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Synthesis, part of a Special Feature on Applied Research for Enhancing Human Well-Being and Environmental Stewardship: Using Complexity Thinking in Southern Africa

Complexity, Modeling, and Natural Resource Management

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ABSTRACT. This paper contends that natural resource management (NRM) issues are, by their very nature, complex and that both scientists and managers in this broad field will benefit from a theoretical understanding of complex systems. It starts off by presenting the core features of a view of complexity that not only deals with the limits to our understanding, but also points toward a responsible and motivating position. Everything we do involves explicit or implicit modeling, and as we can never have comprehensive access to any complex system, we need to be aware both of what we leave out as we model and of the implications of the choice of our modeling framework. One vantage point is never sufficient, as complexity necessarily implies that multiple (independent) conceptualizations are needed to engage the system adequately. We use two South African cases as examples of complex systems—restricting the case narratives mainly to the biophysical domain associated with NRM issues—that make the point that even the behavior of the biophysical subsystems themselves are already complex. From the insights into complex systems discussed in the first part of the paper and the lessons emerging from the way these cases have been dealt with in reality, we extract five interrelated generic principles for practicing science and management in complex NRM environments. These principles are then further elucidated using four further South African case studies—organized as two contrasting pairs—and now focusing on the more difficult organizational and social side, comparing the human organizational endeavors in managing such systems.

Key Words: *complex systems; diversity; management; mental models; resilience; social complexity; social–ecological systems*

INTRODUCTION

Natural resource managers have to deal with the interactions between people and natural landscapes with their associated ecologies. It has become increasingly clear that the issues that natural resource managers are confronted with are complex in the sense that the natural and social systems they have to deal with are interwoven in ways that make the prediction of their response to interventions highly problematic. However, pinning down and managing this complexity, even discussing it, is not easy and is compounded by the fact that there is no clear and coherent disciplinary framework within which one can engage with complexity in a coherent way (Bonabeau 2008, Lloyd 2001); different researchers make different claims for what can be achieved by studying complex systems (Rasch 1991, Chu et al. 2003). Some hope that a general theory of complexity will provide a new master model for solving all the remaining great problems. Others argue that, instead of delivering grand solutions, the study of complexity opens up our understanding by showing us why it is difficult to model and understand complex systems—an approach that is concerned with the limits of our understanding (Stirzaker et al. 2010). This second, more critical approach to the study of complexity should not be seen as negative. Considering the limits imposed by complexity may be the responsible way to engage with the world. Disregarding these limits can lead to the illusion of neutrality or objectivity (von Foerster 1981).

The first section of the paper discusses the distinguishing characteristics of complex systems, and the second section unpacks the implications of the more critical approach to complexity; the latter showing what these implications could mean for scientific practice and natural resource management (NRM) actions. This introduction to complexity and the problems of understanding complex systems naturally leads to a discussion of the modeling of complex systems, followed by two sketches of illustratively complex cases—to make the point that real-world examples clearly exhibit all the characteristics of complex systems, even when society is focusing on understanding and managing only the immediate biophysical subsystems. Finally, we consider more directly the implications that the acknowledgment of complexity has on the additional social complexity of management practice in NRM, and again illustrate that with two examples, each with an elucidating contrast.

WHAT IS COMPLEXITY?

An argument developed from the perspective of complex systems as discussed below is that conventional reductionist methods can often fail as an analytical approach (Morin 1992). Conventional reduction attempts to reduce the overall behavior of a system to a number of essential elements that then explain what happens precisely. Although we never escape the process of reduction in some sense (see below when

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we discuss models of complex systems), complexity cannot be reduced in a pure and neutral way. For this reason, it is also not possible to give an exact definition of what is meant by "complexity." Definitions are by nature reductive. Nevertheless, the notion can be given meaning by means of a network of ideas and characteristics that allows us to differentiate it from other notions. Some of these are unpacked below.

Complexity is a characteristic of a system and arises because of the interaction between the components of a system (Cilliers 1998); it is not so much the properties of the individual components, but their relationships with each other that cause complex behavior. The properties of the system emerge as a result of these interactions; they are not contained within individual elements. Decomposing a complex system into individual components destroys the system properties. Thus, complex systems, such as the brain, living organisms, social systems, ecological systems, and social–ecological systems, must be studied as intact systems. Simple or merely complicated systems, on the other hand, can be taken apart and put together again without losing anything.

