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Future landscapes: managing within complexity

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A regional landscape is a complex social–ecological system comprising a dynamic mosaic of land uses. Management at this scale requires an understanding of the myriad interacting human and natural processes operating on the landscape over a continuum of spatial and temporal scales. Complexity science, which is not part of traditional management approaches, provides a valuable conceptual framework and quantitative tools for dealing with cross-scale interactions and non-linear dynamics in social–ecological systems. Here, we identify concepts and actions arising from complexity science that can be learned and applied by ecosystem managers and discuss how they might be implemented to achieve sustainable future landscapes.

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It is unlikely that the multiple objectives of current ecosystem management frameworks can be met without managing at the scale of regional landscapes. Environmental managers in many parts of the world are increasingly faced with the task of implementing policies that optimize land use to meet regional objectives specifying the maintenance of ecosystem services, while at the same time maintaining other aspects related to the quality of life and prosperity of human communities. Doing so is a multi-criteria optimization problem to which several social and economic constraints are added (Figure 1). Environmental conservation is only one form of land use within a landscape that is increasingly dominated by urbanized areas and production ecosystems (Foley *et al.* 2005; Fischer *et al.* 2006).

Regional landscapes can be viewed as coupled social–ecological systems that include a dynamic mosaic of different types of land use (Liu *et al.* 2007b). Changes to the landscape and choices regarding how ecosystem goods and services are used in a region are the result of multiple trade-offs and negotiations between different stakeholders, ranging from individual landowners to government institutions (Folke *et al.* 2002; Dietz *et al.* 2003). Developing desirable and renewable future landscapes in this context will require visionary management policies and scenario-building based on multidisciplinary frameworks founded in complexity science. Here, we provide an overview of the key attributes of complex systems, discuss the implications for the management of regional landscapes, and offer some guidelines that should assist managers to "manage within complexity".

In a nutshell:

- A regional landscape is a complex system in which human and biophysical processes are intricately linked across multiple scales of space and time
- Planning and intervention at the scale of regional landscapes will require new methods of integrated resource management in which the various components and processes in a landscape are not treated as decoupled entities
- Complexity science can provide useful quantitative and conceptual tools to guide management decisions in this context
- Incorporating complexity into the management process is an essential step in attaining sustainable landscapes that are resistant and robust to future human and environmental disturbances

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The landscape as a complex system: key concepts for managers

Long-standing approaches to landscape and ecosystem management are being replaced by paradigms that accept that landscapes are complex social–ecological systems, characterized by uncertainty and emergence – the sometimes unexpected patterns and processes that arise at the system level and are the aggregate result of local interactions between system components (Folke *et al.* 2002; Liu *et al.* 2007a, b; Lindenmayer *et al.* 2008; Norberg and Cumming 2008). The dynamics of complex systems are inherently unpredictable as a result of non-linear relationships, feedback between emergent patterns and processes and the components that created them (Figure 2), and (in many cases) constantly changing external drivers or boundary conditions. Natural landscapes are the result of many interacting processes operating over a continuum of spatial and temporal scales. Human activity on the landscape may affect these processes at many different scales; one of the major challenges of landscape management is to recognize the multi-scale nature of human impacts and to assess how key environmental processes will be affected both in the present and future. Doing so requires an understanding of both complex systems dynamics and the ways in which seemingly small interventions can sometimes lead to system-scale impacts via phenomena that link processes across scales.

When landscapes are envisaged and managed as complex systems, the understanding, planning, and implementation of management actions are likely to be different from current practice (Harris 2007; Norberg and Cumming 2008). Although there is no universally accepted definition of a complex system, most researchers would agree that a complex system (1) is composed of many interacting components and (2) has structure and dynamics that are the collective result of these interacting components and are thus difficult to analyze or describe using only one scale or resolution (Simon 1962, 1976; Parrott 2002; Mitchell 2009). This definition encompasses a diverse class of biological, social, and technological systems, ranging from unicellular organisms to the internet. These systems all share many characteristic features, including: cross-scale linkages, emergence, non-linear dynamics, uncertainty, and memory (in the form of historical legacies that persist in the system's structure and functioning) (Levin 1999; Phillips 1999; Liu *et al*. 2007b; Ryan *et al*. 2007). In this section, we describe how each of these five features occurs in landscapes in the form of key concepts that should be used and applied by managers.

