Operationalizing Resilience in Australian and New Zealand Agroecosystems

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Abstract

We present techniques that we have developed to operationalize the concept of resilience, as promoted by The Resilience Alliance (www.resalliance.org). We also outline a new program of research applying these techniques across a diverse range of Australian and New Zealand systems to begin operationalizing resilience management wherever humans interact with the natural environment.

Resilience is an emergent system-wide property that describes the capacity of a system to absorb perturbations and persist in a variable environment. In human-modified natural systems, such as agroecosystems and landscape mosaics containing both farmland and remnant native vegetation, we claim: a) that long-term system dynamics is determined by interactions and feedbacks between social, economic and ecological sub-systems, rather than instantaneous stocks and flows of material throughout a system; and b) that instantaneous system behaviour is often dominated by stochasticity, variability and uncertainty. We propose a new implementation of a mathematical technique based on dynamical systems theory and systems science, which embraces uncertainty using the concept of resilience. We hope that this approach will provide a useful complement to “precise” simulation models of agricultural systems.

We examine these techniques in the context of a new research program studying resilience in Australian and New Zealand agro-ecosystems. This research program is allowing us to apply these techniques to a wide range of case studies, producing quantitative results that operationalize the concept of resilience at a scale not previously achieved.

Keywords: resilience; agriculture; ecology

Introduction

There is an increasing recognition that many human-modified ecosystems (social-ecological systems), even those that are being “sustainably managed”, are failing as a result of small compounding events or extraordinary environmental, political or economic conditions (Millennium Ecosystem Assessment 2005). This has significant implications for humanity, given that many of these systems provide the food and environmental quality required by human societies. For example, Anderies (2005), Carpenter (2003) and Folke et al (2004) report on the degradation or collapse of agricultural ecosystems related to intensification and development, and aquatic ecosystems due to eutrophication and over fishing. Other studies report on the collapse of whole societies such as those of Easter Island (Brander and Taylor 1998). If we want these social-ecological systems to persist despite the variability, uncertainty and unknowability of the real world, we must learn to manage for their *dynamic resilience*, as well as their sustainability in "average" conditions.

Resilience is an emergent system-wide property that describes how a system responds to external forces in an effort to maintain its fundamental structure. Because it is not a physical component of the system *per se*, but an emergent property, resilience has been difficult to understand, measure, and manage. However, as evidence arises of its importance in determining the persistence of real world systems, it becomes apparent that we must make the effort to develop ways to understand and managing for resilience. Although difficult in the real world, it is possible to estimate resilience within conceptual and mathematical models integrating social, economic and ecological components of human-modified ecosystems. By building an understanding of resilience through these models, and combining that knowledge with practical know-how, traditional simulation models, and experimentation at appropriate scales, the concept can be usefully applied to the management of real systems. Importantly, building this *understanding* is perhaps the most vital step towards averting disaster and collapse of many of the social-ecological systems that form the foundation of our societies.

We refer to the general idea of "ecological resilience" championed by the Resilience Alliance (www.resalliance.org), as well as specific mathematically tractable subsets of these definitions. Resilience is the capacity of a system to undergo disturbance or perturbation and maintain its defining structure, functions and controls by absorbing the disturbance and reorganising (Gunderson & Holling 2001; Folke et al 2004; Walker et al 2004). Specifically, ecological resilience recognises the potential for a system to experience nonlinear responses to perturbation, including hysteresis and permanent collapse to an undesirable alternative state. This differs distinctly from the common definition of "engineering resilience", which measures how long it takes systems to recover following a perturbation, implicitly assuming that perturbed systems will always be able to recover (e.g. Pimm 1984). In ecology, "engineering resilience" is most often found in studies of succession, as a post hoc measure.

Members of the Resilience Alliance have developed much of the way that we understand ecological resilience. There is a healthy and increasing body of descriptive qualitative theory around adaptive change in socio-ecological systems (i.e. Panarchy theory - Gunderson & Holling 2001), and resilience is a key or foundation concept within this theory. However, as yet few attempts have been made to operationalise this concept in a quantitative manner in real systems in order to test hypotheses about the resilience of socio-ecological systems and develop pathways to acceptable solutions (Carpenter et al. 2001).