One can summarize the central characteristics of complex systems (condensed from Cilliers (1998)):

- Complex systems usually consist of a large number of components. The interactions between these physical or nonphysical components (such as information transfer) are fairly rich, i.e., any component influences and is influenced by a number of others.
- The dynamic interactions through which the components interrelate have three properties. First, at least some (in practice often many) of the interactions are nonlinear. Nonlinearity ensures that small causes can have large effects and vice versa. This is a precondition for complexity. Second, some interactions create feedback loops. The effect of any activity can feed back onto itself, sometimes directly, sometimes after intervening stages. Feedback can be positive (enhancing, stimulating, reinforcing) or negative (detracting, inhibiting, counterbalancing). Third, the interactions usually are fairly short range, i.e., information is received primarily from immediate neighbors. Each component in the system is, therefore, ignorant of the behavior of the system as a whole. If each component "knew" what was happening to the system as a whole, all the complexity would have to be present in that component, which is physically impossible. Short-range interaction does not preclude wide-ranging influence—since the interaction is rich, there are multiple routes to enhancement, suppression, or alteration.
- Complexity emerges as a result of the patterns of interaction between components. Emergence is often used in a way that creates the impression that something mysterious happens when "things come together." The way we use it denotes nothing ineffable. Emergence relates to the dynamic nature of interactions between components in a system and can be explained in terms of the complex system's organizational structure. The dynamic character of emergent phenomena is not a property of a pre-established, given whole, but arises and becomes apparent as a complex system evolves over time (Goldstein 1999).
- Complex systems are thermodynamically open systems, i.e., they interact with their environment and, therefore, operate under conditions far from equilibrium. Energy input is essential for system organization and survival. This interaction makes it difficult to determine the border of a complex system, so that, instead of being a characteristic of the system itself, the extent of the system is usually determined by the purpose of the description of the system and the position of the observer, a process called framing.
- Because they change with time, complex systems have histories. Not only do they evolve through time, but their past is coresponsible for their present behavior. Any analysis of a complex system that ignores the dimension of time is incomplete, at most a synchronic snapshot of a diachronic process.

A consideration of these characteristics leads to the following insights (Cilliers 2005):

- The structure of the system enables it to behave in complex ways. If there is too little structure (i.e., many degrees of freedom), the system can behave more randomly, but not more functionally. Therefore, the mere capacity of the system (i.e., the total number of degrees of freedom available) does not serve as a meaningful indicator of its complexity. Complex behavior is possible only when the behavior of the system is constrained (Levin 1999). Yet, a fully constrained system has no capacity for complex behavior either. Complex systems always show a balance between flexibility and constraint.
- As different descriptions of a complex system decompose the system in different ways, the knowledge gained by any description is always relative to the perspective from which the description was made. This does not imply that any description is as good as any other. Only a limited number of characteristics of the system can be taken into account by any specific description. Although there is no a priori procedure for deciding which description is correct, some descriptions will deliver more interesting results than others (Allen 2001), as discussed under the section on modeling complexity.

- In describing the macro-behavior (or emergent behavior) of the system, not all the micro-features can be taken into account (Richardson 2004). Any macro-description reduces complexity and cannot be exact. Moreover, emergent properties on the macro-level, in turn, influence micro-activities, a phenomenon sometimes referred to as top-down or downward causation (Ellis 2008). Nevertheless, macro-behavior is only the result of micro-activities, keeping in mind that these are influenced by their mutual interaction, top-down effects, and the interaction of the system with its environment.

These insights have important implications for knowledge claims we make. As we do not have direct access to the full complexity, our knowledge is, in principle, limited. We discuss this in more detail below.

UNDERSTANDING COMPLEXITY

The argument runs as follows: to fully understand a complex system, we need to understand it in all its complexity (Cilliers 2002, 2011). Furthermore, because complex systems are open systems, we need to understand the system's complete environment before we can understand the system, remembering the environment itself is complex. This is humanly impossible. The knowledge we have of complex systems can only be based on models, but in order to function as models—and not merely as a repetition of the system—they have to reduce the complexity of the system. This means some aspects must be left out of consideration. That which is left out interacts with the rest of the (real-world) system in a nonlinear way, and we cannot predict what effects this reduction of complexity will have, especially as the system and its environment develop and transform over time (Allen et al. 2010).

We cannot have complete knowledge of complex systems (Skyttner 2001); we can only have knowledge in terms of a certain framework. As we are finite beings, there is no stepping outside of complexity; thus, there is no framework for frameworks. We choose our frameworks. This choice need not be arbitrary, but does mean that the framework itself cannot be used as the basis for objective knowledge. The generation of knowledge of complex systems is an exploratory process. As the context in which this knowledge is to be useful changes, we have to continually revise the framework from which we generate this knowledge. Our knowledge of complex systems is thus always provisional, and therefore, we have to be modest about the claims we make.

One should not interpret this state of affairs as somehow inadequate, as something to be improved upon. There is a necessary relationship between the imposition of a limiting framework and the generation of knowledge. One cannot have knowledge without a framework (Cilliers 2001). Although our knowledge is of necessity limited (Allen 2001), these limits are enabling, allowing us to make claims that are neither relativistic nor vague (see Cilliers 2005). Such knowledge is not the result of free-floating truths; it is contextualized in time and space. Because we know this knowledge is not objective in absolute terms, we cannot use it as if it were objective. This means there is always a normative dimension to our claims, for which we must take responsibility. We cannot shift this responsibility onto some process we call scientific in a naïve sense of the word. Next, we discuss the implications complexity thinking has for modeling complex systems.

