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Synthesis

Complex Land Systems: the Need for Long Time Perspectives to Assess their Future

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ABSTRACT. The growing awareness about the need to anticipate the future of land systems focuses on how well we understand the interactions between society and environmental processes within a complexity framework. A major barrier to understanding is insufficient attention given to long (multidecadal) temporal perspectives on complex system behavior that can provide insights through both analog and evolutionary approaches. Analogs are useful in generating typologies of generic system behavior, whereas evolutionary assessments provide insight into site-specific system properties. Four dimensions of these properties: (1) trends and trajectories, (2) frequencies, thresholds and alternate steady states, (3) slow and fast processes, and (4) legacies and contingencies, are discussed. Compilations and analyses of past information and data from instruments and observations, palaeoenvironmental archives, and human and environmental history are now the subject of major international effort. The embedding of empirical information over multidecadal timescales in attempts to define and model sustainable and adaptive management of land systems is now not only possible, but also necessary.

Key Words: *adaptation; complex systems; Global Land Project; land systems; multidecadal timescales; resilience; socioecological systems; sustainability science*

INTRODUCTION

Land Systems

Climate change continues to be a major research thrust within global environmental change and sustainability research, but with increasing emphasis on how society may adapt to future stresses. At the international level, this emphasis is visible within global environmental-change research reports and agendas, such as those of the Intergovernmental Panel for Climate Change (IPCC), the Millennium Ecosystem Assessment (MA), the International Geosphere–Biosphere Programme (IGBP), the International Human Dimensions Programme on Global Environmental Change (IHDP), and the newly minted Programme on Ecosystem Change and Society (PECS). Among these, the IGBP (2008) defines urgent research needs in terms of identifying thresholds or tipping points, regions where society is vulnerable to climate, that is, climate hotspots, and "climate information systems" for adaptation. Carpenter et al. (2009) summarize the priority needs for managing ecosystem services. They identify the need to improve the means by which socioenvironmental systems are anticipated and managed in the face of likely or projected changes in, for example, climate, biodiversity, resource use, demography, economics, and governance from global to local scales.

The Global Land Project, sponsored by IGBP and IHDP, focuses on "land systems" (GLP 2005): the kind, amount, distribution, and pattern of land uses and covers, among major socioenvironmental systems (Turner et al. 2007). Assessing land-system dynamics requires attention to processes operating at different spatial and temporal scales, to interactions between different drivers and, especially, to policy shifts that often lead to emergent properties and nonlinear outcomes. As it becomes more apparent that future societies may be exposed to multiple, simultaneous perturbations and stressors (e.g., Leichenko and O'Brien 2008,

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Rockström et al. 2009, Turner et al. 2007), and not just climate change, national emphases on the means to understand and manage land systems are becoming stronger and clearer, for example, in the UK (Living with Environmental Change) and USA (United States Global Change Research Program).

At the same time, we are beginning to see a change in our understanding of the nature of interactions between the social–economic–cultural and the biophysical environment. Well into the 20th century, the dominant public view in the Western World envisioned humans as adapting to or improving environmental dynamics through changes made in the environmental subsystem at regional scales (Marsh 1864, Thomas Jr. 1956). Subsequently, that view has shifted to encompass the detrimental effects of human stresses at the scale of the earth system (Turner et al. 1990, Steffen et al. 2004). This shift is part of a wider reconceptualization of how to view, investigate, and deal with socioenvironmental dynamics (Newell et al. 2005). New avenues of research now define societal and ecosystem interactions, vulnerability, and resilience (e.g., Elmqvist et al. 2003, Turner et al. 2003, Eakin and Luers 2006, Diffenbaugh et al. 2007) as part of the process by which we assess what knowledge is required to anticipate future impacts.

