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AN ECOSYSTEM APPROACH FOR SUSTAINABILITY: ADDRESSING THE CHALLENGE OF COMPLEXITY.

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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. Short examples are given. We also link SOHO system descriptions to issues of human preferences and choices concerning the preferred attributes of particular SOHO systems, and to the implications for achieving them through adaptive management, monitoring and appropriate structures for governance. A heuristic framework to guide reasoning for this is presented, and reiterative steps for applying it are identified. In this way we provide a coherent conceptual basis, in the workings of both natural systems and decision systems, for the practice of Post-Normal Science.*

1. Introduction

Much discussion about ecosystem management, or taking an ecosystem approach emphasizes the need to work across all manner of human boundaries at different geographic scales. However the growing understanding of the dynamics of ecosystems entails much more [1]. In this paper we suggest an approach to understanding these systems in the context of “Post-Normal Science” grounded in complex systems thinking. At its heart is the portrayal of ecological and human systems as Self-Organizing Holarchic Open (SOHO) systems whose dynamics are predominated by both positive and negative feedback processes operating over a range of spatial and temporal scales. These systems exhibit loose hierarchical structures, various emergent phenomena, and relatively sudden reconfigurations from one state of system organization to another. Some changes in these systems are inherently unpredictable.

The understanding of SOHO systems requires a major change in some of the ways in which science and decision making are conducted. Traditional reductionistic disciplinary science and expert predictions, the basis for much of the advice given to decision makers, have limited applicability. Narratives about possible futures for given SOHO systems are better able to capture the richness of possibilities. Other epistemological “mindsets” or causal metatypes [2] must be brought to bear, notably explanations based on morphogenetic causal loops that involve both positive and negative feedback processes and autocatalysis. Expectations that decision makers can carefully control or manage changes in societal or ecological systems have also to be challenged. Adaptive learning and adjustment, guided by a much wider range of human experience and understanding than disciplinary science, are also necessary.

This paper sketches a theoretical approach for understanding the dynamics of SOHO systems. It also situates this approach within an extensive heuristic framework for relating human choices and preferences concerning the attributes of SOHO systems to the implications for achieving them through adaptive management, monitoring, and governance. The main focus of this paper is on the features of SOHO systems that require different modes of human responses, and also constitute the initial steps for using the heuristic framework.

2. Self-Organizing Holarchic Open (SOHO) Systems

Complex systems thinking follows in the tradition of von Bertalanffy's general systems theory, and draws upon other concepts from the “new science” emerging over the past three decades, for example, catastrophe theory, chaos and complexity theory, non-equilibrium thermodynamics and self-organization, and Jaynesian information theory. The phenomenon of special interest is self-organization.[3]

The Emergence of SOHO systems

Spontaneous coherent behaviour and organization occurs in open systems (such as ecosystems and human systems). The key to understanding such phenomena is to realize that open systems are processing an enduring flow of high quality energy (exergy). In these circumstances, coherent behaviour appears in systems for varying periods of time but can change suddenly whenever the system reaches a catastrophe threshold, [4] and “flips” into a new coherent behavioural state. [5] (A simple example is the vortex which spontaneously appears in water from draining a bathtub, or more dramatically, the appearance of tornadoes “from nowhere”).

Kay and Schneider [6] examined the energetics of open systems and have taken Prigogine's work one step further. An open system with exergy (high quality energy) pumped into it is moved away from equilibrium, but nature resists movement away from equilibrium. This is the second law of thermodynamics restated for non-equilibrium situations. When the input of high quality energy and material pushes the system beyond a critical distance from equilibrium, the open system responds with the spontaneous emergence of new, reconfigured organized behaviour that uses the high quality energy to build, organize and maintain its new structure. This reduces the ability of the high quality energy to move the system further away from equilibrium. As more high quality energy is pumped into a system, more organization emerges, in a step-wise way, to dissipate the exergy. Furthermore, these systems tend to get better and better at "grabbing" resources and utilizing them to build more structure, thus enhancing their dissipating capability. There is however, in principle, an upper limit to this organizational response. Beyond a critical distance from equilibrium, the organizational capacity of the system is overwhelmed and the system's behaviour leaves the domain of self-organization and becomes chaotic. As noted by Ulanowicz [7] there is a "window of vitality", that is a minimum and maximum level in between which self-organization can occur.

The theory of non-equilibrium thermodynamics suggests that the self-organization process in SOHO systems proceeds in a way that captures increasing resources (exergy and material); makes ever more effective use of the resources; builds more structure; and enhances survivability. [8] These seem to be the kernel of the propensities of self-organization. This conception of self-organization, as a dissipative system, is presented in Figure 1.

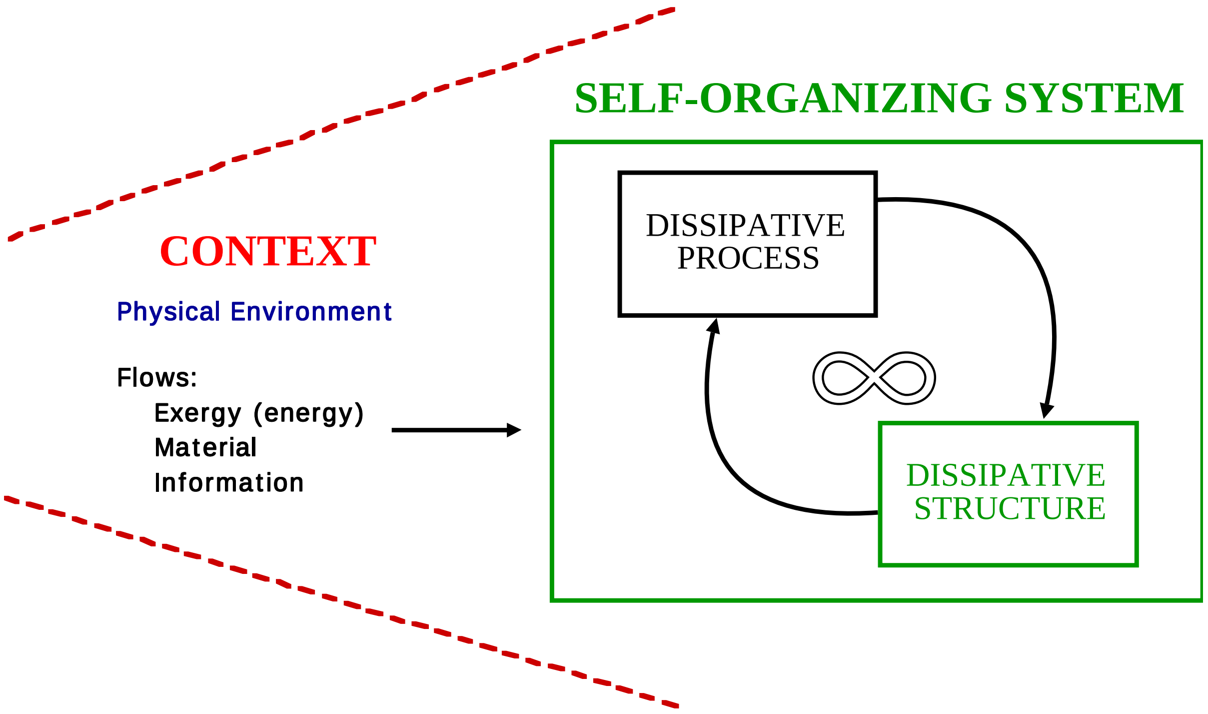
How these propensities manifest themselves as morphogenetic causal loops and dissipative processes is a function of the given environment (context) in which the system is imbedded, as well as the available materials, exergy and “information”, the latter defined as factors embedded internally within the system that constrain and guide the self-organization. The interplay of these factors defines the context and associated constraints on the set of processes which may emerge. Generally speaking, which specific processes emerge from the potential set are uncertain.

