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Integrating research on ecohydrology and land use change with land use management

Brad Bass,[1]* Ralph E. Byers[2] and Nina-Marie Lister[3]

[1]*Great Lakes and Corporate Affairs, Environment Canada–Ontario Region, 4905 Dufferin Street, Downsview, Ontario M3H 5T4, Canada*
[2]*Orillia, Ontario, Canada*
[3]*School of Urban and Regional Planning, University of Waterloo, Ontario, Canada*

Abstract:

One objective of the International Geosphere–Biosphere Programme is to provide a scientific basis for sustainable development policies. Land use change and ecohydrology are important components of this scientific basis, but predicting change is difficult because of the scale and complexity of the interactions between non-linear ecohydrological and socio-economic processes at different spatial and temporal scales. A systems framework, the Ecosystem Approach, has been developed to conceptualize these interactions for the purpose of providing information for sustainable development policy. The Ecosystem Approach combines the dynamics of the Holling figure-eight model — a conceptual model of dynamics that stresses discontinuous change and destruction as an internal property of the system — and the properties of self-organizing systems with the socio political aspects of decision making.

The Ecosystem Approach highlights the problems of managing change in complex systems when that change may involve unpredictable shifts to a different attractor. Although there are methods available to detect the occurrence of such shifts, both detection and modelling are complicated by the presence of semi-stable attractors. When a model or an ecosystem is on a semi-stable attractor, it may appear to remain stable for an extended period prior to changing as a consequence of inherent instabilities. When the shift to a new attractor occurs, it is quite sudden and unpredictable. A technical discussion on prediction under conditions of semi-stability and chaos is included because it enhances our understanding of the role of surprise in ecosystems, as well as the utility of simulation models.

The principles of the Ecosystem Approach are derived from the theoretical discussion and an example of a land use policy in the Huron Natural Area in south-western Ontario. These principles provide a clear role for scientific research, and particularly simulation modelling, within the larger context of policy and land use management. © 1998 John Wiley & Sons, Ltd.

KEY WORDS modelling; ecohydrology; land use; semi-stability; ecosystem approach

INTRODUCTION

> Ecosystem models are always wrong, in the sense that reality conforms to their numerical projections only very rarely. Models are indispensable because without them human misunderstanding persists, unaware of its errors (Lee, 1993, p. 62).

Lee (1993) summarized the basic conundrum that faces any scientific research programme, particularly one, such as the International Geosphere–Biosphere Programme (IGBP), that relies heavily on numerical simulation models in translating the science into effective decision making. What is clear is that the role of

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* Correspondence to: Brad Bass, Great Lakes and Corporate Affairs, Environment Canada–Ontario Region, 4905 Dufferin Street, Downsview, Ontario M3H 5T4, Canada.

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science, and particularly of models, in policy is not to provide the answer, but rather to illuminate policy options and trade-offs (Lister, 1998). However, models are also invaluable in pursuing the qualitative implications of various assumptions (Lee, 1993). This paper addresses the problem of translating science into policy, particularly the use of the scientific research and models in two IGBP research programmes, the Biospheric Aspects of the Hydrological Cycle (BAHC) and Land Use and Land Cover Change (LUCC), which recently held a joint conference to explore areas of common ground.

One objective of the IGBP is to provide a scientific understanding of global change so as to better inform the policy debate on sustainable development. The IGBP is carrying out its mandate through 11 programme elements. Two elements, BAHC and LUCC, are linked, since changes in land use[1] can affect runoff, evapotranspiration and precipitation on a local level, while the regional and local effects of changes to the hydrological cycle will affect land use and related management choices. It is difficult to translate the science of BAHC and LUCC into policy because of three scientific factors:

1. One of the main drives for change for both BAHC and LUCC is climate change, a global phenomenon for which predictions are difficult to evaluate and impacts are difficult to resolve at the regional and local scales, where many decisions are made.
2. Land use is a complex phenomenon, and changes in land use are driven by the interaction of several physical, biological and socio-economic processes that are non-linear and range over a variety of spatial and temporal scales.
3. The non-linear dynamics inherent in land use change open up the possibility for sudden changes that are difficult or impossible to predict.

The first factor, that of the scale of climate change and the scale of decisions, is being addressed by a research programme in BAHC to translate, or downscale, climate model output and climate data to the regional or local scale. Although there are methodological problems associated with downscaling, and some debate as to its effectiveness, a great deal of progress has been made in this effort (Bass and Brook, 1997). The second and third factors reflect characteristics of any complex system, and, as land use systems are complex systems, they present conceptual and sociopolitical as well as computational difficulties for modelling in BAHC and LUCC.

In addition to the science barriers, Lee (1993) identifies three sociopolitical barriers that often occur in translating science into effective decision making to promote sustainable development.

1. Management is often restricted to jurisdictional boundaries, yet ecosystems are often multi-jurisdictional.
2. Management is often driven by concerns for single species-based conservation, yet management of a multi-jurisdictional ecosystem requires a larger system-wide focus (e.g. from genetic to landscape based) and a toleration of occasional failure at the individual species level.
3. Management often conforms to time-scales dictated by the budget process, the electoral timetable or the business cycle, instead of the time-scale of a biological generation.

To Lee's (1993) list, we can add a fourth sociopolitical barrier which pertains to the use of ecosystem science, and which is a basic component of the Ecosystem Approach.

4. Human values for ecohydrological systems, their functions and their services are rarely acknowledged explicitly within the land use planning and management processes. The failure to recognize or articulate these values explicitly results in management decisions that, while ostensibly driven by 'good science', are based implicitly on the value orientations of the policy makers. This is due, in large part, to the

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[1] The term *land use* applies to both land use and land cover. The authors consider the dichotomy between the two to be arbitrary. Whether a piece of land is exploited for human purposes or protected in a natural state is a political decision, as illustrated by the management decisions in the Huron Natural Area.

> uncertainty that characterizes the science being used to support or drive policy, and is compounded by a lack of expert and public debate about which land uses are worth fostering, or how system dynamics should be managed (Lister, 1998).

The Ecosystem Approach, developed for '... evaluating the current state of ecological integrity and the ways that our actions might influence it in the future,' (Kay, 1994, p. 4), is a framework that places scientific research within a process that makes explicit: (1) the geographical context and the hierarchical relationships at different scales; (2) the management goals and stakeholder visions for the landscape; and (3) the value judgments that underlie the resulting management decisions. The essential elements of this approach have been identified by Kay (1994) and Schneider and Kay (1994):

- As a complex system or self-organizing system, land use change involves a degree of unpredictability, phases of rapid and surprising change, and the emergence of system-wide properties;
- Ecosystem analysis is done in the context of a hierarchically organized system description of the area, involving the thermodynamic, information and cultural aspects of living systems because each perspective generates a different hierarchical representation of the system;
- The ability to make quantitative predictions in many situations is quite limited, and hence management must be both anticipatory and adaptive;
- The task of ecosystem management is to promote the capability for self-organization while managing the societal interactions with ecosystems which by necessity involves value judgments and politics.