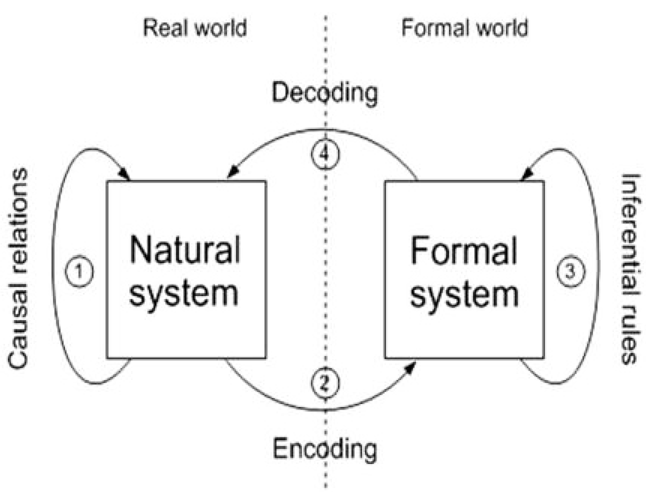
MODELING COMPLEXITY

Science rests on the beliefs that there are regularities (i.e., causal relationships) to be observed in natural phenomena perceivable through our senses and measuring instruments. A scientific investigation of a natural phenomenon consists of creating a model of these relationships that, if a "good" model, can aid us in understanding, predicting, or even controlling, the behavior of the system exhibiting the phenomenon. Profound implications for the way we do our science arise from the fact that we can only apprehend and understand ourselves and the world around us in terms of the models we create. Modeling lies at the heart of science—we have, in the end, nothing but models. In this section, we explore the effect of acknowledging complexity on the standing of our models.

What does the act, or better, the art of modeling involve? Models can take many forms. In the natural sciences, the predominant form is mathematical, so much so that for many this is what models always are: formal symbolic systems. However, this is too limiting, as a form, and in terms of what can be modeled. For some phenomena, a mental representation or a textual, visual, or spatial narrative (like a dance) can be more appropriate; a mental model, for example, is needed to cross the street safely, a novel can be a model of a particular social phenomenon.

How do we make our models? Robert Rosen, a theoretical biologist working during the last part of the previous century, made a deep study of the modeling process in general, and in particular, in the context of complexity. According to Rosen (1985,1991), to make a model is to establish a modeling relationship between that part of the natural world we choose as our object of study (let us call it the natural system) and, for want of a better word, a formal system, the inferential structure of which mimics the causal structure in the natural system (Fig. 1). This is done by choosing a set of observables that we believe characterizes the natural system, and then constructing a dictionary that maps observables in the natural system to input variables in the formal system (a process of encoding). The inferential rules for manipulating the entities in the formal system are then supposed to be the images of the causal relationships in the natural system. What we hope to achieve is to bring the entailment structures in the two systems (causal structure in the natural system and inferential structure in the formal system) into alignment, so that, given an input set, the result of an inferential process (an "experiment") in the formal system can be decoded into the natural system to make a prediction about its behavior. When our prediction matches the behavior of the natural system, we can claim that the formal system is a model of a particular aspect of the natural system. The aim is to establish a relationship between the natural system and the formal system so that arrow 1 = 2 + 3 + 4. If this is achieved, the modeling relationship is said to commute.

Fig. 1. The modeling relationship (Rosen 1985, 1991, Casti 1989).



The acts of encoding and decoding, although integral to the modeling relationship, are not part of the model. They are entailed from outside, and are in that sense arbitrary. The art of modeling lies in choosing suitable encoding and decoding dictionaries; the modeler is the "keeper of the encodings and decodings" (Casti 1989).

All models are abstractions and reductions in the sense that the modeler chooses to encode a finite subset of possible observables. Casti (1989) discusses various examples, including Forrester's so-called global "world models" (Forrester 1973). In his first model, Forrester chose from very many possibilities five observables: population, natural resources, capital, pollution, and fraction of capital devoted to agriculture. Postulated links between these observables were formalized in terms of sets of finite-difference equations, solved numerically to predict the behavior of the real-world system.

What are the implications of complexity for the models we make of real-world systems? As a starting point we can use Mikulecky's (2007) definition of complexity, which he based on Rosen's ideas:

> *"Complexity is the property of a real-world system that is manifest in the inability of any one formalism being adequate to capture all its properties. It requires that we find distinctly different ways of interacting with systems. Distinctly different in the sense that when we make successful models, the formal systems needed to describe each distinct aspect are NOT derivable from each other."*

This is an alternative, equally valid, way of characterizing complex systems, not, as described earlier, in terms of their properties, but rather in terms of our models and their relationships with each other. Whereas a simple system can, in this view, be fully characterized by a model (a so-called "largest" model), a complex system cannot, but may require several (ultimately an infinite set of) nonequivalent models. In this sense, all real-world systems are complex; the only simple things are our formal models of the world. For simpler systems, causal relationships are well defined and distinct, systems can be taken apart and put back together again without losing anything: they are fragmentable. In contrast, causal relationships in complex systems are rich and intertwined, fragmentation resulting in irreversible loss of information or function.