Self-organizing dissipative processes emerge whenever sufficient exergy is available to support them. Once a dissipative process emerges and becomes established it manifests itself as a structure.[9] These structures provide a new context, nested within which new processes can emerge, which in turn beget new structures, nested within which... Thus emerges a SOHO system, a nested constellation of self-organizing dissipative process/structures organized about a particular set of sources of exergy, materials, and information, embedded in a physical environment, that give rise to coherent self-perpetuating behaviours. [10]

Holons, Propensities and Canons

Koestler [11] perceived the unit/element features of systems, and posed the term “holon” (a term derived etymologically from whole/part) as an entity that exists contextually in a nested network of holons referred to as a “holarchy”. A holarchy is a generalized version of a traditional hierarchy (not to be confused with Allen's notion of hierarchy [12]) with reciprocal power relationships between levels rather than a preponderance of power exerted from the top downwards. A holon of particular interest for an observer occurs in some holarchic relationships with mutual causality guiding reciprocal interactions between a holon and proximate contiguous holons of different scales — inside, outside and lateral to the holon of interest.

Figure 1: *A conceptual model for self-organizing systems as dissipative structures.* Self-organizing dissipative processes emerge whenever sufficient exergy is available to support them. Dissipative processes restructure the available raw materials in order to dissipate the exergy. Through catalyse, the information present enables and promotes some processes to the disadvantage of others . The physical environment will favour certain processes. The interplay of these factors defines the context for (i.e. constrains) the set of processes which may emerge. Once a dissipative process emerges and becomes established it manifests itself as a structure. These structures provide a new context, nested within which new processes can emerge, which in turn beget new structures, nested within which... Thus emerges a SOHO system, a nested constellation of self-organizing dissipative process/structures organized about a particular set of sources of exergy, materials, and information, embedded in a physical environment. The canon of the SOHO system is the complex nested interplay and relationships of the processes and structures, and their propensities, that give rise to coherent self-perpetuating behaviours, that define the attractor



Ulanowicz [13] developed further some proposals by K. R. Popper [14] to extend a perception of indeterminacy in the quantum realm to other scales of phenomena by generalizing the usual Newtonian concept of force to obtain a notion of systemic dynamical cohesion which Popper called a “propensity”. A propensity is always contextual (as are Koestler’s holons) rather than universalistic as in the Newtonian sense of “force”. Ulanowicz proposed that a mutual-causal kind of autocatalysis plays a self-organizing role in Popper’s propensity, perhaps in generating dynamical cohesion through forces that act asymmetrically, and not symmetrically as in the Newtonian sense. Ulanowicz also implied that “dynamical cohesion” tends to be attenuated in a step-wise manner at the interfaces of interacting holons, both with respect to nested and non-nested kinds of relationships and that these attenuations may be perceived as boundary-like.

For our purposes, a central question to be addressed by the narrative description of a SOHO system is an elaboration of its propensities. The elaboration delineates the mutual causality of the feedback loops and autocatalytic process which give the system its coherence as an entity. We refer to this set of propensities, which characterize a holon, as its "canon".

Attractors

A SOHO system exhibits a set of behaviours which are coherent and organized, within limits. The nexus of this organization at any given time is referred to as an attractor. The term "attractor" comes from the state space description of the behaviour. The system has a propensity to remain in a limited domain of state space (for example a gravity well). It behaves as if it were "attracted" toward this domain and hence the term "attractor". As SOHO systems evolve they shift between attractors within the SOHO system's overall state space. The re-organization that these shifts entail is not smooth and continuous but rather is step-wise. The system “flips” its organizational state in often dramatic ways.

Ecosystems have multiple possible operating states or attractors, and may shift or diverge suddenly from any one of them. The notion of alternate stable states in ecosystems is not well known in the ecological, and particularly the resource management communities, but it is also not new [15]. Yet the importance of this notion for explaining ecosystem phenomena remains largely unexplored.

Human systems exhibit similar phenomena of self-organization, such as economic markets, communication networks, and urban expansion or rural contraction. Self-organization does not deny human agency, but suggests only that the collective striving of many individuals and organizations can lead to larger scale structures which are both unplanned and unexpected. The striving itself may be directed towards realizing aspirations (an “attractor”?) and reducing the gradients between perceived conditions and desired goals. Human systems also exhibit the dynamics of SOHO systems.[16]

3. Science and Decision Making in the Context of Complexity

Some facets of complexity have been highlighted in this discussion. The first is that self-organization inherently involves internal causality. A self-organizing system has the ability to maintain itself at an attractor despite changes in its environment. It is possible for a system’s environment to change substantially, without the system exhibiting major change. Self-organizing systems can respond in a synergistic way to multiple environmental factors such that changes in the system cannot be tied categorically to specific environmental factors. Furthermore, such systems have the capability to generate new behaviour which may emerge independently of changes in the environment.

Table 1: Properties of *complex systems* to bear in mind when thinking about SOHO systems.

- **NON-LINEAR:** Behave as a whole, *a system*. Cannot be understood by simply decomposing into pieces which are added or multiplied together.

- **HIERARCHICAL:** Are *holarchically nested.* The system is nested within a system and is made up of systems. The "control" exercised by a holon of a specific level always involves a balance of internal or self-control and external, shared, reciprocating controls involving other holons in a mutual causal way that transcends the old selfish-altruistic polarizing designations. Such nestings cannot be understood by focusing on one hierarchical level (holon) alone. Understanding comes from multiple perspectives of different *type* and *scale*.

- **INTERNAL CAUSALITY:** non-Newtonian, not a mechanism, but rather is *self-organizing*. Characterized by: goals, positive and negative feedback, autocatalysis, emergent properties and surprise.