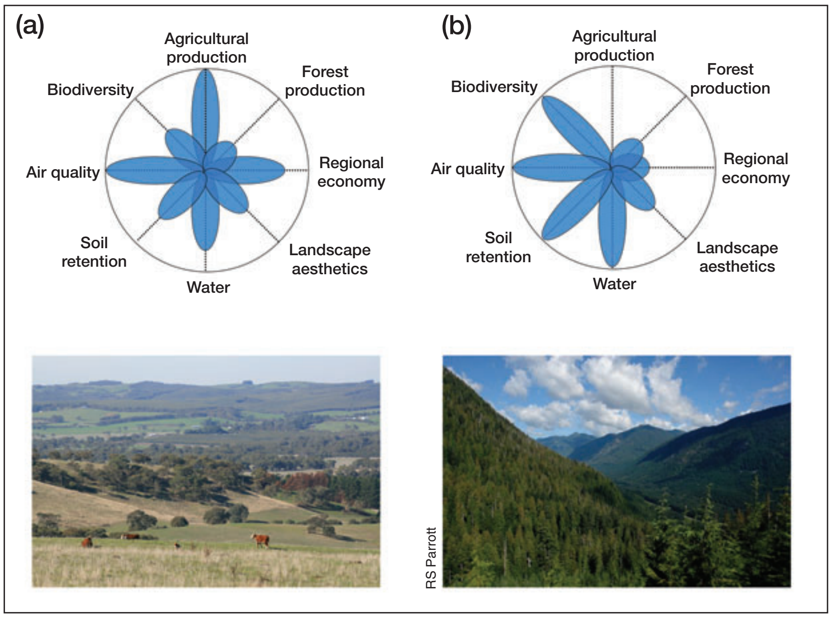

Figure 1. *Regional landscape management as a multi-criteria optimization problem. The objective of any management scenario is to maximize ecosystem services and community well-being within a landscape. Choices will result in trade-offs between competing objective functions. In these two examples of multi-use landscapes, a few of the services that a manager might wish to maximize are shown as axes on the "flower". The relative size of the "petals" indicates the degree to which each service is provided (figure inspired by Foley* et al. *2005). (a) A South Australian rural landscape. (b) Seymour River watershed, Greater Vancouver Regional District, British Columbia, Canada.*

Concept 1: cross-scale linkages – human and biophysical components are connected across multiple scales

Landscapes, like all complex systems, have a hierarchical structure (Figure 2; Pattee 1973; Ahl and Allen 1996). Like a Russian nested doll, a landscape is composed of systems made up of systems. This conceptualization, common in ecology, is fundamental to understanding and interpreting the dynamics of a complex system (Simon 1962; Rosen 1987; Allen and Holling 2008). It provides a framework with which to explain many examples of emergence (Concept 2, below) as well as the potential for interactions between processes and entities across hierarchical, spatial, and temporal scales. In keeping with geography's human-environment tradition, this framework acknowledges that the geophysical environment is not a fixed background but rather structures, and is structured by, human and ecological processes (Abel 1998). It also clarifies the necessity of considering all scales and potential interactions when studying, or applying interventions to, landscapes.