This is because it is difficult to integrate many of the social and ecological drivers of change in these systems, and because mathematical techniques for describing them are only just beginning to be applied in this field. With the exception of a few key systems studied by just one or two individuals, analysing the resilience of real systems remains a scientific challenge (Carpenter et al. 2001), although methods for doing so have recently been proposed (Allen et al 2005; Bennett et al. 2005; Berkes et al. 2005; Carpenter et al. 2005; Cumming et al. 2005). We present a developing research program that seeks to operationalise resilience theory in Australian and New

Zealand agro-ecosystems, and showcase the utility of dynamical systems models in this research.

An International Program of Resilience Research

The International Program of Resilience Research in Agro-Ecosystems (IPRRA) aims to operationalise the concept of resilience for human-modified ecosystems utilised for agriculture. Currently, IPRRA is focussed on Australian and New Zealand systems, with some comparative studies in the UK. Australian and New Zealand economies have been underpinned by the transformation of indigenous ecosystems and landscapes in the last 200 years to provide agricultural products and services, and their economies will continue to depend on agricultural production in the foreseeable future. Designing management strategies that foster resilience and allow these systems to persist in variable social, ecological and economic environments will be vital to deliver sustained productivity over the long term.

The Australian and New Zealand experience forms a useful comparison set. Both countries share a Gondwanan heritage, have an indigenous population, and a low population density relative to other parts of the world. Both have developed into first world nations "on the sheep's back", and the large-scale agricultural modification to the indigenous landscapes of both countries reflects the imposition of European farming and cultural practices. However, although culturally similar, Australia and New Zealand are biophysically very different. Current agricultural practices reflect their European roots with adaptation and diversification due to environmental differences, although it is debateable whether either country has learnt to farm sustainably within its environment.

The climates of both Australia and New Zealand are dominated by the El Niño / La Niña cycles, although the effects are very different in each country. Australia, a largely dry landscape, exhibits dramatic climate variability over periods of a decade, from drought to periods of marginally useful or even excessive rainfall. Farming techniques that assume relatively consistent conditions year-to-year, such as those developed in Europe, may overstress the natural capacity of the land during times of wider environmental stress. The effects of high natural variability in climate are not linear: short-term damage wrought due to overstocking during times of drought can destroy the long-term potential of the landscape to support the current exploitation system, e.g. grazing systems may be made unviable due to soil structure damage and gully formation around watering points or extended periods of over-consumption killing the crown of the forage plants, preventing regeneration once grazing pressure is removed. Australia is also a very old continent, with poor, weathered, salt-encrusted soils and a deep water table. Farming techniques that cleared the land of the deep-rooted native trees to make way for annual agricultural crops disturbed the established balance, raising the water table to the surface, bringing hundreds of thousands of years of slowly distributed salt to the surface (Anderies 2005). In other places, clearing the poor soil removed what little organic matter held the precious topsoil in place, leading to massive erosion that has forever diminished the agricultural capacity of the landscape at the same time as polluting the Great Barrier Reef. Farming techniques that *mine* soil nutrients without replenishing them quickly deplete what limited resources are available.

New Zealand, on the other hand, has a maritime, temperate climate ideally suited to traditional European agriculture. Consequently production is comparatively predictable and may be year round in most locations. Periods of low rainfall are shorter and less widespread than in Australia, but do occur in the east of the country and in rain shadow areas adjacent to mountain ranges. El Niño tends to intensify the rain shadow effect so that easterly areas become drier than normal, and may lead to drought. A significant consequence of agricultural development has been the loss of native vegetation, including forests, wetlands and tussock grasslands, and biodiversity. Farming in New Zealand ranges from intensive to extensive practices. Intensive farming has higher concentrations of animal waste, fertilisers and pesticides and is implicated in the contamination of soil, groundwater and streams. Extensive farming of hill country has resulted in mass erosion, due to the loss of vegetation, resulting in the loss of topsoil and increased sedimentation of waterways. Agricultural development has been driven largely by economics, fluctuating with export prices and past government subsidies. There is currently increasing pressure for farmers to intensify due in particular to the global market for dairy products and niche market products, and improved technology.