On reflection, both characterizations of complex systems lead to the same conclusions. As any model is a reduction of the real system being modeled, understanding gained by modeling complex systems is always partial. We can never have complete knowledge of complex systems; as stated before, our understanding is always provisional.

EXAMPLES OF COMPLEX SYSTEMS

In order that NRM practitioners might see the above theory as credibly linked to actual systems with which they work, we describe below an elephant management and a water catchment-related example. Without discrediting earlier NRM styles, we hope the examples illustrate the current need to take, additionally, a broader complex view. Although both are clearly part of social–ecological systems, we have intentionally kept the discussion in each case here focused more on the underlying biophysical elements and their immediate management, as subsequent examples address the implications for society working within such social–ecological systems. The way in which the two examples have been constructed should help readers to make the links to the characteristics of complex systems described in the first part of the paper.

Elephant Management in South Africa

Elephant management has a history of contention, being one reason why the South African government recently convened an elephant management assessment (Scholes and Mennell 2008). Differences in framing elephant impacts vary from a static carrying-capacity paradigm through to a view that ecosystems are dynamic and heterogeneous, subject, for instance, to greatly varying impacts by elephants at different times and places. The benefit of a systemic view is realized when one considers the large number of cofactors that along with elephant, cause ecosystem change (e.g., fire, wood-borers, other herbivores, and drought-induced dietary changes). There are large numbers of local interactions (such as elephants pushing over trees, or debarking trees that happen or do not happen to be subsequently burned in a fire), and system events are largely “ignorant” of each other. The wider ecosystems in which these happen have long been shown to oscillate between various system states (Dublin et al. 1990). More elephant managers today see the environment as shifting between these states rather than bouncing back after disturbance to some pre-ordained position if they are “managed well.” Disappearance of large trees (one frequently cited concern) is not universal across elephant-impacted savannas, and can be considered an emergent property of several additional cofactors (fire, wood-borers, other herbivores, such as impala, which can prevent small tree recruitment, drought). The number of different states (for example, grassy, savanna, closed woodland, shrub-encroached) into which the ecosystem can pass is finite, i.e., there are not unlimited degrees of freedom. The ecosystem is held in a particular state at a particular time by enhancing or inhibiting feedbacks, or it passes a threshold to reach another state. System boundaries are difficult to draw—does one include global climate-change effects, which may be speeding up tree growth relative to grass? History also matters. Whether the system “started” in 1900 after near extermination of elephant due to hunting, and other herbivores due to rinderpest, has made a major difference to current trajectories. Ecosystem managers need to question their models on a continuing basis, as no single line of thought appears to have even near full explanatory power. Top-down and bottom-up factors (sensu Ulanowicz 2009) clearly form an often unpredictable interplay of effects that produces the observed system that is to be managed according to human values—and once these are taken into account, as they must be, the system complexity increases. But even at a mainly biophysical level, as described, the attributes above qualify the elephant management system as a complex one.

How has the elephant management system in the country responded to this reality? The government assessment (Scholes and Mennell 2008) makes it clear that contexts for elephant management differ widely and recommends that elephants will need to be managed differently in different places and at different times, and even that moral pluralism be condoned. Ecosystem managers, except in a few highly focused situations concentrating mainly on elephant, are encouraged to manage elephant as part of a wider complex social–ecological system. The assessment brought a sense of diversity to what was a confrontational situation and somewhat relaxed polarized participants. There is indeed no single correct formula, yet many potential solutions that are appropriate to particular contexts. All need to be adaptive.

The Complexity of Managing Land for Water

Society depends on sustained generation of water-related ecosystem goods and services. Water crosses social, political, and economic boundaries, and scientists and water managers, even when viewing just the underlying biophysical complexity of water resources systems, need to consider at what levels this complexity should best be engaged.

Land-water interactions are one set of obvious key factors, and an appropriate and effective level of understanding is difficult to find. We need to recognize that the interaction of land use and water resources varies in time and varies in space. Water moves both vertically (evaporation, transpiration, and infiltration) and laterally (through hillslopes, soils, groundwater, and rivers), so any impacts can be transmitted through a catchment and may emerge unexpectedly in time and space. Often these are threshold driven, so there are different stable states for that system. Feedbacks between the system components occur at a range of spatial and temporal scales and these may involve a change in state (e.g., liquid to vapor) and are not necessarily catchment bounded.

