country rather than charting a scientifically determined course to a known end point. Decisions must be made about which of the ecological possibilities (i.e. attractors) to promote and which to discourage Tradeoffs must be made. Decisions must also be made about how to deal with the inherent uncertainties, what risks to take, what contingencies to plan for, what backups to have in place. These decisions must be informed by science, but in the end they are an expression of human ethics and the socio-political context that they are made in. Thus choosing a path forward requires the input of a variety of actors and stakeholders whose desires, perceptions, and knowledge must be integrated with scientific understanding.

A framework for this integration is presented in Figure 1 and it is this that we refer to as the adaptive ecosystem approach [Boyle 1998; Boyle and others 2000; Kay and others 1999; Lister and Kay 2000]. In this post-normal approach to sustainability, those acting as scientists provide decisions makers and the community with an appreciation, through narrative descriptions (scenarios), of how the future might unfold. (See the top left hand box in Figure 1.) This delineates the ecological possibilities and constraints, the ecological realities of the situation. Essential to the narrative is the hierarchical description of the system. Its relevance depends on choosing the appropriate perspectives and scales for observation, the appropriate processes and structures for study. The appropriateness of these choices depends on the issues which are of human concern.

The business of establishing an issues framework is the undertaking represented by the right hand box. It involves establishing who the actors and stakeholders are, what their values and concerns are, what their vision for the future is. It also means understanding the socio-economic system, the power structures, the institutional arrangements which exist and their history. Various participatory techniques are useful in this regard. See, for example: [Borrini-Feyerabend



DEVELOP A SOHO ECOSYSTEM DESCRIPTION
• Identify ecosystem of interest (extent)
• Hierarchical description (scale and type, nesting)
• System description (structure & processes, external influences)
• Attractor analysis (including feedbacks and propensities)
• Evaluation of current integrity
• Synthesis (narrative description of self-organizing behaviour)
DEVELOP AN ISSUES FRAMEWORK
• Identify stakeholders and other participants (actors)
• Describe current governance and institutional relationships and their evolution
• Issue identification and analysis by actors (i.e. Checkland CATWOE)
• Define integrity & sustainability in terms of a vision for the future
• Hierarchical mapping of human concerns and preferences onto the SOHO ecosystem description.
Science and other Knowledge
Complex Systems Theory
Culture and Values
General Vision
ecological possibilities
SCENARIOS
vision and preferences
SYSTEMS APPROACHES
COLLABORATIVE PROCESSES
Which self-organizing entities (SOHO and attractors) do we want to encourage and when?
DESIGN THE CONTEXT
Design the human & ecological infrastructure and circumstances required to encourage the desired SOHO
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ONGOING ADAPTIVE MANAGEMENT
The continuing process of learning, revisioning, resolving tradeoffs, and planning by the parties to adapt to the unfolding situation. This will entail the ongoing evolution of governance arrangements.
GOVERNANCE
MONITORING
MANAGEMENT
Development and implementation of strategies to promote/ discourage self-organization in the context of the communal vision and plan. This involves the identification of external contextual changes, flows into and from the system, and feedback loops which are to be encouraged and discouraged. Generally this entails managing human activities rather than direct intervention in the system.
The continuing collection of and synthesis of information into a narrative of the present and anticipated evolution of the system

1999; Burgoyne 1994; Ramírez 1999]for methods in stakeholder analysis and collaboration. Related discussions on public participation in environmental planning may be found in: [Beckenstein and others 1996; Oxley 1998; Warriner 1997]. We have found that a variant of the Soft Systems Methodology (SSM) [Allen and others 1993; Bunch 2000; Checkland 1981; Checkland and Scholes 1990; Wilson and Morren 1990]; is a useful way to proceed to develop an issues framework that recognizes and incorporates the perspectives of all stakeholders.

Of course everyone's perceptions, concerns, and visions will be altered during the exercise of developing the narrative descriptions and issue frameworks. So the undertakings of developing an issues framework and a SOHO narrative depend on each other and thus are recursive in nature.

When this phase has been accomplished, an image of how participants would like to see the landscape of human and natural ecosystems co-evolve and the ecological realities will have been constructed. A dialogue must ensue (the diamond box in Figure 1) which explores the desired and the feasible options and reconciles these in a vision of how to proceed. Science inform this dialogue by providing future narratives that will evolve as those acting as scientists partake, as equals, with other participants in the process of resolving the vision. This vision will be in terms of those attractors which are to be promoted and those which are to be discouraged. Having resolved a community vision for how the human and natural ecosystems should co-evolve as a self-organizing entity, the next phase is to design an adaptive programme for the realization of the vision.

This adaptive programme consists of a plan and infrastructure for the triad of activities, governance, management and monitoring. *Governance* refers to the continuing process of learning, revisioning, resolving tradeoffs, and planning to adapt to the unfolding situation. The ongoing evolution of governance arrangements and structures is required to accommodate these activities. All around the Great Lakes, for example, this is happening with the emergence of virtual governance, community based initiatives which organize to focus on specific elements of the landscape such as watersheds or bays. *Management* is the activity of translating the vision into reality. It involves the development and implementation of strategies to promote or discourage specific forms of self-organization in the context of the communal vision and plan. This means maintaining the context for the self-organizing complex (SOHO) systems, rather than intervening in the system in a mechanical way [Allen and others 1993; Kay and Schneider 1994]. Maintaining the context involves identification of external contextual changes, flows into and from the system, and feedback loops to be encouraged and discouraged. Generally, management concentrates on the relationship between humans and natural ecosystems, and guides the human side of the relationship. *Monitoring* is the activity of observing the human and natural systems and synthesising the observations together into a narrative of how the situation has actually unfolded and how it might unfold in the future. This narrative is used as the basis for governance and management; that is, for learning, revisioning, and adapting human activities so that the human and natural ecosystems co-evolve as a self-organizing entity.

In this adaptive ecosystem approach, monitoring, governance, and management make up a triad of activities that are carried out in the context of an issues framework of human concerns and an explicit conceptual model of the ecological-economic system. Taken together, the issues framework and the conceptual model provide the focus for the discussion of sustainability. By furnishing a means for informed resolution of the tradeoffs necessary to sustain the health and integrity of the ecological economic system, the activities of monitoring, governance, and management, carried out in concert, chart the course to sustainability.

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