In short, there are many reasons that the agricultural systems and practices in place in both Australia and New Zealand might be operating in a manner that is not sustainable over the long term. Specifically, these systems are generally operated at a local economic optimum, even those managed sustainably, but they may still be far from the dynamic optimum characteristic of a resilient state. Although systems may be operating usefully in the current social, economic and environmental climate, it may be the case that only a small perturbation or sequence of perturbations in any of a few sensitive processes might be enough to shift the system into an undesirable economic, social or ecological state. Importantly, the crossing of a catastrophic threshold may not be a directly observable phenomenon – in some cases it may take 50 years for the damage to become measurable (e.g. land clearing driving salinization). However, it is that first "invisible" crossing of this threshold that signals the irreversible decline of these systems. Modelling is one way of estimating the existence of these thresholds before it is too late.

Australia and New Zealand are both experiencing a rapid pace of change in various sub-components of the systems supporting landscape exploitation. In particular, environmental variability driven by the El Niño / La Niña cycle is expected to worsen with many climate change scenarios; both countries face the economic effects of globalisation, driving production intensification; and social change is driving many family-run enterprises to sell out to larger industrially-managed farms. Will these perturbations be large enough to push Australian and New Zealand systems over previously unidentified thresholds – as we've observed with salinization of prime agricultural land in much of Australia? Can we learn our lessons from these past examples, before we suffer a much larger collapse such as many early civilizations underwent when they overexploited their own limited natural resources (Brander and Taylor 1998)? Even if we are prepared to invest in the dynamic capacity of our agroecosystems, by what management practices will we improve the situation?

The answer for complex social-ecological systems appears to be something beyond "command and control". Holling and Meffe (1996) have discussed the pathology of command-control strategy in natural resource management. They point out that when command and control practices are applied to social or ecological systems in response to surprising or erratic system behaviour, resilience is typically lost as natural variation in the system is reduced. This pathology is particularly apparent when agencies focus on increasing the efficiency of control, often at the expense of the original goal, becoming isolated from the system and inflexible in practice. Intensification of agriculture and the social and economic institutions that support and are supported by them may be susceptible to this pathology. Management is likely to focus on short-term fast variables, and fail to incorporate feedback loops and cross-scale effects, thereby locking systems into a mode of operation that makes them brittle to unexpected change. Conversely, farmers and their institutions may be adaptable and amenable to system transformation, allowing them to avoid catastrophic change.

An improvement to command and control is “adaptive management” (Walker et. al. 2004, Folke 2004), which is a key tenet of resilience research being investigated by members of the Resilience Alliance. Techniques for operationalising adaptive management are still being developed, and the model systems discussed below will provide tools to support this process. Nonlinear models able to describe systems with multiple alternative states and the potential for catastrophic collapse are vital to inform our attempts to manage complex social-ecological systems, because external perturbations or management actions in one component of the system (e.g. government subsidies for graziers during drought periods) can have unexpected effects that interact with other components of the system (e.g. the quality of physical soil structure around watering points) in highly non-linear ways that can lead to unrecoverable total system collapse. Given the drastic consequences, these outcomes need to be tested, in models if possible, *before* they are implemented.

Resilience theory offers a framework for understanding the dynamics of complex socio-ecological systems, such as Australian and New Zealand agro-ecosystems. Understanding these dynamics is necessary for ‘managing’ and/or benefiting from complex systems. That is, adopting a resilience approach should allow effective management to a) prevent the system from moving to an undesirable configuration or changing its state; and b) to preserve the elements that enable a system to reorganise following massive change resulting from disturbance (Walker et al. 2004). In this sense resilience is a key component of sustainable management.