Concept 2: emergence – local-scale events may have system-wide consequences

The nature of complex systems is such that local interactions may trigger the emergence of patterns or processes at larger scales, which in turn affect and feed back upon the behavior of lower-level entities, creating a reinforcing cycle (Figure 2). A classic example would be the formation of vegetation patches in arid ecosystems as a result of positive feedback between the presence of vegetation and the availability of water and nutrients (Rietkerk *et al*. 2004). In this case, the seemingly random initial establishment of a plant on bare soil can give rise to the emergence of a patch of vegetation that is persistent over time. The emergence of cooperative systems of land sharing in arid rangelands is another example (McAllister *et al*. 2006); in this case, individual farmers managing grazing stock will dynamically adjust stocking densities and cooperative agreements with their neighbors in response to the availability of forage at the local scale. This collective behavior gives rise to emergent landscape-level patterns of forage availability that in turn feed back upon, and influence, the behavior of indi-

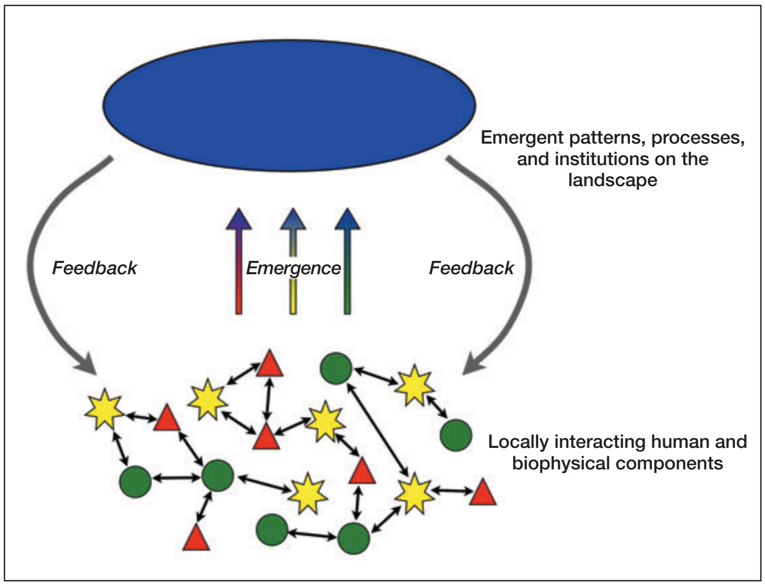

Figure 2. *Conceptual diagram of a complex social–ecological system. A regional landscape can be viewed as a complex social–ecological system composed of locally interacting, heterogeneous components whose combined behaviors give rise to emergent patterns, processes, and institutions on the landscape. Such emergent aggregates may arise at many scales (eg aggregates of aggregates) and are not necessarily the result of just two scales, as shown here.*

vidual farmers. Such emergent patterns and processes are often very difficult to foresee or predict from individual actions.

Concept 3: non-linear dynamics – landscapes are subject to continual change

Regional landscapes are dynamic systems; their states will change with changing external (eg climate, global economy) or internal (eg local community initiatives, interspecies interactions) drivers. In addition, this dynamic is non-linear and typically far from being in equilibrium, such that the response of the system may not be proportional to a disturbance or management intervention. Change can be continuous and gradual or in some cases – especially episodic events – dramatic and rapid. The concepts of stable equilibrium and final successional states therefore probably have limited relevance for regional landscapes, which are regularly shifting and re-organizing over decadal and longer timeframes (Harris 2007). On a more dramatic scale, there are also many examples of ecosystems that change rapidly from one state to another as a result of the removal of an important structural (internal) or environmental (external) driver (Scheffer and Carpenter 2003). Classic examples include the shift in marine ecosystems between kelp forests and rocky sea bottoms overgrazed by sea urchins as a result of removing fish and lobster stocks (Hughes *et al.* 2005) and the shift between grass- and shrub-dominated systems in Australian rangelands as a result of specific sequences of wet periods, fire, and drought (Walker 1993).