This process acknowledges that the condition and consequences of land systems involve multiple tradeoffs of climate and other stressors within and among social and environmental subsystems. Some of these stressors are environmental, such as the acidification of the oceans or the impact on ecosystems of phosphorus in runoff, where there is already increasing evidence that the environmental subsystem is approaching potential thresholds (Pielke 2006, Lenton et al. 2008, Rockström et al. 2009). Stressors inherent in the dynamics of the human subsystem involve demographic, economic, governance, and environmental-perception factors. In many situations, these are brought about by societal transformations that are altering the context for adaptation to climate change (Liechenko and O'Brien 2008). The subsystems involved tend to respond more quickly and strongly to extreme events than to changes in their mean operating conditions. This implies that when these subsystems are coupled, the responses to multiple stresses may be amplified by positive feedback, resulting in a high probability of crossing thresholds (Doherty et al. 2009, Rockström et al. 2009). Therefore, understanding and anticipating the outcomes of these coupled dynamics is made difficult by the multiplicity of processes operating over various spatial and temporal scales with the associated unpredictable properties (e.g., Liu et al. 2007). A focus on any particular subsystem or preoccupation with simplistic causation will fail to deal with the real challenge of reducing uncertainty in regional land systems.

The Need for Long Timescales

It is well understood in climate-change research that the temporal scale of assessment affects the understanding of the dynamics and outcomes observed; subdecadal observations may run contra to decadal or centennial ones. Here, we argue that assessments of multiple stresses acting on complex and coupled land systems are similarly affected, demanding a new and explicit focus on multidecadal timescales of past information that are longer than those normally represented by observational and instrumental data (Dearing et al. 2006*a*). Therefore, a major research priority for sustainability science is not only place-based and comparative, but long-term (Carpenter et al. 2009).

In the absence of such a focus, we will be unable to view some of the slow, decadal–centennial or even millennial trends in environmental and cultural dynamics that define stability. Nor will we be able to identify the existence of second-order changes, such as changes in the perception of challenges as a society evolves, or changes in the land dynamics that are because of continued appropriation of the environment by that society. Likewise, assessing the types of threshold change inherent within a system and the likelihood of transgressing thresholds in the future is daunting without the benefit of hindsight (cf. Lenton et al. 2008). Also, the predictive value of models is substantially increased where the models are shown to simulate known changes over the same decadal time span as desired for the future.

Without a long-term perspective, we impose an a priori limit on the total number of states of the socioenvironmental system that we are able to study and understand, and bias our knowledge toward the heavily perturbed system states observed in the recent past. This is comparable to examining a seriously ill patient without knowing what a healthy one looks like. In short, without a long-term focus, our understanding of the evolution of socioenvironmental systems will likely inhibit robust assessments of the challenges facing us. Some notable exceptions notwithstanding (Turner et. al. 1995, Foster and Aber 2004, Turner et. al. 2004), current assessments of existing land systems or their future states are often flawed by the sparse attention to timescale.

At the outset, two potential barriers face attempts to construct long-term perspectives for land systems. First, a framework for studying land systems would ideally encompass the whole range of relevant temporal (and spatial) scales from the very long, multimillennial to the very short (annual, seasonal or even shorter), even though in practice the relevance of any timescale cannot normally be known a priori. However, the practitioners of the study of these different timeframes are weakly linked within the research community (Dearing 2007*a*), even though their joint efforts are crucial for determining the full range of temporal variability within a system.

Second, there is a paradox implicit in the study of long timescales that is exemplified by the Anthropocene (Crutzen 2002, Steffen et al. 2004). A long timescale of observations was needed to place the contemporary world in its historical context and to identify the growing impact of human activities on the Earth’s system. However, the rapidity of contemporary change is such that the natural and social-science research communities alike have not fully come to terms with the no-analog implications of the Anthropocene, especially in terms of whether the pace of recent change (Steffen et al. 2004) renders useful comparisons to the past difficult—or invalid. This issue is further complicated by the growing recognition that complex systems demand analysis of dynamic behavior, which shifts the emphasis away from equilibrium to nonequilibrium approaches. It is, perhaps, excessive to conclude that stationarity is completely dead, as some have asserted for water resources (Milly et. al. 2008), but the point is well taken: understanding coupled system dynamics, land or other, requires attention to changing boundary conditions and the possibilities that multiequilibria may exist (e.g., Berkes et al 2003). Therefore, the epistemological basis for learning from the past, especially with regard to the analog approach, demands further discussion.