Operationalising Resilience

There are few examples of resilience operationalised in the context of Australian agroecosystems (Anderies et al. 2002, Anderies 2005, Kaine and Tozer 2005) and none for New Zealand. As part of our progress towards operationalising resilience in these systems we have developed a more general approach to operationalising resilience for generic landscape exploitation systems (Fletcher and Hilbert submitted). What we hope to do is extend these and other compatible techniques to a wide range of agro-ecosystems and contexts to build a critical mass of data, models and literature addressing these issues. We do not yet have the capacity to model every aspect of adaptively managed Panarchies, and we may never be able to do that successfully. But that does not mean that beginning to apply developing mathematical techniques to these imperfectly understood systems will not provide another useful source of information to help inform more qualitative socially-informed research, as well as more precise simulation models of ecosystems, agricultural systems and economic systems.

Every model must identify the boundaries over which it will attempt to approximate a real system. Our claim is that the appropriate scope for many human-managed natural resource systems requires a dynamic model of interacting social, economic and ecological subsystems, in line with Panarchy theory. We require a whole-of-system model because interactions between sub-systems support feedback loops that *dominate* the short and long-term deterministic response of the system. We require a dynamic model because it is the response of these underlying mechanistic processes that determines the long-term ability of human-managed resource systems to persist in strongly variable social, economic and ecological environments.

In addition to these mathematical considerations, by focusing on interacting social, economic and ecological systems, we are fundamentally dealing with inter-disciplinary research. Understanding whole-of-system dynamics requires true integration; i.e. integration between disciplines and disciplinary methods, and integration of results. Because feedback processes dominate the dynamics of the systems in which we are interested, simply compiling a pool of discipline-polarized models or results is not enough; each model must be integrated into the system-wide context. This is often difficult both scientifically and logistically. We propose to address this by framing our study systems in terms of conceptual systems models, and using these conceptual models to identify gaps in our knowledge of how these systems function and the consequences of those dynamics. We will then focus the experimental and dynamic modelling research on those gaps. The results from this research will be integrated back into the conceptual models, improving understanding, and inevitably opening up further research avenues.