Land–water interactions show emergent properties, one manifestation being surprising behavior at scales different from observation or study (e.g., Gordon et al. 2008). Emergence is something that is characteristic of the system as a whole. If we oversimplify reductively, viewing components in isolation or by averaging away the variability, the ability to account for emergent properties disappears. Over simplistic indices (such as the water footprint, Jewitt and Kunz (2011)) can lead to perverse outcomes; instead, a requisite simplicity (Stirzaker et al. 2010) needs to be sought. This should be based on the processes and links between different components, an understanding of their structure and function and of the spatial and temporal scales at which they are dominant or dormant. Humans easily grasp anthropocentric scales for which we have an intuitive feel, but are slow to grasp those beyond “the measuring rods of our own world” (Gould 1993).

In South Africa, the concept of streamflow reduction activity (SFRA) illustrates an attempt to engage with several attributes of complexity in practice. Section 36(2) of the National Water Act of 1998 defines a “stream flow reduction activity” as:

> *“... any activity (including the cultivation of any particular crop or other vegetation) ... [that] ... is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly.”* [The “Reserve” is the amount of water set aside (that is, “reserved”) for environmental flows and to provide for basic human needs].

Declaring a land use as qualifying for an SFRA requires (i) recognition/identification of the crop as something that may cause an impact on the water resources, (ii) quantification of that impact on the flow regime, and finally, (iii) a management process to enact and enforce the declaration. Important considerations arise due to the word "significantly," and through the concept of the Reserve. "Significant" has both spatial and temporal scale dimensions. How widespread is a potential SFRA and where is its impact felt—for how long, or at what critical times of the year?

South Africa is semi-arid, and flow variability is high. The mean (e.g., of annual runoff), the bastion of water resources management in the past, and the basis for many indicators, is meaningless as a measure of complexity. Long-term research into land-use impacts has highlighted the low flow periods as those when impacts of land use are most significant (Jewitt 2006). High biomass crops continue to transpire (use water) when natural land use is dormant and thus have the highest (relative) impact on streamflow, and at the time when people and natural systems most need water. Hence, the focus in SFRA is on the low flow periods, and water-use licences take this into account. Spatially, South African water management is operational at the scale of the quaternary catchment, but considers the hierarchical structure through which these form part of their larger catchment when licences are issued. In this way, commercial forestry is regulated to reduce streamflows, based on recognition of the complexity of the land–water interactions within a catchment, through a pragmatic, yet scientifically robust method.

COMPLEXITY AND MANAGEMENT

Because complex systems are difficult to talk about and understand, it is tricky to base management decisions on the concept, as people lack a systemic appreciation of how to alter their practices to match reality in a defendable manner (Beautement and Broenner 2011). Despite this difficulty, it is essential for managers to learn to do so. This paper assumes that adaptive management is implicitly, if not explicitly, accepted as an important practical basis for dealing with complexity in NRM. To root this adaptive management in complexity thinking, we now suggest five key principles that we believe practitioners may concentrate on to assist them in the formulation of their own particular appropriate responses to complexity when facing management decisions. These are not meant as a primer or as a set of detailed guidelines. Many such guidelines exist, although they are invariably poorly connected to complexity thinking. As part of the initiative under which this paper is being written, several others follow as papers in their own right, often dealing with further detailed unpacking of one or more of the broader topics alluded to in this paper. The five principles we discuss below are thus more akin to generic mental beacons from which to start. They are like fingers of a hand, all interrelated. These principles deal predominantly with the cultural attitudes of scientists, rather than with matters of quantification and empiricism.

Harness Diversity

Natural resources such as water and biodiversity are essentially intermeshed with social systems, which typically have a range of stakeholders with very different values, expectations, and time horizons. Although diversity in a social–ecological system is believed to enhance resilience (Levin 1999, Folke 2006, Ives and Carpenter 2007), it can also carry costs such as compromising a sense of solidarity. Too much conformity lessens the potential response range. Overall, a reduction in diversity can increase short-term efficiency but create long-term vulnerability (Nelson et al. 2011). This diversity is often seen as a hurdle—how can we in practice manage it to achieve short-term goals and retain long-term resilience? Concentrating for the moment on knowledge diversity, in which each individual has a differing mental model (Jones et al. 2011), we invariably see clustering of mental models into relatively homogenous domains (e.g., scientific disciplines as group mental models), each of which has an identity and a degree of exclusivity. Within each domain there are effective rules and modalities for communication. The invisible boundaries between knowledge domains (e.g., between scientific disciplines, between science, policy, and management, or between sectors such as agriculture, health, and conservation) pose hurdles, and groups often resist influence. However, these same boundaries also connect domains, where the interfaces represent areas for rich learning opportunities, and potentially, radically new insights.