A longer discussion of these points can be found in Schneider and Kay (1994), Hansell *et al.* (1997), Lister (1998) and Norton (1992).

The non-linear dynamics of land use change are fundamental to the Ecosystem Approach, but recent discoveries of semi-stability in simple non-linear models further complicates the problem of the prediction and management of complex systems. Semi-stability is manifested as an apparent robustness to changes in parameters. In numerical experiments with population models, Byers *et al.* (1992) found that the expected changes, owing to changes in a model parameter, occurred thousands of iterations after the change, and the timing of the change was unpredictable.

The presence of semi-stability in a non-linear model introduces a large amount of uncertainty in a prediction and suggests that systems are capable of surprising and sudden change. Holling (1978) noted that the occurrence of surprise must be accommodated within any policy directed towards sustainable development. A common misunderstanding of surprise is that it is a result of limited theory and poor data (Lee, 1993). Holling (1986) altered that view with the presentation of an ecosystem dynamic that incorporated surprise, suggesting that ecosystems are not completely predictable, and that socio-economic systems and the interaction between these two is even less so. His view of ecosystem dynamics not only includes the exploitation and climax community phases, but also includes a role for destructive events, which are necessary for adaptation. Surprise is linked to these destructive events, and to how ecosystems are managed, to mitigate or eliminate these events.

In the development of landscape indicators for the Ontario Ministry of Natural Resources (OMNR, 1996), Holling's view of system dynamics was used to describe both ecological and socio-economic processes and their interactions as determinants of land use change. The OMNR report demonstrated that the Ecosystem Approach is relevant to incorporating BAHC and LUCC research into policy. The possible emergence of semi-stability in managing land use adds additional uncertainties to land use management.

The next section briefly reviews the elements of complex systems thinking that are the theoretical basis of the Ecosystem Approach. Particular attention is paid to Holling's description of ecosystem dynamics and self-organizing systems. The third section discusses the theory and application of semi-stability in non-linear models, and there then follows a discussion of the linkages between semi-stability and management. The penultimate section presents an example of land use management, and finally we build upon the theory and application to formalize the principles of the Ecosystem Approach.

THE THEORETICAL BASIS OF THE ECOSYSTEM APPROACH

Systems of land use are complex systems involving ecological and socio-economic processes in the context of broader global change (Kay, 1994; Hansell *et al.*, 1997). Complexity is characterized by a wide range of behaviours, which emerge from within the system. These behaviours emerge as a result of self-organizing processes that can lead to sudden and surprising changes and are historically dependent on previous states. Complex systems may also be open systems, and complexity can arise from the interaction between different components as well as interactions between the components of the system and the inputs into the system (Hansell *et al.*, 1997). Describing change in complex systems requires a new vocabulary (Hansell *et al.*, 1997).

The first stage in describing change in complex systems is to identify those variables that describe the state of the system in order to define the *state space* or the boundary within which the system must operate. The second stage is to identify the *attractors*, those points in state space where the system is drawn to following a perturbation. They are sets of points in the state space that are left unchanged by the system's dynamics. The *basin of attraction* or *domain* of an attractor is the set of all points of the state space that serve as initial conditions of trajectories that tend towards the attractor, just as an object placed in a bowl will be drawn towards the centre. Points on the rim of the domain form the boundary of the basin of attraction. The boundary of a basin of attraction is an invariant unstable set.[2]

The system's trajectory can escape the attractor if it is perturbed so that it either touches or crosses the boundary of the basin of attraction. Or, if there is a parameter change that results in a tangency between the attractor and the boundary of its basin of attraction, the point of tangency provides the route of escape from the attractor.

A thermodynamic description of self-organizing open systems provides an account of the emergence of new attractors in the complex systems. Nicolis and Prigogine (1977, 1989) demonstrated that dissipative structures[3] self-organize in open systems as a result of small instabilities. These small instabilities lead to abrupt changes that are not predictable. Dissipative structures emerge or self-organize in a narrow window where the energy input is high enough — such that structures can emerge to dissipate the extra energy, as long as the energy gradients are not too large.

If the energy input falls below a minimum threshold, self-organization cannot occur and the structures cannot emerge, or existing structures cannot be supported. If the energy input crosses a critical threshold, it overwhelms the ability of the organized structures to dissipate the energy and remove the gradient. At this point the behaviour of the system is highly unpredictable and chaotic. Essentially, the thermal or energy gradients across the system act as control parameters that take the system through a series of bifurcations, ultimately leading to some combination of chaos and structure.

A closed system is governed by the second law of thermodynamics and must eventually reach a state of equilibrium, at which point it can no longer perform any work. Schneider and Kay (1994) proposed a refinement to the second law which states that, as open systems are moved away from thermodynamic equilibrium, they will attempt to resist and dissipate the energy gradient across the system. As the gradient increases, a system can draw on more sophisticated mechanisms, including the emergence of new dissipative structures, to store energy and dissipate the increase in input to the external environment. An open,

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[2] An unstable invariant set is a set of points that is left unchanged by the system's dynamics around which volumes of the phase space expand. The unstable equilibrium is a simple example in which the set consists of one point. In iterated function systems, an unstable period two orbit is another simple example in which the unstable invariant set consists of two points. In continuous time systems, an unstable periodic orbit is an example of an invariant set consisting of infinitely many points.

[3] Dissipative structures emerge when a gradient of sufficient strength exists across the system. The structures emerge to dissipate the gradient.

self-organizing system has the capability to remain in non-equilibrium as long as an energy gradient exists across the system. Thus, the emergence of structure or organization in open systems can be explained thermodynamically (Schneider and Kay, 1994).

Kay (1994) provides a thermodynamic interpretation to Holling's description of ecosystem dynamics, providing a linkage between the dynamics of land use change and the language of complexity. Holling (1986) reviewed a number of resource management case studies involving situations where the ecosystem collapsed or was seriously damaged. He formulated a conceptual model of ecosystem dynamics that stressed discontinuous change as an internal property of the systems and provided insight as to when such an event would occur. The model includes the two phases that determine ecosystem succession: exploitation related to r-strategists (species that invest their energy principally in the reproduction of large numbers of offspring, and which tend to be smaller bodied and short-lived) and conservation related to K-strategists (species that invest their energy principally in the survival of the adult, and which tend to be larger bodied and longer lived). The third phase is one of discontinuous change caused by large-scale events such as a fire, pest outbreak or an extreme climatological condition, or, on a smaller scale, gaps in the forest canopy generated by wind throw and tree fall. The fourth phase is one of reorganization or renewal, as resources that are released through the phases are linked in a figure-eight (Figure 1).