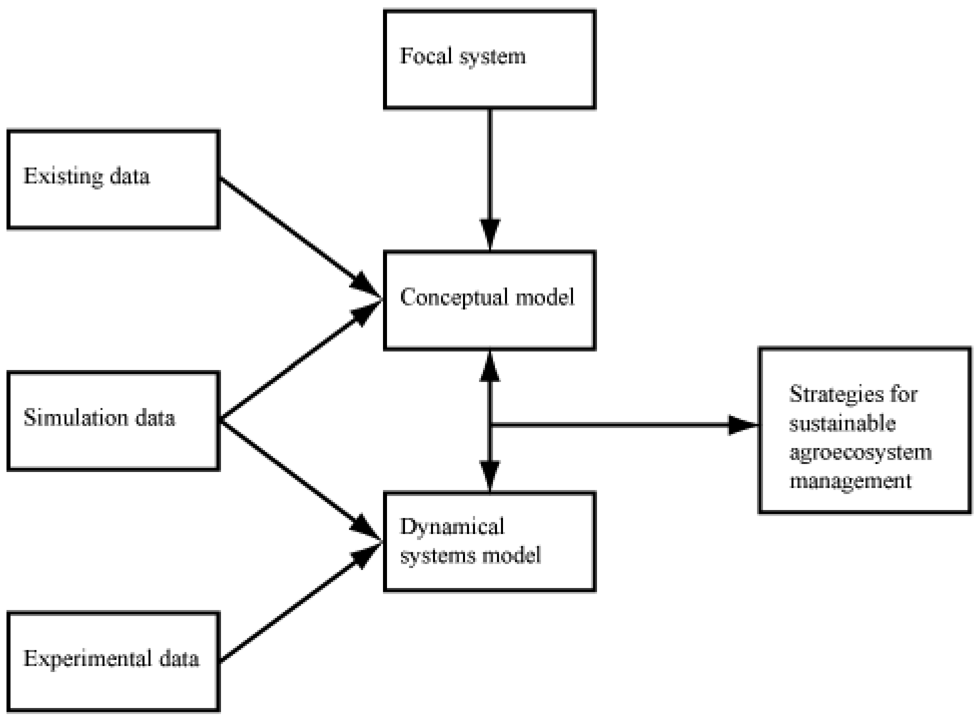

Figure 1. Typical configuration of a case study under the IPRRA. A conceptual model is established to address a specific question for a given focal system. The conceptual model begins as a systems-wide description encompassing social, economic and ecological sub-components, which is gradually refined to focus on the dominant processes and feedbacks appropriate to the question and scale of the study. The conceptual model is informed by expert disciplinary knowledge, including existing data and data generated by simulation models. The focused conceptual model is then formalised as a dynamical systems model. Knowledge gaps, especially those at disciplinary boundaries and related to feedbacks, are addressed by combinations of simulation-generated data and specifically focused experimentation to generate new data. The output from the dynamical systems model feeds back into the conceptual model of the system, and vice versa, such that both models develop concurrently. These models then represent our understanding of the focal system, and, in particular, our understanding of the potential nonlinear response and collapse of the system, which can be used to inform the development of strategies for sustainable agroecosystem management.

The model design and validation will mirror the project design, refining the broad conceptual model as information becomes available. The results of this process will, of course, feed back both to the mathematical model and the conceptual model framing the project, ensuring that a system-wide approach perspective is maintained at all times. We will use the following approach to our research:

1. Identify a focal agroecosystem to be studied.
2. Develop a conceptual model of the system, identifying the components that make up the system and the interactions between components, and determining which subsets are of greatest interest.
3. Identify the scale at which components or interactions arise and the scale at which they act.
4. Identify the variables that maintain system dynamics.
5. Identify the variables that may lead to novel responses to change.
6. Develop a dynamical systems model, or suite of models, that incorporates data from existing studies, simulation studies (e.g. Ecomod [NZ]), and targeted research.
7. Results from the dynamic models will feed back into the conceptual models of the focal systems, resulting in improved understanding of how the systems operate.
8. Improved understanding of how the systems operate will allow the development of new or improved strategies for sustainable agro-ecosystem management.

Each specific case-study that we examine under this developing research program will share this common dynamic social, economic and ecological framework, but will necessarily focus at appropriate spatial and temporal scales, with a varying emphasis on each sub-system. This common framework underpins the strength of the program: there are many congruent lessons to be learnt about fostering dynamic capacity and to be applied across a range of human-managed natural resource systems, at a variety of scales. For instance, regional scale resilience of extensive Australian grazing systems may depend on efficient communication of economic indicators across solid social networks, but the same mathematical techniques focused with different emphasis at different scales might be able to quantify the pressures exerted by intensification of New Zealand's already intensive dairy grazing industry on down-stream water quality, or the susceptibility of an individual NZ dairy farm to loss of production capacity following over-fertilization as a short-term response to an introduced pest like clover root weevil (Sitona lepidus (syn. flavescens)). Trying to encompass this range of systems in a single grazing system model is not practical, but creating separately focused, efficient models to a common framework allows some of this learning to be leveraged across these systems.

We intend to examine the resilience of the dairy industry (intensive farming) and the meat industry (extensive pastoralism) in both New Zealand and Australia, as well as the resilience of native biodiversity within these agricultural landscapes. In addition to the dynamical systems approach discussed below, we will use other methods where appropriate, such as network analysis (e.g. Janssen et al 2006), to increase our understanding of resilience in these social-ecological systems.