- **WINDOW OF VITALITY:** Must have enough complexity but not too much. There is a range within which self-organization can occur. Complex systems strive for *optimum*, not minimum or maximum.

- **DYNAMICALLY STABLE?:** There may not exist equilibrium points for the system.

- **MULTIPLE STEADY STATES:** There is **not** necessarily a unique preferred system state in a given situation. *Multiple attractors* can be possible in a given situation and the current system state may be as much a function of historical accidents as anything else.

- **CATASTROPHIC BEHAVIOUR:** The norm

  Bifurcations: moments of unpredictable behaviour

  Flips: sudden discontinuities, rapid change

  Holling four box cycle Shifting steady state mosaic

- **CHAOTIC BEHAVIOUR:** our ability to forecast and predict is always limited, for example to between five and ten days for weather forecasts, regardless of how sophisticated our computers are and how much information we have.

This capacity to organize and maintain itself about an attractor is the hallmark of a self-organizing system. Such behaviour requires causal explanation in terms of synergistic positive and negative feedback loops. The explanation must also take into account different scales and types of interactions. An adequate description of self-organizing behaviour must be in terms of holarchical, multi-observer/disciplinary perspectives and morphogenetic mutual causality. Linear cause and effect explanations, in principle, cannot provide the kind of causal explanation required to describe self-organizing behaviour. In addition to the complexity associated with the issue of causality and self-organization, there is the possibility of more than one appropriate self-organizing response (i.e. multiple attractors). There is not necessarily a unique preferred state to be deduced from scientific arguments. Furthermore, system responses are a function of their particular histories or circumstances of the moment. Thus there is an element of irreducible uncertainty about self-organizing behaviour, uncertainty about what may come to pass as well as uncertainty about what ought to come to pass.

Table 1 summarizes the properties of SOHO systems and notes features which have to be addressed for understanding them. The nature of SOHO systems requires that they be studied from different types of perspectives, each emphasizing certain processes and structures such as the geophysical (abiotic), ecological (biotic) and human cultural components, and at different scales. There is no unique correct perspective. Rather, a diversity of perspectives is required for understanding, and the relative emphasis placed on some perspectives over others depends on the purpose of the inquiry.

In situations dominated by self-organizing behaviour, the properties of inherent uncertainty and emergence limit the capacity to predict how the situation will unfold. In principle, it will not be possible in many situations to construct accurate quantitative models which forecast the future to the degree required for anticipatory management. Anticipatory management is based on the premise that it is possible to predict and anticipate the consequences of decisions and hence to make a proper decision once all the necessary information is gathered to make a scientific forecast. But anticipatory management is a central doctrine of the "normal" orthodox science for decision making and is, in principle, not sufficient to deal with the complexity associated with the dynamics of SOHO systems.

Other epistemological traditions are required for understanding SOHO systems. For example, Maruyama [17] identified four causal metatypes that, as related to scientific substance and process are:

H: explanation in terms of cause and effect models, where the cause and effect relationship can be deterministic or probabilistic and is often linear in nature. No reciprocal relationship between effect and cause is considered and hence there are no causal loops in this mode of explanation. For example- sequential cause and effect analysis in the old engineering science mode used safety factors in the design of works to cover features of reality that do not conform to this mindscape. Similarly, it was assumed that incremental decreases in anthropogenic impacts on environments will result in incremental improvements in environmental quality.

I: explanation in terms of independent event models in which the most probable states of an isolated system are random distributions of independent events, and non-random features tend to decay. From this perspective any systemic linkages within an ecosystem are only opportunistic and temporary, hence any synergism among the effects of different human uses is unlikely and the term “ecosystem” has little meaning;

S: explanation in terms of homeostatic causal loop models, that is, negative feedback that maintains steady-state. The cause is controlled by the effect. Causality may be probabilistic or deterministic. Homeostatic causal loops can maintain organized heterogeneity in a system. This form of explanation underlies the old "Clementsian" view of ecological systems in which succession to a climax community led early preservation naturalists to hope that an ecosystem could remain in perpetuity in a particular preferred state; and

G: explanation in terms of morphogenetic causal models, that is explanations that involve both positive and negative feedback loops and autocatalysis. These probabilistic or deterministic loops of mutual causality can increase the pattern of heterogeneity towards higher levels of organized complexity. For example, consider the task of ecosystem regeneration from an unacceptably altered ecological system (say a eutrophic state in a lake) into a more desirable (for example an oligotrophic state in a lake) but not fully predictable state with strong self-organizing and self-sustaining capabilities, with constrained autocatalysis. This would be accomplished by changing a number of contextual elements (for example phosphorous loading) beyond critical thresholds so as to precipitate a flip in ecosystem state.

The understanding of SOHO systems draws upon all four mindscapes, especially G.

4. Preparing the Narratives

In the post-normal paradigm, a scientist's role in decision making shifts from inferring what will happen, that is, making predictions which are the basis of decisions, to providing decisions 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 SOHO 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, that is our degree of uncertainty.

Having sketched 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. Table 2 summarizes the analysis of ecosystems as SOHO systems.

Table 2: Analysis of ecosystems as Self-organizing Holarchic Open Systems : The term ecosystem here is used in its broadest sense and refers to natural as well as human constructs, such as economic systems. Note that while the activities of ecosystem analysis are written out below in a linear way, the analysis itself is not linear. Thus the activities will be accomplished in different sequences depending on the case at hand.

<u>A. Define the ecosystem</u>

Type:
  What perspectives will be used to look at the system? (abiotic, biotic, human cultural...)

Scale and Extent (the horizontal perspective, where do things begin and end?)
  What are the boundaries of observation?
  What are the processes which define the whole?
  What are the boundaries of the ecosystem, the holon of focus?

Holarchy: (The vertical perspective, what is a part of what?)
  Define the Nested Holons (nested systems); this defines the contextual relationships.

Holarchic Structure
  Delineate the vertical and horizontal relationships between holons

<u>B. Describe the ecosystem as a self-organizing entity</u>
The attractors (organizational states) and their domains:
  What are the attractors?
    In what direction will the ecosystem tend to develop? What are its propensities? (Self-organization theory of dissipative structures helps answer this.)
  What is the behaviour of the ecosystem about the attractors?
    (Homeostatic, Stable, Figure ∞, Unstable but persists, chaotic?)
  Are there bifurcation points?
  What are the potential flips between attractors?
    What triggers the flips?
    How can we monitor for them?
The context:

What is the interplay of energy, exergy, available materials, information and environmental conditions (in space and time) which shapes the ecosystem?

Morphogenetic casual models

The synergistic relationships, the cycles, the feedback loops, virtual worlds.