Concept 4: memory – the current state of a landscape is a function of its history

Historical events (or "accidents of history") may often have a pivotal effect on the future trajectory of a complex system. This is especially true for landscapes, where historical land-use practices or interventions often have a legacy effect on the system (MacNally 2008). For example, land use in France during the time of Roman occupation (CE 50–250) is still detectable in chemical and structural soil properties, affecting patterns of species richness and community composition in contemporary forests growing on ancient agricultural and village sites (Dupouey *et al.* 2002). Similarly, different plant species affect soil properties (Lucas 2001); these effects become more or less permanent and the succession of species associated with this soil–plant interaction results in a persistent vegetation type that limits use or colonization by other species. Another example is the legacy of raised mounds created by pre-Columbian peoples for agriculture in the flooded savannas of Amazonia, which still persist today (McKey *et al.* 2010). This originally anthropogenic modification has been maintained for centuries resulting from a complex system of feedbacks between ecosystem functioning and ecosystem engineers. Thus, understanding the history of a landscape is key to understanding how it reached its current state and is important for informing future management decisions.

Concept 5: uncertainty – prediction of a landscape's future state cannot be made with precision

Non-linear dynamics, feedback between entities at different hierarchical levels, emergence, and, for regional landscapes, constantly changing external drivers or boundary conditions (eg environmental variability, climate change, global economy) all contribute to future uncertainty. Consequently, the dynamics of complex systems are sometimes statistically predictable (eg climate, the frequency distribution of forest fires) but cannot be predicted in detail (eg weather, the location and timing of forest fires). With our current understanding and tools, the best that we can do is identify the range of possible outcomes given our best estimates of likely future conditions. For instance, current models of urban growth may accurately predict the area of land that will be developed over a 20-year period but may not be able to identify the exact locations of new development projects (Brown *et al.* 2005).

■ Management actions for complexity

While there is no clear guidance for managers on how to manage within the framework of complexity, there are several actions that can be taken in response to some of the known properties of complex systems. In this section, we summarize current thinking on this subject in the form of a list of five actions, each linked to one of the key concepts identified above. A case study is given in Panel 1.

Action 1: work with a conceptual model of the landscape as a complex system

Managers should start by developing a model of their system and its subsystems, identifying hierarchical levels, linkages, interactions, and feedbacks. This model may take the form of a simple schematic, a sophisticated network representation, or any other conceptual representation of the tangled web of interacting entities within the system. By embracing this new conceptual model, each subsequent management action can be framed in terms of which entities or processes will be affected, either directly or indirectly. Our experience has been that the development of a simple, diagrammatic representation of the system being considered is both vital and powerful. Development of such a diagram will facilitate the critical process of making explicit the differing mental constructs of various stakeholders. A well-facilitated process engenders communication, engages stakeholders, and provides a common picture around which the vision and goal can be developed. Subsequently, all actions can be framed to explicitly contribute to the agreed goal. An excellent case study that applies this action to the ecosystems in the Greater Yellowstone region of Wyoming can be found in Bennett and McGinnis (2008).

Action 2: understand and document emergent patterns and processes by monitoring the landscape at multiple spatial and temporal scales

Managing a landscape as a complex social–ecological system requires a thorough understanding of the different interactions that may lead to emergence. New conceptual models (Action 1) and effective monitoring will be necessary to achieve this goal. Most landscape changes are the result of the cumulative, emergent effects of repeated small disturbances that may link processes across scales, and that often occur over generational timeframes. Given the shortcomings of human memory, such changes often go undetected and are only recognized in retrospect, after a major collapse of one or more environmental processes in the system. For example, the clearing of perennial vegetation from large areas of Australia (for "development" of agricultural areas) and its replacement with mainly annual crops has caused small changes in the soil water balance, such that slightly larger amounts of winter rainfall move past the root zone and into the regional groundwater systems. Over time, the groundwater systems have become more active, discharging larger volumes of very old, saline water into the rivers and low-lying areas of the landscape. In effect, persistent small changes in land use and associated vegetation triggered a new hydrologic state, the consequences of which will continue for many decades (Williams *et al.* 2001). In retrospect, a long-term and spatially distributed monitoring scheme might have foreseen this transformation. A well-structured and rigorous monitoring scheme, with extensive sampling at multiple scales in space and time, is therefore necessary to assess and quantify gradual change in a landscape (in addition to more rapid change) and can help to identify key linkages between subsystems and across scales. New initiatives, such as global-scale biodiversity monitoring programs (Malone and Cole 2000; Pereira and David Cooper 2006; Scholes *et al.* 2008) and programs that link satellite monitoring with automated sensor networks, are a first step in this direction (Hart and Martinez 2006). Methods developed in complexity science can help to identify whether the system under study shows scale-free properties or has characteristic scales that should be the focus of monitoring programs (Brown *et al.* 2002; Habeeb *et al.* 2007).