The most productive knowledge overlap occurs when domains are not too close, nor too far apart. Ways of stimulating this generative tension are documented (Wenger 2010). Identities are critical to social learning systems—based on past learning, they help define what matters to us, whom we trust, and with whom we share knowledge. Bridging boundaries requires that we engage other domains, partly suspend our identity, opening it up to other ways of being (Wenger 2004) in a nonthreatening way. We should acknowledge our multiple identity memberships (e.g., parent, engineer, volleyball player, and photographer). In some domains, we may be core members, in others peripheral. Reconciling identities across knowledge domains can assist personal growth and social cohesion. Where different identities of multiple stakeholders co-exist in a social–ecological system, cooperation is fostered if a higher-level identity (referred to as collective identity; Hardy et al. (2005)) is shared.

Acknowledge Provisionality, Keep Revising

Provisionality and revisability are core to dealing effectively with complexity. This should not be construed in a way that implies that there should be no rules. Rather, rules arising from a crisp, understandable strategy are essential for NRM. The extra nuance now required is to realize that the rules are invariably provisional, and the skill of dealing with "real-world complexity" is judging when and how these rules should be revised. Rules should, therefore, be set up in such a way that they can be revised and that transitions can occur sensibly. In a world of many rigid bureaucracies, revision often needs to be prompted sooner rather than later, although judging how long to "wait out" the longer runs can be crucial, as there can also be merit in slowness (Cilliers 2006). We have to measure and reflect sensibly so that we can best decide when to revise these rules. This same paradox is contained in, for instance, the way resilience theory (Gunderson and Holling 2001) deals with balancing stability and change. Because the system cannot be known completely, it is impossible to have a "complete" strategy. But this does not imply that our strategies should be vague, as this would further paralyze our initiatives. We need good plans, but we also need to realize they will ultimately be (at least slightly) wrong. A culture in which provisionality prevails, with its inherent and necessary tensions, is the responsible and strong position.

Build (Mental) Models in a Systemic Way

Models provide a simplified representation of a system and are very useful for establishing a NRM platform by providing the opportunity for a "what if" discussion. Providing a representation or model of a system means recognizing, understanding, and representing patterns for both biophysical and social components of the system and so provides a means of moving from perception to conceptualization. Mind maps or "systems model" software, possibly used in a group setting, provide a powerful way of doing this as well as a basis for forming a common understanding of a shared problem.

Patterns or structure can be recognized as emergent behavior of a system where the dynamics at one scale can be seen as the collective behavior of components from another (Levin 1992). These dynamics emerge as a function of their material substance, the energy flows through the system, and the balance between the forces interacting between the different biophysical and social components of a system. Conceptualizing such models means determining which forces are dominant, but a complexity context means recognizing what information is lost or gained as one frames the model differently, for example by moving from one spatial or temporal scale to another.

Thus, a complexity perspective means that understanding a pattern and building a model to represent such a pattern must be constrained by a parallel recognition of the limits imposed by the boundaries in which we frame the model. So, it must be recognized that our mental model or worldview is imperfect, and needs to be dynamic and flexible to reflect a changing and dynamic world and a context where the drivers may change and the balance between forces will shift.

Thus, we need to revisit continuously the boundaries we have drawn around our system, re-testing the hypotheses through which we frame our models and allow different, and perhaps uncomfortable, patterns to emerge. This requires open-mindedness, an ability to reflect, and a willingness to reject a hypothesis or a model and move onto another should the context require it. However, this does not mean that we should be too tentative in framing our boundaries. Rather, we should be clear and precise, as this provides us with a more rigorous approach for refining and retesting our hypotheses and assumptions.

Measure, Scan, and Sense

Measurement, as a management tool, is useful in understanding the patterns of relationships in a complex system. Being able to assess (in qualitative and/or quantitative terms) and understand the interactions between components, and the behavior of the components themselves, provides a basis for management action. Despite its necessity, measurement is not sufficient in and of itself. Reductionist approaches to measurement are characterized by the oft-used maxim "If you cannot measure it, you cannot manage it" (Drucker 1993). This view distinguishes between hard measurables (perceived to be of value) and nonmeasurables (perceived to be of no consequence, nor impacting on the functioning of the system), an approach that is overly constraining for complex contexts. The limitation of this framing is that, although one cannot have a view of all the complexity in a system, it even further inhibits the observable complexity by too narrowly focusing on a chosen set of strictly measurable aspects of the system.

Rather, two aspects of measurement in complex contexts should extend the notion beyond the traditional idea of measures. The traditional quantitative and/or qualitative measurement and monitoring of a physical phenomenon needs to be augmented by scanning (being mindfully on the lookout) and sensing, (picking up intelligently on processes or patterns, and their meaning). Scanning and sensing are about being sensitive to what can be learned about the system by paying attention to relationships between measures. Sensing requires taking a step back from individual, potentially isolated measures in order to minimize fragmentation.