The third phase occurs with increasing connectedness and energy storage in the maturing ecosystem. The connectedness becomes the 'backcloth', (Atkin, 1978) that allows the rapid spread of a disturbance, while the stored energy provides the fuel. Holling terms this 'creative destruction' after Schumpeter (1950).[4] Although massive disturbances may cause significant losses, both in terms of area and species, the previously accumulated yet unavailable energy, or stored capital, is now released. This stored capital is made available through decomposition and retained through mechanisms, some of which are the colloidal behaviour of soil,

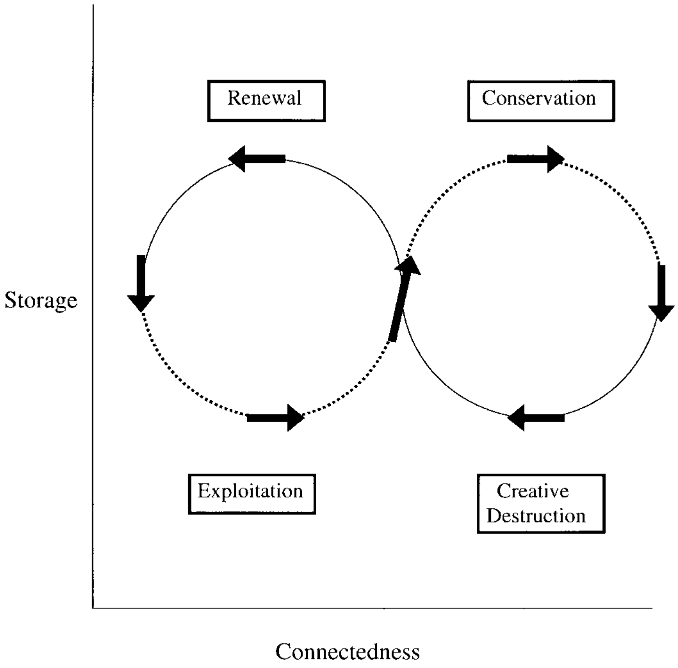

Figure 1. The Holling figure-eight

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[4] Schumpeter (1950) proposed a similar dynamic to account for the growth of new firms and new innovations as well as the effects of an economic recession.

rapid nutrient uptake by remaining vegetation and reduced rates of nitrification (Marks and Bormann, 1972). Stored capital may also be released in the form of biomass reproduction, as in the case of jack pine (*Pinus banksiana*) which requires the heat of a forest fire to release its seeds — a case in point of Holling's (1986) notion of 'creative destruction'.

Thermodynamically, the *y*-axis of Holling's figure-eight model represents the rate at which a system uses energy, while the *x*-axis represents the energy stored in the biomass of that system. In the exploitation phase, given sufficient material and biological information, dissipative processes emerge, utilizing the incoming solar energy. A positive feedback loop emerges; as energy storage becomes larger, the ecosystem develops more structure which allows the system to better utilize incoming energy, leading to the further development of more structure. In this way, the system maintains itself some distance from thermodynamic equilibrium. Schneider and Kay (1994) use the outgoing long-wave radiation from different landscapes in Oregon, USA (Luvall and Holbo, 1989), ranging from a rock quarry to a 400-year-old forest, to demonstrate that as ecosystems mature they are better able to utilize incoming energy to build structure.

Kay (1994) argues that in the conservation phase the energy input exceeds the narrow energetic window. The energy storage is at a maximum, and the system is unable to utilize fully the available energy and other resources to build more structure. The energy stored in biomass provides fuel for the emergence of a new dissipative process, such as fire or a pest outbreak. An event such as a fire moves the system to a new state that is closer to thermodynamic equilibrium, allowing for the release of stored energy, which is necessary to complete the figure-eight. Thus maximum energy storage at the conservation phase implies maximum thermodynamic risk.

Kay (www.fes.uwaterloo.ca/u/jjkay/musings) suggests that maximum thermodynamic risk and thermodynamic equilibrium are both attractors at the conservation phase of the Holling figure-eight, with eventual domination by the equilibrium attractor. It will be argued later that the Holling figure-eight is a chaotic attractor composed of at least two semi-stable attractors. The attractor remains stable, unless an attempt is made to maintain the thermodynamic risk by attempting to reduce the role of surprise.

Holling (1986) linked the role of surprise to the second and third phases of the figure-eight. Kay (1994) suggested that land use management should not strive to eliminate surprise. Rather, the goal should be to maintain the resiliency of the system and its self-organizational capacity in the face of change. This goal may be achieved by a focus on facilitating the Holling figure-eight, rather than attempting to maintain the system at the conservation stage that is a point of maximum thermodynamic risk, through adaptive management and designing and planning for dynamic change. The recognition of surprise as an important aspect of sustainable development policy is also echoed in Lee (1993) and Clayton and Radcliffe (1996). This point is fundamental to the Ecosystem Approach, in that uncertainty, limited predictability and surprise events are considered basic ecological principles that must be acknowledged, accepted and incorporated into decision making processes in order to deliver effective and relevant land use planning and management decisions.

It is important to recognize that the system is capable of surprising change after the renewal phase as well, when it could shift to another attractor. This new attractor is characterized by a different set of dominant species, and this shift can occur on a seasonal basis. For example, Scheffer *et al.* (1993) demonstrate the existence of multiple attractors in shallow lakes that operate on a seasonal basis. Shallow lakes can have two alternative equilibria, either a benthic attractor (high turbidity dominated by high algal biomass and associated bottom-dwelling species) or a pelagic attractor (clear state dominated by aquatic vegetation and could include the larger sport fish species). The particular attractor is largely determined by spring snowmelt and the associated nutrient off-loading.

Each attractor is characterized by its own Holling figure-eight. The creative destruction is determined by the spring snowmelt and nutrient loading. In this particular type of system, if it is at a pelagic attractor, snowmelt and nutrient off-loading will not necessarily be large enough to shift the system to the benthic attractor, and a pelagic state could be followed by another pelagic state after the renewal phase. Hansell and Bass (1998) have redeveloped the Holling figure-eight to describe these situations where the creative destruction occurs, but is relatively small.

ECOLOGICAL MODELS, NON-LINEAR DYNAMICS AND SEMI-STABILITY

Ecosystems are dynamic systems. As such, they are appropriately modelled using systems of ordinary differential equations, perhaps involving derivatives with respect to space (as in models of the flow of groundwater), or using iterated maps (such as the logistical map, particularly appropriate in models of discrete generation populations). There is a rich mathematical literary corpus devoted to the study of dynamic systems, from which a number of observations may be made.