Action 3: build and maintain adaptive capacity to buffer against change

Current literature discusses the importance of maintaining the adaptive capacity of social and ecological systems as a means of increasing a system's resilience, or ability to persist and recover from the cumulative effects of multiple disturbances over time (Folke *et al.* 2002; Hughes *et al.* 2005; Cumming 2011). This may be achieved by providing landscapes with enough redundancy, and structural and functional complexity, so that they can recover from disturbances. A simple example is that of maintaining biodiversity, which provides some redundancy in the functioning of an ecological community. In more general terms, it is important to have multiple pathways for transferring energetic and material flows, so that if one pathway is affected, essential ecosystem services are still maintained. This redundancy needs to be balanced, however, against the notion of excessive "baggage" that might come from trying to be prepared for all possible outcomes. For this reason, adaptability is also an essential feature of a healthy regional landscape. A system that is capable of rapidly modifying its structure or other characteristics should be better able to adapt to and absorb change. One of the problems in managing regional landscapes is the cultural and institutional inertia that exists in the system, complicating rapid responses even when environmental indicators signal impending change or deterioration in key ecosystem services (Liu *et al.* 2007a). Contemporary management literature is calling for schemes of "adaptive co-management", which combine the dynamic learning aspects of adaptive management with the cross-institutional linkages and social networks used in cooperative management schemes (Olsson *et al.* 2004; Armitage *et al.* 2008). A flexible and well-linked network that connects institutions across multiple scales of governance will

Panel 1. Managing for complexity: the case of the St Lawrence estuary

The St Lawrence estuary in Quebec, Canada, is a land- and seascape in which human and biophysical components are intricately linked (Figure 3). The estuary is an area of exceptional biodiversity resulting from the unique oceanographic conditions that lead to mixing of different currents with distinct salinity, temperature, and oxygen profiles. The estuary is home to many species of marine mammals, including a resident population of beluga whales (*Delphinapterus leucas*) and migratory whales that come to feed during the summer season. The estuary is also an area of extensive human activity, both on land and water. Multiple human communities along its shores depend largely on natural resources and the tourism industry for their economic well-being. On the water, an extensive network of maritime traffic, including ferries, cargo ships, pleasure craft, and whale-watching boats, traverses the estuary.

In 1998, a national marine park (Saguenay–St Lawrence Marine Park; SSLMP), protecting most of the Saguenay River and part of the St Lawrence estuary, was established. A terrestrial park was created conjointly to protect adjacent shores, while a marine protected area covering the rest of the estuary not protected by the marine park has been proposed by Fisheries and Oceans Canada. The dynamics of this system occur on many scales, from the diurnal cycles of the tides to longer-term changes related to tourism demand, governmental priorities, and marine mammal population dynamics. All are interrelated, and there is the potential for a large-scale system shift in response to changing climate, new economic conditions, or a disturbance, such as an oil spill. There is also a richly connected social network, with strong potential for organization leading to collective human responses to change coming from within or outside the system.

Here, we describe how the five actions suggested in this paper have been implemented in the estuary by managers working for the SSLMP and Fisheries and Oceans Canada.