The canon:

Think carefully about the dissipative processes and structures, their interplay (e.g. Figure ∞), their scale and extent, the nested holons and their interactions and connections, the information available to the ecosystem, and the environmental conditions it is set in.

(Ecological history and non-equilibrium thermodynamics help answer this)

C. How do we evaluate *Integrity* for this ecosystem?

(What states of ecosystem organization are acceptable to us?)

What are the ecological, economic and other processes (at each of the nested levels) we value and/or need?

How do we identify these?

How do we measure the status of these processes?

(Notice that this takes us back to step A above)

Which attractors represent unacceptable ecosystem conditions?

D. Is this *integrity* threatened?

What are the external influences which could effect the organizational status of the system?

What are the thresholds of flips to the unacceptable attractors? (states of ecosystem organization)

E. How do we maintain *integrity* in this system?

How do we mitigate known threats (that is contextual changes which promote undesired attractors)?

How do we promote positive influences? (For example; fire in a prairie, subsidies for clean technologies)

How do we monitor the ecosystem so as to detect changes due to previously unidentified external influences?

F. How to deal with Emergent Complexity..........

When all is said and done, our ability to predict is severely limited. Unexpected events and trends will occur. Surprise will happen, complexity will emerge. We must therefore rely on anticipatory and adaptive management.

Always remember "The system imbedded in another system imbedded in another system imbedded in another system ...." and the challenge of sustaining a dynamic, changing, evolving, self-organizing ecosystem.

Narratives I. Systems and Issues of Interest

The narrative to describe a SOHO system must begin with identification of the relevant set of constituent holons, the self-organizing entities of interest. Consideration must be given to the types of perspectives required and the appropriate scales of investigation [18]. The SOHO systems of interest are critically related to the human issues to be addressed. Care must be taken to identify the issues at hand and the appropriate perspectives and scales of investigation necessary to deal with these issues in the SOHO systems 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. This in turn, often depends upon who is invited to the consultation or negotiation sessions to design the collaborative inquiry, and the values and concerns each stakeholder brings to the table. Issues of inclusiveness, relative power among stakeholders, and extent of mutual trust in the process are all relevant .

One example of regional development in a rather isolated region in northern Peru illustrates this. When the issues of sustainability of food production and nutrition for rural residents were investigated by external researchers, the focus of attention was on cattle ranching and range management. When a more inclusive consultation was held locally, it became apparent that fish, not cattle, are the important food source. This shifted the research focus from cattle ranching and range management to the condition of riverine fisheries. [19]

Interest in maintaining “natural” ecosystem conditions in a small site at the edge of Kitchener, Ontario, for environmental education purposes, posed questions about the conditions and desired compositional changes in forest stands and in a stream-pond system flowing through the site. However, both are driven by subsurface hydrogeological systems which could not be managed directly. The hydrogeological systems were affected, however, by land use changes, through urbanization, occurring away from the site of interest, and involving landowners not involved with concerns about the impacts on the site of interest for educational purposes . Thus a critical system type or perspective, that of land ownership patterns and land uses in the region of interest, needed to be considered in addition to the conventional biological analysis of the site.[20]

Narratives II: Exergy, canons, and attractors

The task of characterizing SOHO systems is to describe how these systems unfold over time. The description is a narrative, literally a story, that is qualitative with multiple threads of explanation, portraying a number of possible pathways for development (or storylines). The narratives characterize the attractors and canon of SOHO systems in terms of how the local context of exergy, materials and information and biophysical environment, and the global propensities of capturing more resources (exergy and material), making more effective use of the resources; building more structure, and enhancing survivability, give rise to the emergence of the nested structures and processes which constitute a self-organizing holarchic open system. Two examples summarized below demonstrate the role of the dissipative system model and thermodynamics in generating a narrative description of ecological systems as SOHO systems.

Regier and Kay [21] provide an example from Lake Erie which proposed a two-attractor catastrophe cusp model (Figure 2) as a way of integrating much empirical information of how aquatic systems might transform under powerful, careless human interventions. Two different attractors for shallow lakes have been identified [22]. In the oligotrophic/benthic state, a high water clarity bottom vegetation ecosystem exists. As nutrient loading results in increasing density of planktonic turbidity in the water, the internal state of the adapting ecosystem eventually hits a catastrophe threshold and the ecosystem then flips into an eutrophic/pelagic state. Lake ecosystems have been found which may be perceived to flip between these attractors irregularly. (Lake Erie appears to be currently in the midst of such a flip, from pelagic to benthic.) 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. An ecosystem adapts through a shift in phase to major fluctuations in factors at a larger scale in the overall regional holarchy.

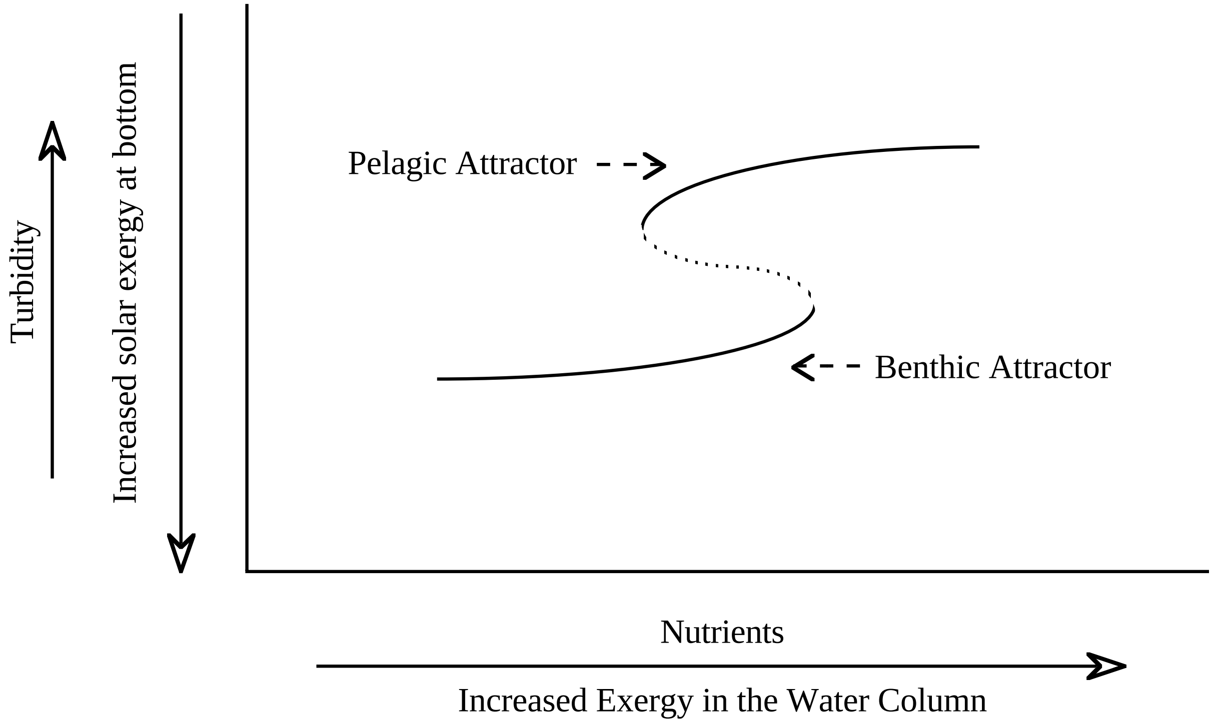
The essence of the canon of the benthic system is that it depends on solar energy reaching the bottom, for the exergy necessary to energize the system. The solar exergy is captured by the green matter on the bottom and is transformed into forms appropriate to power the benthic processes. These include predation and grazing of the pelagic system, thus suppressing it. Various means emerge to maintain the ecosystem at the benthic attractor. Notable among these are means for keeping the water clear so solar energy will reach the bottom and means for keeping the water column free of sufficient exergy which would empower the pelagic attractor.