All dynamic systems possess attractors, repellors and semi-stable attractors, of which the numbers of each vary significantly, being more numerous with increasing degrees of non-linearity and increasing dimensionality. Attractors, semi-stable attractors and repellors consist of bounded invariant sets with specific properties. Volumes contract around attractors and semi-stable attractors, and volumes expand around repellors. Just as an analogy was made between a bowl and an attractor, a similar analogy can be made between a hill and a repellor. The implication of this for empirical work is that one can expect to observe attractors and semi-stable attractors while one would almost never observe a repellor directly.

The difference between attractors and semi-stable attractors is that distances contract in all directions around attractors, as in moving towards the centre of a bowl, whereas in the neighborhood of semi-stable attractors, there exists a small number of directions in which distances grow, as in moving away from the centre of a bowl, relative to the number of directions in which distances contract. The implication of this for empirical work is that once systems arrive in the neighborhood of an attractor they never leave that neighborhood unless subjected to a sufficiently large perturbation or unless the system is changed such that the attractor is no longer stable. If the system has arrived in the neighborhood of a semi-stable attractor, it will inevitably leave that neighborhood in a finite time, even if it is not subjected to any perturbation and nothing else in the system changes. However, it is not possible to distinguish semi-stable attractors from stable attractors empirically prior to the departure of the system studied from the neighborhood without the development, and mathematical analysis, of a mathematical model for the system.

Attractors, semi-stable attractors and repellors are generalizations of stable and unstable equilibria and some saddle points (not all saddle points qualify as semi-stable attractors). The equilibria of classical dynamics permit only stasis. Once a system arrives at a stable equilibrium, no further change is possible. The first generalization of the equilibrium involved limit cycles. With this generalization, many studies ignored transient behaviours, seeking only stable solutions of rate equations, including only equilibria and periodic solutions. The second generalization involved the discovery of chaotic dynamics. Rate equations cannot be solved to find chaotic solutions. Chaos can be studied only by the use of computer simulation. Chaotic trajectories that are numerically observed in dissipative systems are restricted by dynamics to the neighborhood of either an attractor or a semi-stable attractor (in which case they are commonly referred to as chaotic transients).

Most modern studies of non-linear dynamics involve analysis of the structural stability of dynamic systems. Such studies examine what happens to a system's attractors as one of the system's parameters changes, elucidating various routes to chaos, including period doubling bifurcations and intermittency. These studies are critical for assessment of the ecological effect of climate change and human intervention, particularly those interventions that may be adaptations to climate change, on the dynamics of ecological systems. Management decisions regarding harvesting and afforestation, and unmanaged effects owing to the flow of waste water into groundwater and surface waters can all be analysed as changes in system parameters, such as mortality rate and nutrient input rates, respectively. Development of a suitable dynamic model of the ecosystem of interest, and analysis of it using methods of dynamic systems theory, allows assessment of how significantly environmental change, including human intervention, will affect system dynamics.

IMPLICATIONS OF NON-LINEAR DYNAMICS FOR PREDICTING LAND USE CHANGES

Prior to the discovery of chaos, prediction was implicitly possible since one had either an equilibrium or a limit cycle attractor. Both allow specification of the values of all variables for any time, at least to within the limits of error in estimating model parameters. If the system of interest is chaotic, prediction of the values of all system variables is possible only within a, usually short, time horizon, owing to information production. The more rapid the rate of information production, the nearer the time horizon beyond which prediction, in the conventional sense, is impossible.

The situation is not hopeless, however, since, if the system is at an attractor, one can identify the bounds for all variables between which all observed values for the variables will be found. In other words, the invariant sets supporting chaotic transients are bounded. Once the system is at the chaotic attractor, all observations of the system at any subsequent time are guaranteed to remain within these bounds, and the system is guaranteed to persist, barring significant exogenous environmental change.

The failure of conventional prediction can, in part, be attributed to the existence of chaos. The offending chaos does not even have to be inherent in the system studied. It is sufficient for the system to be open and subjected to chaotic input from the system's environment, much as ecosystems are subject to chaotic input from the atmosphere via weather variables.

Prior to the discovery of semi-stability, prediction based on time-series analysis of empirical data was implicitly possible using any of a variety of statistical models. Since it is impossible to detect semi-stability using time-series analysis of empirical data, systems that appear to be stationary can theoretically show sudden change at any time if they happen to be in the neighborhood of a semi-stable attractor. Given this possibility, prediction of any kind based solely on time-series analysis is inherently risky.

If the Holling figure-eight is an attractor comprised of a periodic orbit, predicting the shift from phase 2 to phase 3 is possible using any of a variety of statistical models. However, the Holling cycle is more plausibly conceived as a chaotic attractor comprised of at least two semi-stable attractors. If this is true, the shift from phase 2 to phase 3 cannot be predicted using any conventional statistical methods. Thus, prediction for any system governed by a Holling cycle carries extreme risk.

The Holling cycle appears to be a competition between two tendencies: thermodynamic disequilibrium, during which structures are maintained to store energy and dissipate excess energy, and thermodynamic equilibrium. This phenomenon might be represented by two stable attractors in an open system, with random perturbations moving the system randomly between the attractors. However, given the instability of thermodynamic equilibrium in the presence of an energy gradient, and the vulnerability of complex systems to perturbation, the phenomenon does not fit well with the properties of stable attractors. Also, a system can remain near either 'tendency' for extended periods of time prior to exhibiting significant change. This property immediately suggests the presence of semi-stable attractors governing the system's dynamics.

Furthermore, the well known Lorenz attractor appears to be comprised of two coupled snap-back repellors, within the basin of attraction, which may be classified as a particular kind of semi-stable attractor. Thus, we have examples of systems moving back and forth between two semi-stable attractors, which is phenomenologically analogous to what can be observed in the Holling cycle. In the case of the Holling cycle, given the complexity of the ecological successional sequences required to move from a state of thermodynamic equilibrium to thermodynamic disequilibrium, it is more likely that the Holling cycle is comprised of a snap-back repellor, representing thermodynamic equilibrium, coupled with a dominating chaotic semi-stable attractor, representing thermodynamic disequilibrium.

Thus, there may be a large number of semi-stable attractors dominating the ecosystem dynamics within a Holling-type cycle. For example, a grassland in which water is available in abundance, but not so abundantly as to cause flooding, is vulnerable to invasion by trees. First a conifer forest will replace the grassland, and will in turn be replaced, in temperate climates, by a deciduous forest or a mixed conifer/deciduous forest. However, if water is scarce during some seasons of the year, natural fires are frequent and will stabilize the grassland relative to invasion by trees. In some areas, then, the grassland may be seen as a semi-stable attractor, and as a stable attractor in drier conditions.