Action 1: work with a conceptual model of the landscape as a complex system

Managers are well aware of the intricacies of the system and the importance of considering cross-scale linkages between human and biophysical processes and components. A diagram illustrating the system as a network of interacting components was produced by a multidisciplinary group of scientists and park managers (Chion *et al.* unpublished). This served to illustrate and highlight key levers in the system and to identify at which scales management actions might have the most impact. A very simplified version is shown in Figure 4.

Action 2: understand and document emergent patterns and processes by monitoring the landscape at multiple spatial and temporal scales

Fisheries and Oceans Canada and Parks Canada have invested extensively in monitoring both human activities and the marine environment. An emphasis has been placed on long-term, consistent monitoring programs that will document changes over multiple scales of space and time. Data collected include: real-time movements of ships; samples of whale-watching excursions (GPS tracking of the trip and notes of all observations made during the trip); land-based observations of whales and boats; transects of the park to detect and map pelagic species, marine mammals, and birds; surveys of tourist activity; and statistics on numbers of land- and sea-based visitors. Monitoring is repeated each year to provide long-term data on patterns and trends in the system. Monitoring protocols are adapted as necessary, to incorporate new requirements or to better meet the needs of scientific analyses.

Action 3: build and maintain adaptive capacity to buffer against change

One way to maintain the system's adaptive capacity is by preserving biodiversity. The creation of the SSLMP, which has a conservation mandate, was a first step in this direction. Additional provincial and federal laws and regulations mandate an ecosystem-based management approach to natural resource extraction, to reduce the impact that human activities may have on biodiversity. In the human system, adaptive capacity can be maintained by ensuring a flexible system of governance and effective communication between stakeholders. Several committees with representatives from all sectors oversee management of the region, and all new regulations are subject to public consultation. The SSLMP works extensively with the whale-watching industry to inform companies about proper codes of conduct on the water. All of these actions facilitate information flow, and the fact that formal stakeholder groups already exist arguably makes communities better prepared to self-organize and adapt to change.

Action 4: take advantage of the system's internal memory – mimic natural processes

This could be achieved in the estuary by establishing a dynamic zoning plan. Unlike traditional zoning, where the areas with use restrictions (eg navigation prohibited) are fixed, the zones could be established according to the rhythm of natural processes (eg depending on the cycle of the tide or on the reproductive periods of certain animals). In addition to being more responsive to natural processes, this type of zoning would increase the awareness of users and the public to the natural dynamics of the system and the timing of core activities (ie foraging or reproduction) of different species, resulting in a positive outcome for public education and species conservation. Second, an adaptive zoning plan could allow free access to certain areas during periods when they are not being used by a species for core activities, providing a compromise between conservation and human use. Implementation and enforcement of dynamic regulations and zoning would, however, pose considerable practical challenges and does require excellent knowledge of the system's dynamics. Currently, no such plan is proposed for the estuary.

Action 5: work with envelopes of possibilities and alternate futures

Models of the oceanographic environment, the marine ecosystem, and human activities on the water have been built to simulate alternate futures for the estuary and to explore the effects of different management actions on the system (Parrott *et al.* 2011). These models serve as decision support tools by allowing multipartite committees to gain greater insight into the possible responses of the system to proposed policies. They also help managers and stakeholders to better understand that the system is unpredictable and may exhibit multiple, and sometimes unexpected, responses to a given intervention.

facilitate information flow and aid in the success of community-based interventions, which may be more rapid in responding to perceived changes in resource availability (Dietz *et al.* 2003).