The pelagic system, on the other hand, depends on exergy in the water column to energize it. Solar energy may be in the water column. However, unless the materials necessary for the existence of dissipative processes, which can utilize the solar energy, are present in the water column, nothing can be done with the solar energy, so it has no exergy. For example, in many lakes, available phosphorus in the water column limits the level of photosynthesis by phytoplankton. Beyond a critical level of available phosphorus in the water column, there is enough availability of solar energy (i.e. sunlight exergy) to support the phytoplankton bloom necessary for the activation of the pelagic attractor. Once this occurs, the solar energy capture happens nearer the water's surface instead of at the bottom and means emerge for promoting and maintaining the pelagic attractor. Of course by its very presence the pelagic system shades the benthic from irradiation by the sun, thus decreasing the exergy at the bottom.

Figure 2: Benthic and Pelagic Attractors in shallow lakes

Two different attractors for shallow lakes have been identified. In the **benthic** state, a high water clarity bottom vegetation ecosystem exists. As nutrient loading increases the turbidity in the water, the ecosystem hits a catastrophe threshold and flips into a hypertrophic, turbid, phytoplankton **pelagic** ecosystem. The relationship of these two attractors, from a thermodynamic perspective, is as follows:

> Let us assume that the benthic attractor is dominant and that the rate at which phosphorus is being added to the water is increasing. The benthic system has means of deactivating phosphorus. However the amount of active phosphorus will increase, albeit slowly, effectively increasing the exergy in the water column. As this exergy increases a critical threshold is passed which allows the pelagic system to self-organize to coherence. Once this occurs the exergy at bottom decreases rapidly due to shading (turbidity) thus catastrophically de-energizing the benthic system. This results in the eventual re-activation of the phosphorus in the bottom muds which the benthic system had previously deactivated, thus strengthening the pelagic attractor even more.
>
> Assuming the pelagic attractor is dominant and if the level of active phosphorus in the water column decreases, a critical threshold is again reached below which it is no longer possible to capture enough solar energy to energize the pelagic system. In effect, the exergy in the water column decreases below the minimum level for the window of vitality of the pelagic system. As this occurs the exergy at the bottom increases thus re-energizing the benthic system. And so the aquatic system flips back and forth between the pelagic and the benthic regime depending on where in the water column the sunlight's exergy is available to energize the system.



Elsewhere, Kay and Regier [23] sketched a more detailed partial narrative of Lake Erie as a SOHO system. This narrative weaves together the themes of organism, species, ecosystem, landscape and biome in the context of physical environment, climate and human habitation and the changes therein. Some of the crucial morphogenetic causal loops, particularly those involving phosphorus, and their relationships to the canon of the pelagic and benthic attractors are outlined. The narrative takes the form of a multilayered account of the ecosystem's operation from different perspectives and scales. While some individual elements of the narrative consist of traditional scientific models and descriptions, the synthesis of these elements together into a narrative transcends normal scientific descriptions.

In this narrative of Lake Erie, the feedback loops, which buffer the system from changes in external influences, are of particular importance. The benthic attractor has elaborate feedback schemes, operating at different spatial and temporal scales, for limiting the phosphorous in the water column. The pelagic attractor has elaborate schemes to accomplish just the opposite. The way in which changes in context enable and disable these feedback loops, and their associated canons, thus re-enforcing attractors or triggering flips between them, has received little attention from the scientific community. Yet our work would suggest that it is precisely these questions concerning the "flip" from one attractor to another, through accounting for how environmental influences (context), acting at different spatial and temporal scales, disable one feedback system while enabling another, that we must understand. This is essential to comprehending the relationships between human activities and changes in the ecology of the lakes.

Another example of the notion of canon and attractor, and the ability to characterize them in terms of the form of exergy utilized, is Holling's four-box cyclical model of terrestrial ecosystems.[24] (See figure 3 at end of paper.) The first trajectory is the "exploitation" to "conservation" thermodynamic branch which culminates in the "climax" community. The biological attractor is the autotrophic system (i.e. a forest). The canon is expressed, for example, as the growth of a forest to maturity and this is energized by solar energy. However in the process of increasing the utilization of solar energy and hence building more structure, much exergy is stored in the biomass. This has the effect of moving the system further and further from thermodynamic equilibrium as it develops.

When, as Holling puts it, the inevitable accident (fire, windstorm, or pest outbreaks) happens, suddenly much exergy is available in the form of dead biomass. This exergy energizes a new biological attractor, the heterotrophic or decomposer system. This is the thermodynamic branch which runs from "release" to "re-organization". As the system progresses along this path it releases the stored nutrients while using the stored exergy. Eventually the stored exergy runs out and the heterotrophic system collapses. However in the process it has released the nutrients necessary for the re-emergence of the solar energy-powered system. This interplay between two biological attractors, which are organized around different forms of exergy, materials, and information is played out giving rise to the landscape we see.

Narratives III: Morphogenetic Causal Loops

The internal causal schemes which maintain the attractor and the canon of SOHO systems can be described in terms of morphogenetic causal loops made up of positive and negative feedbacks, some of which generate autocatalysis. Ulanowicz [25] discusses the importance of these morphogenetic causal loops to the understanding of ecosystems. Two simple examples, taken from DeAngelis [26] are presented below.

Consider forests in dry mountainous areas of the world. Often, as moisture laden clouds pass over bare mountains, they will not drop rain because of the heat reflected from the bare rocks. However as a forest develops on a mountain the re-radiated heat decreases [27]. As the re-radiated heat decreases more rain falls, which promotes more forest growth, which promotes more rain fall....