Since the time period between dry periods may be a random variable (owing to chaos in the system or in the inputs into the system), it may happen that a period between dry periods is sufficiently long for trees to get established to a size where they are invulnerable to grass fire events. These trees will, in due course, lead to better water retention in the system, leading to a reduced frequency of fire, and ultimately to replacement of the grassland by forest. Relating this to environmental management, grass fire suppression may destabilize the very system that the management is intended to protect in exactly the same way that forest fire suppression may destabilize the forest that the forest fire suppression is intended to protect! On the other hand, some of the uses to which grassland is put, such as grazing land for livestock which prevent the establishment of trees, or land uses in which the grass in continually mowed, may serve to stabilize an otherwise semi-stable or even unstable ecosystem.

Hansell *et al.* (1997) suggest that certain landscapes that have been on phase 2 for a remarkably long period of time, may thus be on a semi-stable attractor despite changes in climate and the land use of the surrounding area. It is quite likely, for a number of reasons, such as a human desire to preserve a landscape in a certain state, that there are several land use systems that have been or are on semi-stable attractors. Without knowing when they arrived on their semi-stable attractors, or even if they are on a semi-stable attractor, any decisions based on purely empirical data carry a great deal of risk.

To deal with this risk, one must develop an adequate and reliable model for the ecosystem of interest and analyse this model for the presence of semi-stability. If one can then demonstrate that the attractor corresponding to the empirical time-series data is stable, then prediction remains possible. If it is semi-stable, then one must resort to Monte Carlo simulation methods to obtain statistical predictions for any future time. Only this limited, probabilistic kind of prediction is possible with semi-stable attractors.

The study of structural stability has significant implications for non-autonomous systems, systems whose parameters change through time. If one could assume that the system under study is autonomous, one could assume that it is sufficient to enumerate all stable and semi-stable attractors. One would have no reason to expect that the nature of the dynamics of the system might change. Now, given that most natural systems are open, subject to inputs that may change through time, one must examine the structural stability of each system studied. Fortunately, there are mathematical and computational methods for doing so.

It is possible to determine the circumstance under which one attractor will disappear and another attractor will appear, and when change owing to structural instability will occur. To do so, one must consider two aspects of the eigensystem of the Jacobian of the dynamic system. The eigenvalues of the Jacobian describe how distances in the direction of the eigenvectors change. If the eigenvalues are negative (for continuous time models), or less than one in absolute value (for discrete time models), the distances contract, remaining unchanged for eigenvalues of zero (for continuous time models) or one in absolute value (for discrete time models), and expanding otherwise. Eigenvalues that are very large negative numbers (for continuous time systems) or very small in absolute value (for discrete time systems), imply rapidly shrinking distances. If the system is subject to perturbation (as are all natural systems), and simultaneously the rate at which distances shrink along one eigenvector is reduced, the variance in the direction of that eigenvector must increase.

LAND USE MANAGEMENT IN THE HURON NATURAL AREA

An example of land use management is presented to illustrate: (1) how to apply the theoretical concepts of the Ecosystem Approach; (2) the types of questions that can be addressed from the perspectives of BAHC and LUCC; and (3) the role of science in formulating a land use management plan. The example of the Huron Natural Area (HNA), in Kitchener, Ontario, Canada, is typical of many municipal land use decisions in industrialized nations, in the sense that the development of green spaces is often a major component of any sustainable development policy in urban areas.

Typical of south-western Ontario in general, the Kitchener area has undergone extensive urbanization. This process of development has resulted in a fragmented landscape resembling a patchwork of remnant forest cover. A large part of the Kitchener area, including the site itself, is comprised of forest remnants. In particular, the area including the site had been zoned for industrial use to assist putting lots on the market. The city of Kitchener facilitated sewer and water services for the area, but during the site planning process the local ecological diversity and potential for a natural park became evident.

The Huron Natural Area is an area of approximately 150 hectares within the city of Kitchener bounded by major roadways and with a business park immediately adjacent. It is bisected by Strasburg Creek, a cold water stream supporting a population of brook trout (*salvelinus fontinalis*). The provincially designated Class I wetland known as the *Central Wetlands* forms the eastern boundary of the area. The HNA, located in the Strasburg Creek subwatershed, is part of the Grand River Watershed which, in turn, drains into Lake Erie in the Great Lakes Basin. The Huron Natural Area was originally settled, cleared and farmed in the late eighteenth and early nineteenth centuries. In the post-war years, the area succumbed to the increasing pressure of urbanization, and much of the land was taken out of agricultural production and converted to industrial and residential uses.

The site is characterized by a variety of ecological features, including pine plantations (*Pinus resinosa* and *Pinus strobus*), climax maple beech forests (*Acer saccharum* and *Fagus grandifolia* dominating), regenerating old farm fields, ponds, a dry marsh, varied topography and groundwater recharge areas critical to the Strasburg Creek ecosystem. The biological diversity found in the 14 different vegetation zones comprises 276 plant species, and there exists a variety of representative glacial landforms. These features and the range of microclimates they support, combined with the hydrogeological regime and the presence of Strasburg Creek, represent an opportunity to retain a representative example of the landscape which once characterized much of south-western Ontario. The city of Kitchener, in co-operation with the Public and Separate School Boards in the Waterloo Region, made a commitment in 1990 to preserve and protect the headwaters of the Strasburg Creek and one of the few remaining biologically diverse landscapes within the city.

The goal and objectives of the Huron Natural Area Project reflect the value and vision statements of the stakeholders (comprised of representatives of the Steering, Citizens', Technical, and Master Planning Committees) and the identification of preferred system attributes, which were developed with input from the Citizens' Advisory Committee (HNAWG, 1995). The goal can be encapsulated in the following stakeholders' statement: 'Using our definition of ecological integrity, we want to develop an ecosystem-based management approach and complementary monitoring program which allow us to use the site sustainably while maintaining the valued ecosystem features.' Here, ecosystem integrity refers to the ability of the system to maintain its organization and continue the vital process of self-organization following changing events.[5]

Within the context of the project goal, there are three key objectives:

1. to promote an awareness of natural ecosystems as functioning, dynamic entities;
2. to improve linkages between ecosystem science and municipal land management decision making within the region of Kitchener–Waterloo; and
3. to use the information gathered through the monitoring programme to inform directly and specifically the planning and management process on a continuing basis.

The promotion of these objectives will be through the development of a series of demonstration projects within the HNA and related activities at local schools and universities.