Resilience of Landscape Exploitation Systems

Simple, low dimensional models with aggregate state variables can usefully abstract the general dynamics of agroecosystems, in a similar manner to the way in which a predator-prey model abstracts the population dynamics of general trophic interactions (Lotka 1932, Volterra 1931). Of course, these simple models may not describe a specific system optimally for all purposes, but they do achieve a general applicability across the wide range of systems in which we are interested. They strike a balance between precise, reductionist description and a whole-of-system perspective that is appropriate to answer the question: "what are the fundamental drivers of resilience in *all* exploitation systems?" These simple model structures are useful because in human managed agroecosystems it is the *feedbacks* between the social, economic and ecological sub-systems that determines the long-term system behaviour. Moreover, feedbacks are less well understood than stocks or flows of physical materials, and are extremely difficult to quantify precisely. The accuracy of such simple models is compatible with the random variability of natural and human systems which often exceed variability of external variables. We attempt to look for *structural* descriptors of major system interactions that result in properties, like thresholds, beyond which the system might experience catastrophic collapse or regime shifts from stable to oscillatory behaviour.

Like the predator-prey model of ecology, we define our systems as a system of differential growth equations for key state variables. We aim to include some aspect of the social, economic and ecological system components in each model, while at the same time maintaing a model structure simple enough to maintain analytical tractability. Achieving this fine balance requires constructing a new models not only for each specific system, but also for each perturbation regime in which we are interested. By referring these suites of dynamical systems models back to our conceptual systems models, and because many of the mathematical relationships will be transferrable between various dynamical systems models, we will build a practically useful understanding of the resilience of real systems from these simple models.

Once we have specified the basic structure of the system, we can begin to analyse key measures of system performance: both traditional indicators, like profitability; and indicators of dynamic performance, such as resilience (Fletcher and Hilbert submitted). One of the strengths of the dynamical systems approach that we apply is that it is possible to analyse the general system analytically, *without* limiting parameter values. This allows us to analyse systems extremely broadly to find *all* possible thresholds in the system, something that simply cannot be done efficiently with more complex simulation models.

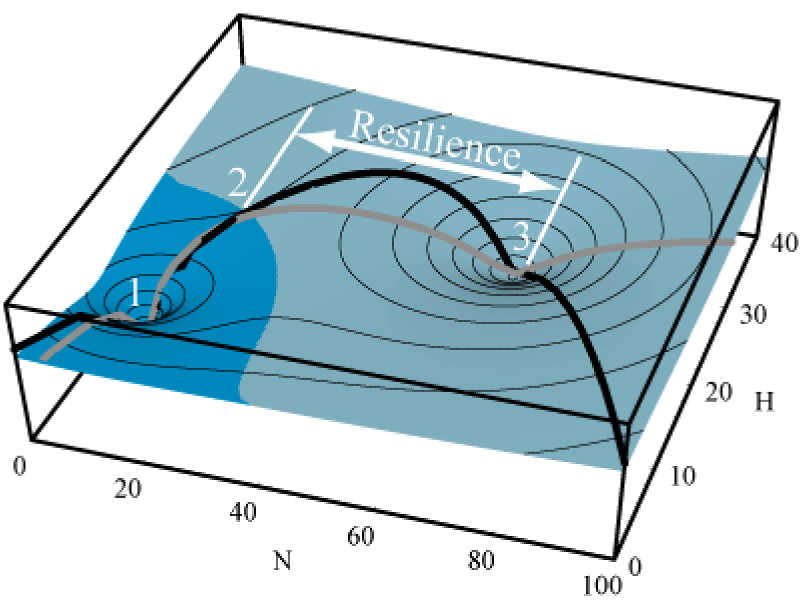

Figure 2. The familiar basin of attraction analogy of resilience. Two basins (light blue, dark

blue) exist centred about stable critical points at 1 and 3. The edge of the basins passes through point 2 at the unstable critical point of the system. The surface making up the basins is generated (analogously, not literally) from the differential equations that define the system. We can imagine the instantaneous state of a real system being represented by a ball at a single coordinate located somewhere on this surface. A ball representing a system initially located the desirable basin (light blue) would roll about the basin, but gradually move towards the stable point at the bottom of the basin (3). Similarly, a ball in the dark blue area would move towards the undesirable stable point (1). Within a given model structure the ball can only cross from the light basin to the dark (i.e. a system "collapse" from a desirable to an undesirable state) under the action of "perturbations" or forces outside the scope of the model. The size of the perturbation needed to kick the ball across the boundary and cause the collapse of the system is called the resilience. In this case, we are interested in the resilience of a generic landscape exploitation system to loss of the state variable named *N*, so we measure the distance parallel to the *N* axis between the desirable stable point (3) and the unstable node (2). This is a summary indicator of the "typical" size of perturbation needed to cause system collapse; in a particular situation the actual perturbation required might be larger or smaller depending on the instantaneous configuration of the system. The point is that, in general, a system with larger resilience is more likely to survive a perturbation than a less resilient system.