In southeastern Australia the dominant trees are sclerophyllous eucalypts, 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. The morphogenetic causal loop of sclerophyllous dominant forest, fire, and soil infertility obstructs the development of temperate rain forests.

Another important aspect of SOHO systems is the role of morphogenetic causal loops in maintaining the canon of a system in spite of a changing context [28].Consider for example the acidification of lakes. The acidity in the precipitation changed substantially, but rather incrementally, over a number of years. However, the pH of the receiving lake waters did not change substantially, relatively speaking, over the same period [29]. In our terms, the pH of precipitation is part of the context of the SOHO system. While this changed substantially over time, the lakes maintained their canon through a series of feedback loops that largely buffered them from the environmental change. Eventually the inflows or runoff reached a level of acidity which exceeded the compensatory capacity of these loops. Once this happened, the effectiveness of the SOHO system to maintain its existing state decreased, which in turn decreased the capacity of the loops to compensate, which decreased the effectiveness of the SOHO system.... and then quickly the canon unraveled and the SOHO system flipped to another attractor, in this case a "dead" lake. The narrative description of a SOHO system must not only delineate the morphogenetic causal loops, but also the contextual circumstances in which they can and cannot operate. Doing this in effect defines the domains of the attractors, the resiliency of the canon, and its window of vitality.

5. Decision Making in the Post Normal Mode

Funtowicz and Ravetz [30] distinguish problem-solving strategies for different circumstances defined by the inherent uncertainties in the situation and the severity of consequences arising from the decision to be made. “Normal science”, either as applied science or mission-oriented research, succeeds where the relative uncertainties are low (and most of it can be handled by standardized procedures), and the stakes or outcomes associated with decisions to be made are modest. In contrast, SOHO systems are situations for which there may be little useable science, high levels of inherent uncertainty, and severe potential consequences from decisions that have to be made. These are “Post-Normal Science” situations. Some similarities between this depiction of decision making circumstances and “mindsets” to understand SOHO systems are noted in Table 3.

Table 3: A comparison of the normal applied, professional consultancy and Post-normal science approaches to environmental concerns. (Based on discussions with S.Funtowicz and J. Ravetz)

Normal Applied Science	Conventional Professional Consultancy	Post-normal Science and Inquiry
	Essentials	
Certainty	Uncertainty (reducible in principle, we lack knowledge)	Uncertainty (irreducible in principle)
Low stakes	Intermediate stakes	High stakes
Facts: Truth found	Solution: client happy, society is satisfied	Resolution: a course of action chosen
	Results	
Hard	Try to be hard	Soft
Predictable	Error reduced to an acceptable level	Unpredictability a fact of life
Quantitative	Quantitative ±	Quantitative + Qualitative
	In the service of	
Truth	Client in a societal institutional framework	Decision makers, policy, public
	Judgment of results	
Truth accepted	No mistakes (i.e. surprises)	Quality of process, integrity
Peer review	Holds up in court, client happy	Holds up to public scrutiny, move forward
	Mode of Inquiry	
Hypothesis testing	Problem solving	Ecosystem approach
Pursuit of TRUTH	Mission and product oriented	Pursuit of understanding
Reductionism		Holarchic
Analysis	Analysis + Design	Analysis + Design + Synthesis
	Explanations	
Linear cause and effect	Non-linear, negative feedback	Negative + Positive feedback, autocatalysis, morphogenetic causal loops
Mechanistic	Mechanistic + Cybernetic	Synergistic, emergence,
Stability	Control, homeostasis	Change, evolution, ∞ cycles
Efficiency		Efficiency + Adaptation
Extremum principles		Local optimum, tradeoffs
Laws		Propensities and constraints
	Forensics	
Fact	Interpretation	Testimony
	Characteristics	
Objective, one correct view	Subjective, client-consultant view	Subjective, plural
Value free	Limited values	Ethical, Integrity
Predictive Management	Control Management	Anticipatory + Adaptive Management
Physics	Engineering	Ecological Economics

In the post-normal situation, the shared understanding of decision making about issues takes on a different complexion. Decision making becomes what it has always been about, finding our way through partially undiscovered country rather than charting a scientifically determined course to a known end point. But to what end? Decisions must be made about which of the systemic 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 preferences, and of the socio-political context in which they are made. This of course raises the question, who decides? At the very least, those who might be affected by the outcomes should have some role in making the decisions.

Given that the ability to forecast is limited, management and decision-making strategies must focus on maintaining a capacity to adapt to changing environmental conditions. Adaptive management involves a very different agenda than anticipatory management [31]. For example, the issues of requisite redundancy, contingency planning and designing human systems which can evolve, come to the forefront. In adaptive management, differences between how the future actually unfolds and how it was anticipated that the future would unfold, are seen as opportunities for learning. This is in sharp contrast to anticipatory management which sees such deviations as "errors" to be avoided. Much of the agenda of adaptive management is learning through experimentation rather than focusing on error avoidance. Adaptive management is not meant to displace anticipatory management but rather to complement it. The program of post-normal science is to provide a basis for the understanding necessary to unravel complexity (emergence, irreducible uncertainty, internal causality), so that we may successfully anticipate, when possible, and adapt, when appropriate or necessary, to changes in the self-organizing systems of which we are an integrated and dependent part.

Choosing a path through sets of SOHO systems not only benefits from bringing a G-type understanding of mutual causality. It also needs to involve those who can identify a range of human preferences and issues to be addressed, i.e. 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 4 (see end of document). It serves as a heuristic for the adaptive ecosystem approach, where it is accepted that human systems and biophysical systems are mutually interrelated in complex ways. This framework presumes that decisions about environmental issues involve mapping out a vision of how the landscape of human and natural ecosystems should co-evolve as a self-organizing entity to meet human preferences. The left hand box in Figure 4 is about developing a SOHO narrative description as discussed in this paper. This delineates the system’s possibilities and constraints, and the contextual realities of the situation. Essential to the narrative is the holarchical description of the system. Its relevance depends on choosing the appropriate system type perspectives and scales for observation, the appropriate processes and structures for study. The appropriateness of this choice 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 visions for the future are. Because people's perceptions, concerns and visions will be altered during the exercise of developing the narrative description, the undertakings of developing an issues framework and a SOHO narrative depend on each other and thus are recursive, as is appropriate in the context of morphogenetic causal loops.

The inherent potentialities of the SOHO systems combined with human vision and preferences gives rise to scenarios of possible and desirable futures. Each of these scenarios will represent different sets of tradeoffs and require planning and negotiations among stakeholders to reconcile these tradeoffs and to develop a plan, or pathway for the future. The nature of this plan is that it encourages and discourages, as is appropriate, human activities based on a vision of how the integrated human systems and ecosystems should co-evolve as a self-organizing entity. It also identifies the institutional arrangements for governance necessary to act and adapt to the way in which the self-organization unfolds.