A variety of ecosystem studies have been undertaken over the past seven years emphasizing the abiotic, biotic, cultural and energetic organizing principles [see Nelson *et al.* (1988) for more detail on the abiotic–biotic–cultural method] that are particularly relevant to BAHC and LUCC (Geomatics International, 1992; HNAWG, 1995). The abiotic features include characteristics of the climate and hydrology. The biotic features include wildlife and community studies as well as individual species and population inventories. The cultural features include human use of the area, the cultural value and the history, and the energetic features include flows of energy and nutrients. The relevant principles for the HNA have been characterized at a variety of scales ranging from the community and Strasburg subwatersheds to the Great Lakes Basin, to

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[5] Specifically, an ecosystem is in a state of integrity when three key characteristics are present: (1) ecosystem health — the system is in a state of health, when it can maintain normal operations under normal environmental conditions; (2) resilience — the ability to cope with stress in a changing environment; and (3) the ability to continue the process of self-organization on an on-going basis. The latter two characteristics differentiate ecosystem integrity from ecosystem health. The notion of ecosystem integrity is discussed in detail in Kay (1991) and Woodley *et al.* (1993).

identify the full geographical context that influences the HNA. The next steps will involve using ecological analyses and the results of preliminary monitoring data will be used to construct possible future ecosystem scenarios (attractors, figure-eights, etc.), and these will be used to identify the necessary trade-offs and planning options, with guidance from stakeholders.

The preferred system attributes and their attractors have already been identified through the management goal and objectives. In particular, the stakeholders wish to preserve a wide biological diversity including both the brook trout population in the Strasburg Creek and the beaver (*Castor canadensis*) ponds for educational purposes. The construction of conceptual figure eights are necessary to identify how interactions with the full geographical context.

Attractor identification is being undertaken through ecological system description and analysis, from which management units will be mapped, and corresponding management strategies and monitoring plans derived. At present, two preliminary attractors have been identified, based on self-organizing Holling figure-eights described in the HNA. The first attractor supports a slow moving, low oxygen, warm water stream interrupted by ponds and small wetlands, in which beaver (*Castor canadensis*) and muskrat (*Ondatra zibethicus*), for example, are dominant species that shape and maintain the habitat and its constituent communities. The current ecosystem state is tending towards this attractor because of several factors, including, for example, the resident population of beaver (*Castor canadensis*), invading purple loosestrife (*Lythrum salicaria*) and increasing nutrient-rich runoff from nearby agricultural areas, which lowers oxygen supply in the stream. The competing attractor is a fast moving, highly oxygenated, cold water stream, in which brook trout thrive and which does not support the pond communities. The latter attractor is perceived to be highly desirable, but probably requires intensive human management to maintain.

From the preliminary identification of the above attractors, there are several issues that have emerged, some of them unexpected, which must be dealt with in pursuing the vision for the HNA (Kay, 1994). There are concerns about the effect on the wetlands of changes to existing drainage patterns with the construction of new subdivisions around the site. Invasion of purple loosestrife (*Lythrum salicaria*), if unchecked, will change the wetland to a dry ecosystem, and an unmanaged beaver (*Castor canadensis*) population could, over time, displace the brook trout population. Continuing and/or increasing runoff from fertilizers and cleared land is introducing a phosphorus loading into the area which results in eutrophic conditions that favour other species.

At this point in the development of the management plan, the preliminary development of simulation models, including an analysis of semi-stability, could provide decision makers with some sense of how the ecosystem might respond to different interventions. However, as the plan development will in turn affect the assumptions about the different system parameters that are used in the simulation models, the process of developing a management plan, by necessity, must become an iterative process, wherein the results of modelling experiments feed into the planning process and the results from the planning process feed back into the model development. This iteration process continues until performance to within some predefined tolerances is obtained or observed, or it is used in a longer term process in which the management of the HNA is continuously adapted to its external environment. It is interesting to note that all of the above issues underlie the role of value judgments, i.e. beaver versus trout, and the need to manage interactions at the boundary of the HNA.

This analysis also provides some insight into a specific role for BAHC and LUCC. For example, land use planning must deal with changes to the surrounding drainage patterns and the associated ecological communities. This requires an understanding of how evapotranspiration and precipitation may change, at different scales, with changes in land use, how these hydrological and climatological changes could affect surface and subsurface flow, as well as scenarios for possible land use changes in similar situations. In addition, management of the HNA will also be contingent on the changing hydrology of the Grand River watershed which could suffer effects through changes in land use and changes in climate. In particular, regional climate changes at the scale of the Great Lakes Basin could be partly addressed through the use of the downscaling methods developed in BAHC and referred to in the Introduction.

The decisions involving the HNA suggest the types of models that, if they were developed, could be adapted to the implementation of sustainable development policies. If these models were analysed for semi-stability, although parameter values and even model implementation might be different for the HNA, they would provide guidance to the formulation of land use management plans and where to look for surprise and uncertainty.

It is interesting to note that underlying the immediate concerns with the external environment are the longer term concerns associated with emergent complexity, uncertainty, limited predictability and surprise. In general, policy makers do not want to be presented with these long term concerns, and, at least in dealing with uncertainty, this has created a gap between science and policy. The Huron Natural Area Project is unique in this respect because the management is adaptive — allowing the HNA to manage itself essentially, with minimal and select human intervention, and dealing with management at the boundary with the external environment. The management is also anticipatory — monitoring various ecological and hydrological parameters, and, while not using models to predict the future, using models to identify trade-offs and test assumptions.

THE ECOSYSTEM APPROACH: SCIENCE AND POLICY IMPLICATIONS

Convergent with recent advances in non-equilibrium thermodynamics and complex ecosystems science, the environmental policy/planning literature has begun to acknowledge the implications of these newer scientific understandings and has considered policy responses that include, for example, adaptive management (Holling, 1986; Lee, 1993), sustainable development (WCED, 1986), cumulative effects monitoring (MacViro Consultants Inc., 1995) and post-normal science (Funtowicz and Ravetz, 1993). An integrated policy response, the Ecosystem Approach, has recently become an accepted concept in the environmental policy/planning literature (e.g. OMOEE 1994, RCFTW, 1992) and is now emerging in a cross-disciplinary hybrid of science policy planning literature (Davies, 1991; Allen *et al.* 1993; Kay, 1994). It has been advocated by a wide variety of both public and private environmental planning and management agencies in Ontario since the mid-1980s, [6] initially as a response to environmental degradation and, more recently, as an attempt at proactive prevention of further degradation or impairment of vital ecosystem functions. It is in the proactive context that the Ecosystem Approach may be most useful in BAHC and LUCC research programme and related decision making.

In general, the Ecosystem Approach refers to a holistic means of conceptualizing humans and their interactions with the environment, recognizing basic ecological principles, and placing equal emphasis on economic, social and environmental issues. As such, it is principally heuristic. More specifically, the Ecosystem Approach is defined as the 'integrated management of natural and managed landscapes, ecological processes, physical and biological components, and human activities, designed to maintain the integrity of an ecosystem' (Environment Canada, 1994). In this latter context, the Ecosystem Approach is essentially an integrated set of policies and management practices that relate humans to the ecosystems that sustain them.