*Figure 3. View looking up the Saguenay River where it meets the St Lawrence estuary at Tadoussac, Quebec, Canada. The region is home to a resident population of beluga whales (*Delphinapterus leucas*) and is regularly visited by larger species of cetaceans. Competing economic, conservation, and recreational interests pose challenges for management of human activities in the region (see Panel 1).*

Action 4: take advantage of the system's internal memory – mimic natural processes

Landscapes have evolved over thousands of years, in conjunction with natural, and in some cases human, disturbance. The resulting ecological communities are the product of evolution and adaptation to these "known" disturbances; for example, species within many ecosystems have adapted to frequent fire events, and the vegetation in such systems depends on fire to regenerate and to maintain particular species compositions. Managers should therefore try to mimic natural disturbance regimes as much as possible. In the Canadian forestry industry, for instance, logging companies increasingly try to imitate the spatial patterns of natural disturbances, such as damage caused by fire or insects, when they plan where to harvest (Burton *et al.* 2003). Although important differences exist between forests that have regenerated after harvesting, as compared to those that have regenerated after a fire, for instance, natural-disturbance-inspired interventions are the foundation for new, sustainable forestry management plans (Bergeron *et al.* 1999). Similar ideas are being applied to stream restoration. Restoring river health and riparian habitat involves restoring the variability of natural flow regimes. In southern Australia, new water allocation operating rules have been negotiated, in which flow regimes are designed to favor connected wetland function and deliberate controlled flooding events are used to reconnect the floodplain to the river stem (White *et al.* 2008).

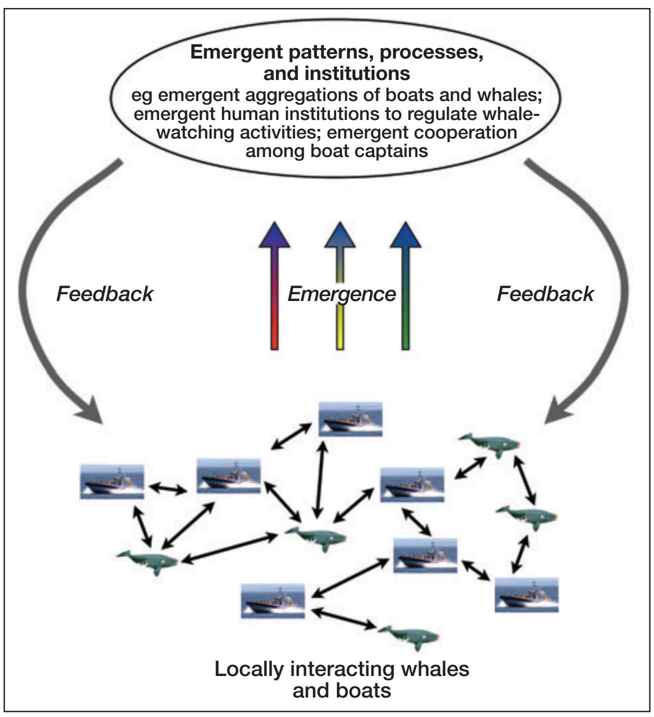

Figure 4. A simplified representation of the whale-watching system in the St Lawrence estuary (see Panel 1), based on the conceptual diagram shown in Figure 2.

Action 5: work with envelopes of possibilities and alternate futures

Given the inherent uncertainty of complex systems, the future of a regional landscape should be discussed in terms of scenarios and "envelopes" or ranges of possible future states (Figure 5) rather than precise predictions (Lempert 2002; Bryan *et al.* 2011). The challenge of management then becomes knowing how to manipulate different parameters in the system, such that its dynamics remain within a desired envelope of possible states. This coincides closely with the "range of natural variability" concept in forest management, in which foresters attempt to define the naturally occurring range of states of the forest and prescribe a management regime that reproduces this range at the landscape scale (Wong and Iverson 2004). Decision support systems and simulation models may be used to develop and explore future scenarios. In a regional landscape, for example, one objective may be to maintain groundwater quality. A series of scenarios may be explored through modeling to ascertain which policies will keep the system within the acceptable range of groundwater quality, with policies that do not maintain water quality being rejected. Carpenter and Gunderson (2001) illustrated this approach using a series of simple examples. More complex hybrid models that combine