In this mode, governance is an activity that focuses on the SOHO systems and adjusts the vision based on how the self-organization process is unfolding. Management seeks to translate the vision into reality by maintaining the context for self-organizing systems, rather than intervening in the system in a mechanical way as is done under the H-type mindset. Generally speaking management concentrates on the relationship between human systems and ecosystems, and on guiding the human side of the relationship. Monitoring is the activity of observing the human and natural self-organizing systems and synthesising the observations into a narrative of how the situation is actually unfolding. This narrative is then used as the basis for governance and management, that is, for revisioning, and adapting human activities, as is necessary.

In summary, in this post-normal mode of decision making, people provide an image of how they would like to see their landscapes and social systems evolve. Science, drawing upon several epistemological traditions, helps identify known constraints and possibilities of the SOHO systems. A dialogue must ensue which explores the desired and the feasible, and reconciles these in a vision of how to proceed. Scientists inform this dialogue by providing the narratives through a process in which they participate as equals with others in the task of articulating the vision, and identifying pathways for the future. To us, this constitutes an ecosystem approach for sustainability as it has to be interpreted in the context of Post-Normal Science grounded in complex systems thinking.

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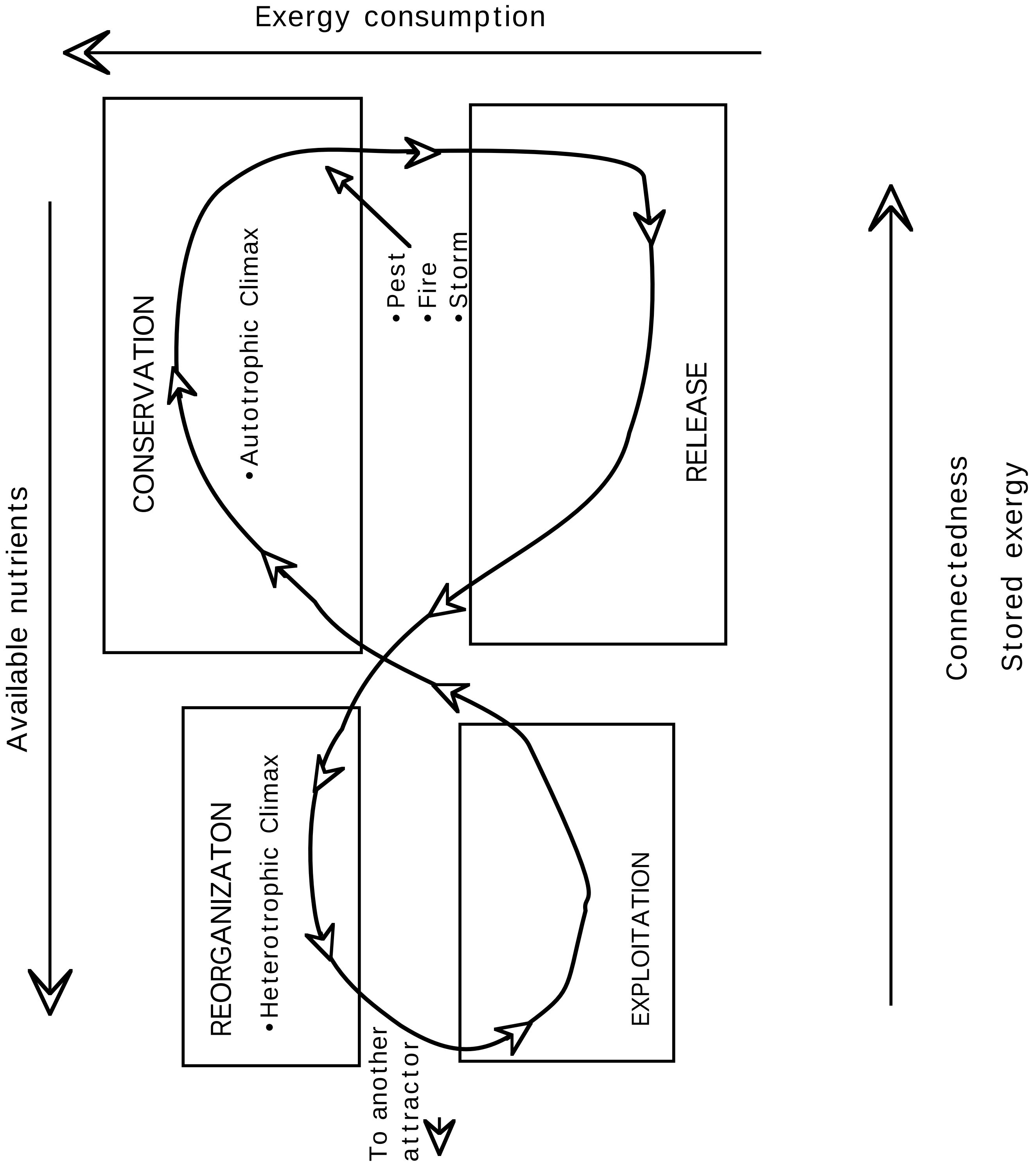


Figure 3: Holling's four box model as a dual thermodynamic branch system.

For the four box model, there are two axises

Horizontal axis: Stored exergy. The amount of exergy stored in biomass. This is related to the amount of nutrients bound in the biomass.

Vertical axis: Exergy consumed. The rate at which exergy is utilized by the system.

From a non-equilibrium/self-organization theory perspective, the four box proceeds as follows

Starting at **exploitation**: If there is sufficient materials and biological information available, then dissipative processes will emerge which utilize the exergy in the solar energy. In other words, some organisms will take advantage of the available resources.

The thermodynamic direction of all self-organizing processes is to increase its utilization (consumption) rate of exergy (Kay). In this case the developmental path taken also involves increasing biomass and hence stored exergy (Jørgensen). The more exergy stored, the bigger the structure, the better able it is to utilize exergy, the bigger it gets, etc. This is the direction of the **first thermodynamic branch**. The exergy source is solar energy.

Problem: The more exergy that is stored in the system, the more likely (according to the restated second law of thermodynamics) that some dissipative process will emerge to take advantage of it. So fire, pest outbreaks etc., occur that take advantage of all the exergy stored in the biomass. The paradox is that the more effective the system is at consuming exergy, that is the more organized it is, the more exergy it contains and hence the more likely it is to be consumed by another self-organizing process (i.e. fire, pest outbreaks etc.)

So **conservation** represents a point of maximum thermodynamic organization in the sense that the system is utilizing the available exergy as fully as possible. But it also represents a point of maximum thermodynamic risk as it as far out of equilibrium as is possible. (Distance from thermodynamic equilibrium is measured by exergy content.)