There are at least two generalized contexts of application for the Ecosystem Approach, related to its definitions. In the first context, an heuristic, it is often used as an *epistemological approach* to understanding the human place in nature. Until recently, the term has been most frequently used in this context, i.e. to guide (or even command) an attitude of respect and stewardship, and a management philosophy of participation in, rather than dominance over, the natural world (Bell, 1994). Yet the growing usage of the term in policy, planning and management literature requires a more pragmatic and operational definition. Thus, in the second generalized context, the Ecosystem Approach may offer guidance as a *decision making approach* to environmental or land use planning and management.

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[6] For example, in reports of private environmental consulting firms, public conservation authorities' watershed studies, municipal planning documents (Metro Waterfront Plan, 1991) and policy statements (OMOEE, 1994).

There are essentially two phases of an Ecosystem Approach to decision making. The first phase is that of information gathering and knowledge generation through scientific analyses, and the second phase is that of knowledge use or synthesis in providing decision making support in the form of management practices. Information gathering results in knowledge generation largely through ecological and other scientific analyses, including research, field studies and monitoring. Knowledge use or synthesis is the responsibility of environmentally based management, including policy and planning. Using the Ecosystem Approach (epistemologically and methodologically), scientific research may generate information and knowledge that is used to inform and support — *but not to determine* — planning and management decisions. This renders the planning and management phase of decision making essentially a political process.

In this sensibility, the Ecosystem Approach requires that the sciences and resulting analyses be used to develop alternative scenarios, illuminate their trade-offs and identify management options, which should then be negotiated through value-laden judgments.[7] It is in this way that the Ecosystem Approach differs most significantly from traditional management approaches. Also, it is important to understand that these phases do not occur in linear sequence, but rather cyclically and iteratively; i.e. each informs the other and, as necessary, adaptive adjustments to the decision making process are made. Hence, the Ecosystem Approach to decision making is both adaptive, in a manner similar to that proposed by Lee (1993), and dynamic, requiring continual learning through experimentation, monitoring and information feedback (Kay and Schneider, 1994; Lister, 1998).

From the theoretical bases and the example of the HNA articulated in the previous sections of this paper, and drawing on the policy, planning and management literature, we can distil a set of generic system characteristics. From each system characteristic, we can derive a basic guiding principle or axiom — adapted from Kay (1991, 1994), Kay and Schneider (1994), Lister (1996, 1998), Senge (1990) and Slocombe (1993) — for ecosystem-based research, planning and management.

- **System characteristic 1: complexity**. Ecosystems and land use systems are open, self-organizing, and highly complex, such that their behaviour and functions are the result of an infinite number of structural and process interactions and other system variables. The ability of management to predict and control system change is poor, while the possibility of unintended consequences is good.

  Principle. Precautionary — favour 'safe-fail' management options and reversible strategies. This principle is being followed in the HNA through addressing the effect of subdivisions on drainage patterns and restricting purple loosestrife and beaver populations whose effects could be irreversible on a management time-scale.

- **System characteristic 2: non-linearity**. Linear cause and effect relationships are rarely established and almost never predictable in a deterministic sense. Quantitative anticipatory models as well as qualitative description and analyses, offer richer management potential than any one tool alone. Limited predictability requires a hybrid of research and analytical tools for adaptive management.

  Principle. Diversify decision support tools and management strategies. In managing the HNA the decision support tools include monitoring and could include modelling. The management team is also highly diversified as is the scientific expertise, which includes consultants, university researchers and students, and local citizen's groups.

- **System characteristic 3: surprise**. Ecosystems follow discontinuous and non-linear paths of development that are usually punctuated by sudden and often unpredictable change events, which are occasionally catastrophic. Synergies, cumulative effects and emergent properties regularly occur.

  Principle. Expect the unexpected. An analysis of semi-stability provides insight into the where and when of some unexpected events.

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[7] This is discussed in more detail by Kay and Schneider (1994) and Lister (1994, 1998).

- **System characteristic 4: dynamic**. System structures are constantly changing as the systems follow figure-eight patterns. Perceived stability may be temporary and sudden change may occur without warning. Management must account for the presence of semi-stability as well as surprise.

  Principle. Strive for dynamic conservation rather than static preservation. This is a goal for the HNA, with its focus on adaptive and anticipatory management, but the implementation has not yet been determined.
- **System characteristic 5: multi-scaled**. Ecosystems undergo dynamic patterns at various temporal and spatial scales. In addition, the local, regional and global operating scales of an ecosystem should be recognized in the decision making context, both ecologically and culturally. No system description or analysis can be meaningful unless the immediately relevant scales of interest and the wider context are identified.

  Principle. Recognize ecological scale(s) and learn historical context. In developing a management plan for the HNA, the recognition of the ecological scale has been incorporated in the use of the abiotic–biotic–cultural method. The historical context has been reconstructed through the use of old photographs and personal narrative.
- **System characteristic 6: uncertainty**. All ecosystem characteristics, particularly complexity, self-organization, non-linearity and surprise, result in uncertainty surrounding the system's behaviour, function, trajectory and future structure. Uncertainty in scientific understanding is exacerbated in decision making and resulting management strategies.

  Principle. Learn by doing: experiment, monitor results modify plans. The Huron Natural Area Project is monitoring various system parameters related to ecological integrity.

These guiding principles illustrate the heuristic value of the Ecosystem Approach to decision making. In a heuristic sense, the Ecosystem Approach offers *guidance* to thinking, rather than *rules of practice* — and that is its strength as a policy support tool. Acceptance of the Ecosystem Approach from an epistemological standpoint results in profound implications for policy and science. Essentially, it challenges policy makers to reform decision making from control-oriented, predictive *management of the environment* to adaptive, and flexible *management of human activities* within the environment to cope with uncertainty and surprise. The challenge for science lies in identifying the dynamics of change, such as the figure-eight, and identifying where the uncertainties and the limitations to prediction are most important. Scientific research can also play a large role in identifying future scenarios, which is an aspect of the IGBP, and trade-offs and using models to query assumptions.

A framework for the ecosystem approach

From the guiding principles above we can advance a framework for the Ecosystem Approach to inform ecosystem-based planning and management pertaining to land use and land cover change. The framework for the Ecosystem Approach consists of 10 iterative steps in a cycle (Figure 2)..