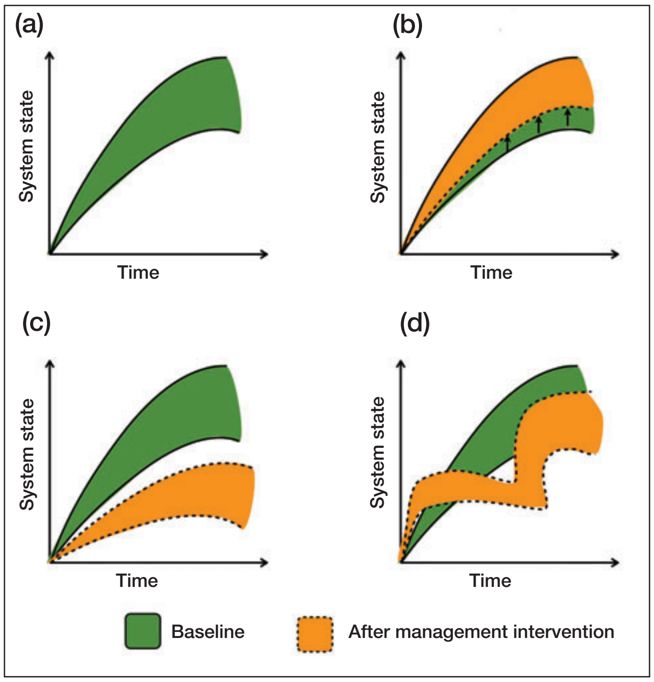

Figure 5. Landscape futures: envelopes of possible scenarios. The future of a landscape can be conceived in terms of ensembles of likely future system states, given a particular management scenario and external drivers. In this figure, all of the variables describing the system state are collapsed onto a single axis for simplicity. (a) An example envelope for a complex system, in which uncertainty about the system state (eg species abundances and their spatial distributions) increases with time. The envelope encloses all possible future states of the system for a single scenario, given current knowledge of the system's state and functioning. States outside of the green area are considered highly improbable for a given scenario or parameter set. (b) A management intervention, such as building a reservoir or culling a predator species, may shift an edge of the envelope so that certain future states (eg highly variable flow regimes; collapse of prey species) are less probable. (c) A system that undergoes a major change (eg a regime shift). (d) The shape of the envelope can be changed by management interventions that are unlike anything seen by the system in its recent history and that potentially affect the dynamics of several internal drivers. An example would be the Quebec government's proposed "Plan Nord" that will open the northern part of the province to development, substantially changing the future trajectories of socioeconomic and ecological processes in the region.

agent-based approaches that represent the local behaviors and interactions of individuals with representations of environmental processes at the landscape level are increasingly being used for scenario building (Bryan and Crossman 2008; Bryan *et al.* 2011; Parrott 2011). Of course, most management plans involve meeting multiple objectives, and the challenge is to find a sufficiently broad envelope of future states that will satisfy each objective and that are attainable, given the prevailing socioeconomic and institutional constraints.

Conclusions

This view of the landscape as a complex system necessarily changes the way we think about and manage regional systems, and is leading to calls for a "conceptual revolution" in environmental management (Harris 2007). Contemporary approaches to natural resource management, such as adaptive management and ecosystem-based management, incorporate some aspects of complexity (eg uncertainty, adaptation) in their management strategies, but much more work is necessary to fully incorporate the science of complexity into environmental management and policy (Harris 2007; Cumming 2011). In addition to this conceptual revolution, complexity science provides a range of new quantitative tools and methods that can improve our ability to model and analyze the landscape as a complex system (see WebPanel 1). Managers should work with scientists to put these methods into practice. Current research is based on improving our understanding of landscapes as complex, social–ecological systems, particularly the linkages across different scales and subsystems (eg social, ecological, physical) and their effects on landscape structure and dynamics (Cumming 2011). This research links the science of complexity with ecology and the human sciences. In our view, such a new, multidisciplinary approach is necessary for achieving sustainable landscapes in the future.

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