Uses of the Past to Inform Land Systems: Analog and Evolutionary Approaches

Learning from the past to inform current and future assessments of land systems has conventionally focused on analogs (Meyer et al. 1998, Costanza et al. 2007). In most cases, past states of land and resource-use systems are more or less disconnected from the present insofar as few processes function in ways that are continuous across the whole timescale or that are common to both the past and present states. In this sense, the analog serves largely as a heuristic. These heuristics, especially those directed toward the public at large, tend to use an unsustainable trajectory or outcome of a past system, such as resource stress and climate change, as providing broad dimensions or understanding of a current complex system (e.g., Glantz 1994, Landes 1998). Examples include the resource stress on Easter Island (e.g., Diamond 2005), the collapse of Classic Period Maya civilization because of land stress, warfare, and climate change (Gill 2001, Haug et al. 2003), and the end of the Roman Empire because of its overextension and excessive administrative overhead coupled with financial mismanagement (e.g., Tainter 1988).

Heuristic analogs offer insights into differences and similarities among cases, and sensitize the expert and public communities about possible surprises and response options (Meyer et al. 1998). However, such analogs are imperfect matches with the present, especially with regard to technological and sociopolitical conditions of the human subsystem, and often inappropriate (Meyer et al. 1998, Wescoat 1991). The complexity of land systems, particularly as it affects system outcomes, is a major reason why sustainability science orients itself toward place- and time-based assessments (Kates et al. 2001). In addition, past case studies tend to be over-represented by disasters and unusual situations, biasing the lessons that may be gleaned from them.

Thus, analogs prove problematic for systematic assessments of current and future land systems, especially as boundary conditions change. However, by studying a substantive number of instances of land dynamics over sufficiently long time periods, even if disconnected from the present, we may be able to generate models that are initially conceptual, and later perhaps quantitative, of the interaction of a number of the more general processes to which such systems are subject (e.g., Zhang et al. 2007). For example, the kinds and magnitudes in the drawdown of certain ecosystem services that serve as tipping points in the environmental subsystem may be revealed. Following Tainter (1988), it may be possible to derive a typology of land-system behavior related to complexity theory, such as the apparent fragility of strongly interconnected systems. Given the uncertainties and assumptions embedded in ancient human subsystems, the phenomena that we are interested in studying, such as structures of resource entitlement, may be better served by case studies in which written records exist. Nevertheless, comparisons of a sufficient number of standardized land-system histories may enhance systematic assessments of postulated generalized complex system behaviors (Integrated History and Future of People on Earth 2009). This more systematic use of analogs fuses into the second means of drawing on the past to inform the now and future.

In contrast to analogs, an “evolutionary” view of the past focuses on long timescales where the present remains continuously and strongly connected to the past, described elsewhere as extending the present to define a “long now” (Brand 1999, Carpenter 2002). These connections address processes that may operate over long timescales, are repeated regularly, or involve time lags, contingencies, emergent effects, or past legacies that are integral to the functioning of the contemporary and future system. Studies that connect the present and past by integrating observational, documentary, and reconstructed data provide a perspective that may be critical to understanding all the elements of contemporary system dynamics (Fig. 1). Importantly, long time series of data and information may be the only means by which to confirm the existence of theoretical or conceptual complex system behavior, e.g., alternative steady states, the adaptive cycle, contingent and emergent properties, and feedback mechanisms, in a real-world system.

In the context of global environmental change, the more that societies face no-analog situations, the more this long and continuous perspective becomes critical. In this nonanalog, evolutionary context, we can ask fundamental questions that are relevant to any contemporary land system. Where in a system do positive feedback mechanisms exist? How have they evolved? How long is their path? What are the key contingent states? How have fast and slow processes interacted to create the feedback mechanisms? Which complex dynamics operate? With this information, how do we anticipate and manage future states? Long timescales are crucial to addressing these types of questions in at least four different, but not mutually exclusive, dimensions.