In the language of attractors, there are two attractors, the attractor of maximum exergy consumption and the attractor of local thermodynamic equilibrium. For this particular thermodynamic branch the attractor of maximum exergy consumption is moving in opposition to the local equilibrium attractor. The **conservation** point is the place where the two attractors are in balance. For some systems this balance is precarious for others less so, but in the end the local equilibrium attractor is always dominant

Once the inescapable happens, that is **release,** a new source of exergy is available for use, that is the exergy in the stored biomass. Again it inevitable that this new exergy source will be utilized. As always, the self-organizing process unfolds in a direction of increasing exergy utilization, except that the processes involved are fundamentally different and instead of storing biomass and hence exergy, they release the exergy in the stored biomass and at the same time release the stored nutrients. This is the direction of the **second thermodynamic branch**. The exergy source is stored energy.

Eventually the **reorganization** point is reached, that is point where the stored exergy runs out. But now the raw materials are available to start along the first type of thermodynamic branch again. Which specific branch is followed is a function of the biological information, nutrients and current environmental conditions. (And this is the point where biodiversity is so crucial, as this is the point where resiliency matters.)

To summarize: There are two thermodynamic branches, that is self-organizing pathways that are followed. One (from **exploitation** to **conservation**) is driven by the exergy in solar energy and involves increasing biomass and hence stored exergy. The other (from **release** to **reorganization**) is driven by stored exergy and involves the release of the exergy and hence biomass. The direction of both is increased exergy utilization. The ecosystem alternates between these two sources of exergy and hence follows two qualitatively different pathways of self-organization. The specifics are determined by the environmental conditions, available resources and biological information, the latter usually being the determining factor.

The first branch has been traditionally referred to as succession, or growth and development. Biologically it is the attractor for the autotrophic system. The second branch is about creative destruction, that is decomposition. Biologically it is the attractor for the heterotrophic system.

So the **exploitation point** is one of minimum exergy use and storage.
The **conservation point** is one of maximum exergy use and storage.
The **release point** is one of minimum exergy use and maximum storage
The **reorganization point** is one of maximum exergy use and minimum storage.

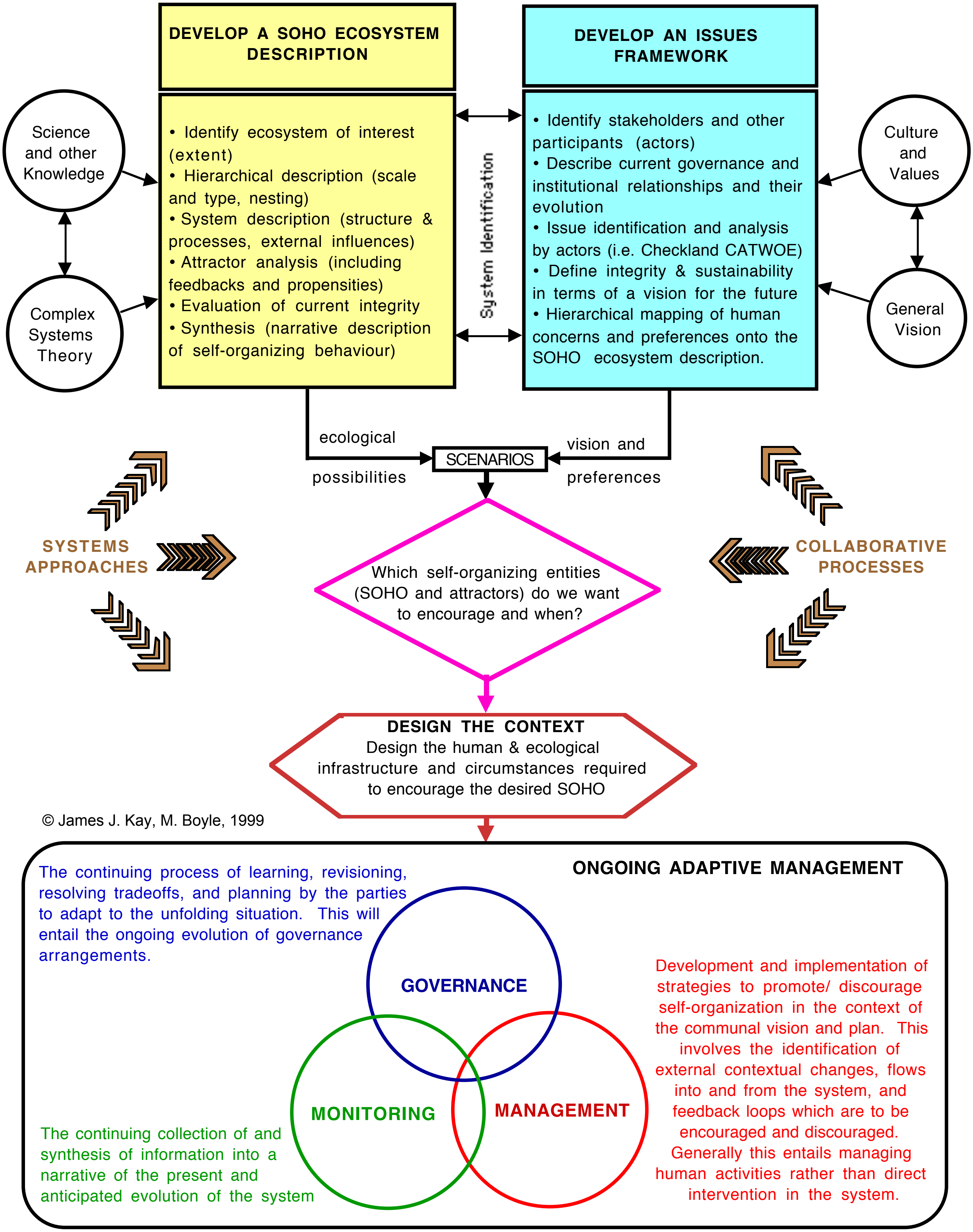
Note:
Exergy: the quality of energy. It measures how much work can be extracted from an energy source. In essence it tells us how good a fuel, an energy source is.

The restated second law of thermodynamics (Kay and Schneider): The more exergy there is, the more likely it is that a self-organizing dissipative system will emerge to take advantage of it. In biology, the more exergy available, the more likely some organism will make use of the opportunity.

The further a system is moved from thermodynamic equilibrium (which is measured by exergy content), the stronger the tendency to return to thermodynamic equilibrium.

Thermodynamic branch: The developmental path taken by a self-organizing system as it develops.

Figure 4: An adaptive Self Organizing Holarchic Open (SOHO) System approach to ecosystem sustainability and health. [32] (A better quality graphic can be found at www.fes.uwaterloo.ca/u/jjkay/about/diamond.html)



- 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)

- 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.

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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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.

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

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