1. *Valuate*. Explicit identification of expert and stakeholder values for the system of interest, including problem and conflict identification.
2. *Vision*. Vision statement of the future, regarding desired land uses.
3. *Plan 1*. Translate vision statement into planning goals.
4. *Describe*. Describe and define the relevant systems and subsystems and the scales of analyses within a regional, or larger if necessary, hierarchy.
5. *Analyse*. Systems analyses including definition of Holling figure-eight(s), attractors, semi-stable attractors, current state and experimentation and/or modelling.
6. *Synthesize*. Synthesize scientific and sociopolitical analyses to create possible future scenarios, and generate alternatives.

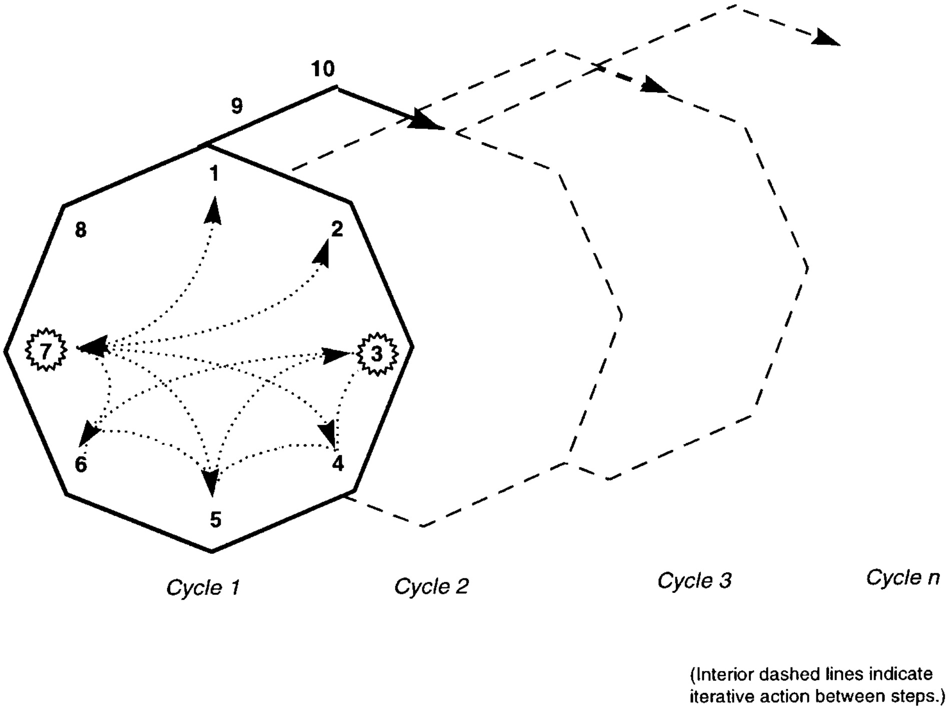

Figure 2. A framework for the Ecosystem Approach: an adaptive and iterative planning cycle (Lister, 1988). Key 1, valuate; 2, vision; 3, plan 1; 4, describe; 5, analyse; 6, synthesize; 7, plan 2; 8, implement; 9, learn; 10, adapt; ≫ shift to next cycle ...

7. *Plan 2*. From synthesis, add to planning goals: management objectives, operating criteria and output targets.
8. *Implement*. Develop land use plan and derived management strategies, and implement.
9. *Learn*. On-going monitoring and experimentation.
10. *Adapt*. Evaluation of results, on-going feedback and adjustment of planning goals, objectives and management strategies as necessary.

As illustrated in Figure 2, the definition of a management plan is iterative. At any step, it may be necessary to return to an earlier step in the process. For example, the analysis in steps 4–6 may necessitate a revision of the planning goals in step 3, which may require a reiteration of steps 4–6 before proceeding to step 7, where the goals are augmented by objectives, operating criteria and targets. The augmented management plan in step 7 may require a rethinking of step 1 (the values) or step 2 (the vision statement). The results of step 10, which implies that the plan has already been implemented with sufficient monitoring, may require a return to steps 1, 2, 3 or 7. Returning to these steps, after the evaluation in step 10, is represented in Figure 2 as a shift to the new cycle. A long-term management plan is continuously iterative in that evaluation, feedback and adjustment of the goals are built into the management plan.

Steps 4–6 concentrate on the history and scale of different processes in the ecosystem. Because these steps are integrated into a larger management framework, steps 4–6 could be repeated through multiple iterations, and this iterative process can detect the presence of multiple attractors or semi-stability. If the monitoring, feedback and reiteration indicate the presence of multiple attractors or a semi-stable attractor, the management plan can be adapted and surprises can be anticipated, although not necessarily predicted in a rigorous quantitative manner. This underlies the importance of steps 9 and 10 in any management plan (Lee, 1993).

Although much of the discussion in this paper has focused on step 5 and the latter steps of the Ecosystem Approach, the importance of the vision statement should not be overlooked. The vision statement is a reflection of value judgments and stakeholder input. It sets the context for the development of a land use plan, and, more importantly, for scientific research and modelling. For example, a vision statement for a particular forested area would be very different if it has to reflect the objectives of the pulp and paper industry as well as environmental groups. Similarly, a plan to preserve biodiversity will very much depend on the initial vision, whether it focuses on the preservation of specific species or on specific ecosystem functions (Bass, 1996; Lister, 1998). It is the vision statement for the HNA, translated into goals and objectives, that provides a context for assessing the effect of changing drainage patterns, invasion by other species and phosphorus loading.

This 10-step process confines the role of science primarily to steps 4–6, and places it in a context of goals and objectives for management. A combined BAHC–LUCC research agenda could contribute to these steps, and is particularly important in step six, where different types of research are synthesized. The scientific role is clearly driven by the goals and objectives of management for a specific land use decision while the agendas of BAHC and LUCC are driven by scientific aims. Perhaps the largest challenge for BAHC, LUCC and the IGBP, in moving from science to sustainable development, is to find a way to be able to present their results so as to fit a local policy agenda on land use change. One approach is to examine various types of land use decisions, and recast them according to the Ecosystem Approach, in order to identify the types of scientific research required for different management decisions. It was in this context that the Huron Natural Area Project was presented as an example of land use management.

The Ecosystem Approach framework has grown out of Holling's (1986) notion of adaptive management. While it is becoming more widely accepted that ecosystems do not lend themselves to management in the strict sense of 'control' as in closed systems, the applied practice of adaptive planning and management is still in its infancy (Lister, 1998). Further research is needed, especially in the design stages of ecosystem mapping and definition of management units, as well as monitoring and feedback of 'learned' information. These areas of applied practice, coupled with case studies, are required to refine the approach and build a portfolio of success stories that can be used to attract the policy community. Furthermore, long-term, multi-scalar data are essential for attractor analyses, many of which are likely to be context dependent. These areas of research, both in theory and applied practice, should provide fertile ground for future cross-disciplinary research between BAHC and LUCC.

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