This not only applies to physical complexity, but also to measuring social complexity. Managing people as if they are mechanistic components fails to account for the complexity in social ecologies, thus introducing a constraining rather than enabling structure for behavior. An added consequence is that measures tend to become performance targets, thus ceasing to be helpful measures.

A complexity view of the measurement maxim should read: If all you do is measure, in the "hard" sense, you will not be able to manage complexity. Scanning for and sensing the interactions of various measurements in the space between allows for a more effective way of engaging with complexity.

Have Reasonable Expectations of Appropriate Design

In our modern world of "efficient" organizations, failure of any sort is neither tolerated nor anticipated. However, failure may be seen as a likely and even necessary phase in addressing complexity through probing the uncertainty and learning sensibly.

In a modernistic sense, the "hope" of design is based on notions of predictability and certainty. Therefore, in this view, more sophisticated design is meant to (and often does) improve results. However, the "complex" counter view requires awareness, even relative comfort, in realizing that specific outcomes may not materialize as planned. Acknowledging the provisionality of your knowledge of the system greatly influences the expectations of the solution, and likely success of chosen responses. Taking into account the uncertainty of a complex context means that monitoring for unintended consequences is important. Knowing that a plan is an imperfect plan is a key mental position for managers within complex contexts. What is required is a willingness to adjust the plan based on new insights, learning, and information gathered from the implementation of that "imperfect" plan. Acknowledging the uncertainty associated with complexity is merely acknowledging that you're in another different space with different dynamics, not "lost in space" in a place where there is no structure. Design remains important, but a more appropriate strategy has many "safe-fail" interventions or "smart experiments" (Heifetz et al. 2009) engaging small amounts of time, money, and resources, rather than an expensive and time-consuming single so-called "fail-safe" solution. All failures then enable greater learning about the system, and as (albeit sometimes) modest gains occur, the successful experiments can gradually be amplified to see what emerges. The process is iterative and is never formally accomplished, given that the complex dynamics are likely to remain and adapt.

This learning-by-doing approach does not mean you are at a loss for managing the situation, in the traditional sense. Rather, there is a requisite positive wandering, where structured learning and being optimally responsive to new information become key competencies. This approach does require a move away from a mindset where it is believed that there is a single right answer and that solutions are concrete, reliable, and predictable. Rather, the mindset needs to be one of growth, where "intelligent mistakes" are viewed as opportunities for learning.

PAIRED CASE STUDIES ILLUSTRATING SOCIAL COMPLEXITY ISSUES IN NATURAL RESOURCE MANAGEMENT

The next two case studies look at the human societal and management organizational responses to complex issues (or ones seen as perhaps less complex) and illustrate the need for the varied use of the five key principles described in the previous section. The first contrast is between catchments, and the second one compares the way complexity is perceived or not perceived, set up with two very different agents, one whose main task is to promote conservation of nature, and one whose main objective is to mine.

Comparing Two Catchment Management Situations

This comparison is between social attitudes and approaches that underlie catchment management in two differing locations in South Africa, one with a long investment in collaboration in a seemingly favorable setting to enable this; and the other with a history of almost gridlocked contention.

The Inkomati Catchment stretches from the eastern edge of South Africa's industrial heartland (Gauteng) all the way to eastern neighbors Swaziland and Mozambique, which share part of the actual catchment—whose economy is highly dependent on water, with the main economic drivers being forestry, irrigation-based agriculture, and eco-tourism. Water user identities, cultures, knowledge, and attitudes vary widely across the catchment, even in the South African segment. The Inkomati Catchment Management Agency (ICMA) is a South African institution (with strong links to neighboring institutions) and the first one established under the 1998 National Water Act, pioneering decentralized and participative water management.

In order to develop a collective roadmap for getting from a current (partly undesirable) reality to a more desirable social–ecological system, the ICMA used an external facilitator to adaptively plan and build a sense of common purpose among all relevant stakeholders. The facilitator took a systemic approach and had a good grasp of how to enable people and groups to deal with complexity. Successful adaptive planning depends on stakeholder inclusivity and constructive dialog among these differing stakeholders (Rogers and Breen 2003). In this process, stakeholders agreed on vital attributes of the catchment and on values or operating principles that should guide management decision making in the future (see Pollard and Du Toit 2007). The facilitator played an important bridging role across knowledge domains, with the shared coconstructed vision providing a higher-level identity for stakeholders, and a shared space for social learning toward a new purpose. The facilitator showed the particular and essential ability of promoting the harnessing of diversity.