The idea is that the system of differential equations define a multi-dimensional surface in state and parameter space that constrains and drives the evolution of any given exploitation system, represented as a single point in that space. This is the generalisation of the familiar "ball in the basin of attraction" analogy, illustrated in Figure 2. This is not a perfect analogy: the surface in the figure is not a potential surface; but it is a useful thought tool to illustrate an important but subtle concept. Often, the "steady states" at the bottom of each bowl are presented as the "solution" to the system equations, because over long time periods a deterministic system will tend towards the steady state. However, it is really the whole surface that represents the behaviour of the system, which is vitally important in highly stochastic social ecological systems. Analogously, whatever the current configuration of the system, it will occupy a single point in state space, and the shape and slope of the surface at that point will determine how the system evolves into the future. We could use the surface to run a simulation of a specific scenario, but instead we choose to measure the topography of the surface using summary indicators. Those summary indicators do not precisely enumerate how a given system evolves, but they do represent an "average" of the dynamic behaviour of the system: that is, how the system responds to change. In this sense, the specific configuration of a system at a given time (the precise values of the state variables and the parameter values) are not vital information: we have accepted that our model is imprecise, that fundamentally it must be so in natural systems suffering climatic variability and social systems at the whim of personal decision, and we measure average indicators of performance compatible with that precision.

The key indicator of dynamic performance that we use is the *resilience* of the system. In the case illustrated in Figure 2, the resilience is the distance, parallel to the *N* axis, between the "desirable" steady state and the edge of the basin. This represents an "average" measure of the maximum instantaneous loss of natural capital the system can receive, and still recover towards the "desirable" steady state. In the real world, we are talking about an early civilization that loses, say, half its food crop to a summer storm, or an extensive Australian grazing system that loses half its forage to a bushfire. Will the system gradually recover, or will the perturbation lead to catastrophic collapse? In a given case the precise location of the system might be closer or further from the threshold to collapse than the long-term steady state, but in some average sense, if the size of the perturbation is less than the resilience the system will probably survive. This is the technique we use to estimate the capacity of generic landscape exploitation systems to survive in a variable real world environment.

Conclusions

We predict that managing social-ecological systems for resilience will become an essential driver of sustainable land management, but that progress towards this goal will only be made when resilience can be effectively operationalised (*sensu* Carpenter et al 2001). Our aim is to further develop a program of research that compares agroecosystems in Australia and New Zealand, utilising novel modelling techniques and experimentation at appropriate scales. We are interested in augmenting our ability to describe the capacity for current agricultural practices, farms and industry sectors to continue operating successfully in an uncertain and variable world. Assessing the resilience of these systems relative to identifiable changes occurring in Australia and New Zealand now and in the future is a key component of our objectives. Where the prognosis is not good, we also intend to identify alternatives that will allow efficient transformation of social, economic or ecological systems to more resilient practices.

Dynamical systems models provide a means of acknowledging and accounting for the uncertainty inherent in social-ecological systems, and they are a significant tool that we will be utilising and progressing through our research. A key tenet of our approach is that we will recast our dynamical systems models not only for different systems, but also for different questions about the same system. What we gain is the otherwise inaccessible ability to model feedbacks and system dynamics, which we claim are the crucial components to determining nonlinear response and potentially identifying thresholds of collapse. The cost is that we must invest in models focussed precisely on a given question in our chosen system. We will also apply other complimentary methods for assessing and determining the resilience of agro-ecosystems, such as the network theory of resilience.

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