Hartbeespoort Dam is situated in the North West Province of South Africa. The dam, originally designed for irrigation, is a significant part of the economic hub of the North West Province and the Crocodile (West) Marico Water Management Area (WMA). The town of Hartbeespoort is situated close to the dam wall, and various (mainly leisure, lifestyle, and regular residential) villages are situated along its banks. The dam is notorious for poor water quality and has been in a hypertrophic state due to elevated phosphate and nitrogen concentrations since the early 1970s (National

Institute for Water Research (NIWR) 1985). The dam impacts a wide diversity of stakeholders, and complaints are many and varied. In 2010, a research project was undertaken for the South African Water Research Commission to investigate behavioral drivers of stakeholder engagement and volunteerism (Blignaut and Choles 2011). Research findings indicate a fragmentation in the social fabric of the town, especially among the affected stakeholders. Different identities appear to be completely invested in their own knowledge domains and seem unable to relate to stakeholders with different views and to harness their diversity. Most of these stakeholders are focusing on solving a small aspect of the bigger problem, with seemingly little awareness of the real complexities they face. There currently exists no effective leadership or unifying vision to address this, and consequently, also no systemic view of the problem. Due to the scale of this water problem, none of these individual stakeholders or stakeholder groupings will be able to have an impact individually, leaving the catchment stuck with a tenacious problem. At one stage several years ago, a potentially unifying pressure group did exist (the Hartbeespoort Water Action Group (HWAG)). Negative experiences in this group seem to have cemented the individual identities even further, and attempts to span the knowledge boundaries are resisted.

Comparing Conservation with Mining: Whether and How Complexity Thinking Is Used for Management

Conventional organizational structures are usually more geared toward enabling command-and-control styles of resource management, rather than using an adaptive approach that recognizes complexity. This approach applies both to the organizational management responsible for, and to the actual, resource management. We have specifically chosen mining (at the "hard" or nonrenewable end of a continuum of NRM styles) and conservation (at the "softer" end). The purpose of an organization enables or limits the extent to which complexity thinking is required, accepted, or implemented. For instance, in our study, the conservation agency, exemplified by SANParks, believes it should be applying insights from complexity theory, at least for ecosystem research and management. The mining sector currently sees it fitting to embrace complexity to a far lesser extent—understandable given their purpose, although recently their operating context is broadening considerably.

In the South African mining sector, there are, apart from specific exceptions (such as technology development), few efforts to embrace diversity in the sense of encouraging heterogeneous sets of ideas as a resource. Rather, there are strong drives toward standardization, which has been very effective in achieving goals (Deloitte and Touche 2009). Recent factors somewhat loosening up this approach include environmental accountability and an increase in humanity awareness (e.g., concerning staff safety). Desired stability of operations works against any attitude of pro-active provisionality, revisability instead being predominantly reactive. The industry considers its "tried-and-tested" model a good fit to reality, and reflectiveness is limited. Measurement is seen as a predictable lever for control. There is a belief that the future can be designed, and perverse outcomes are seldom expected.

Conservation currently adopts a modest position (Roux and Foxcroft 2011). Debates around, for instance, elephant, fire, river, and ecosystem management emphasize that learning about these effectively requires a diversity of opinions and approaches. Perceptions, even about how the system functions or responds, highlight the provisionality of understanding and management, especially after severe droughts and floods in the last two decades in the Kruger National Park. Despite adamancy shown by some scientists, the de facto position reflects ongoing revision of underlying models. Measurement, done at multiple scales, is seen as imperfect, albeit the best available evidence, and is used as a basis more to "nudge" the system and see if it responds as thought, than to control it. Debates continue in the organization around performance management systems for scientists/managers, believed by some to not be as flexible as required to manage this complexity. Overall, there is less discomfort with the attendant uncertainty, yet there are clear (if provisional, evolving) goals and rules.

CONCLUSION

We hope that the combination of theory and practical examples presented in this paper might persuade natural resource scientists and managers to increasingly adopt a complex systems viewpoint in most situations they encounter. Conceptualizing less complex systems as complex (once an adequate complexity orientation has been adopted) holds few risks. Even when systems are treated in a more reductionist manner, complementarity between the two approaches should, where possible, be sought. During most of last century, the command-and-control style approach employed in agriculture, forestry, and water resource management sometimes made great strides forward, but in the last two decades, an increasing awareness of the limitations and side effects of conventional NRM has developed (e.g., Pahl-Wostl et al. 2007), and scientists and managers have been encouraged to begin using complexity thinking (Levin 1999). We have argued why complexity thinking presents a productive new alternative or complementary paradigm (Morin 1992) for wide use by natural resource managers, some of whom had indeed begun using adaptive management styles over the past two decades as a response to what was seen as the problematic performance in NRM ascribed to the challenges posed by uncertainty and change. With few exceptions (e.g., De Leo and Levin 1997, Ruitenbeeck and Cartier 2001, Stirzaker et al. 2011), this swing to adaptive management happened with little recognition that it should be fundamentally underlain by complexity theory, a gap this paper hopes to have bridged.

Complex systems, as we have illustrated, can be tricky to manage, especially if approached in inappropriate ways, but we have also shown how much more tractable they can become if handled with the understanding provided. By choosing to adopt a complexity orientation, significant new windows may open to practice NRM more sustainably.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/5382

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