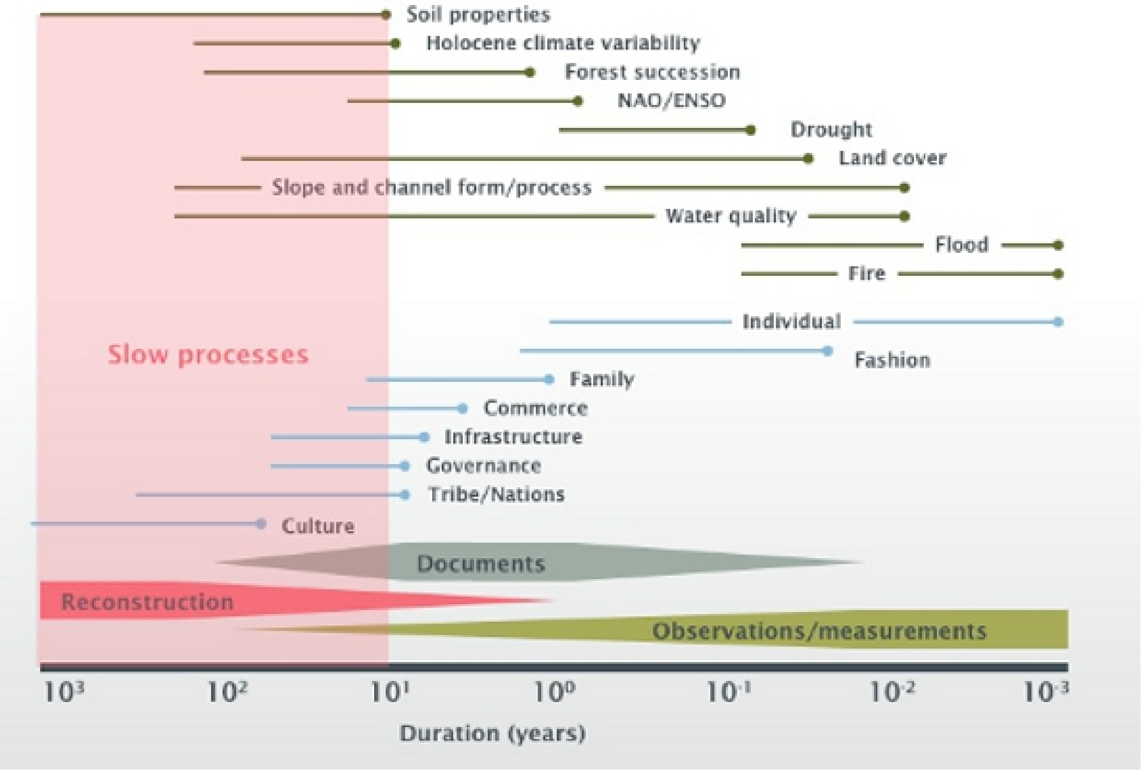
FOUR DIMENSIONS OF LONG TIMESCALES FOR LAND SYSTEM ASSESSMENT

Trends and Trajectories

Signatures indicating the form and direction of change are important to understanding the dynamics of contemporary land systems. They signify the magnitude of change from past periods to the present, possibly indicating how far from an equilibrium state the present system or subcomponents are. Without the long perspective, it is difficult to distinguish between linear, or first order, and accelerating / decelerating, or second order, change. Steffen et al.’s (2004) compilation of global social and environmental processes allows definition of the period since the 1950s as “The Great Acceleration,” vividly illustrating the accelerating pressures, losses, and exploitation of resources (Fig. 2). In the ancient past, we have also observed the accelerating trends of escalating resource and land demands in many case studies, for example, the Easter Islands or Maya heartlands. Such evidence focuses attention on the potential dangers of convergent stressors on modern society and the environment set within “perfect storm” scenarios (Beddington 2009). We may presume that similarly accelerating trends are common for many regions and local scales, such as the desiccation of the Aral Sea, but few systematic subglobal assessments of the magnitudes and rates of socioenvironmental change exist over decadal timescales.

There are attempts to define the environmental health of regions through analysis of recent environmental trajectories; for example, the work on socioenvironmental syndromes (e.g. Lüdeke et. al. 2004), or the European typologies of regional environments (European Spatial Planning Observation Network 2006), and the comparison of regions at risk (Kasperson et al. 1995). However, with exceptions such as Meybeck’s (2003) typology of river water-quality regimes, these are essentially based on relatively short records obtained from census, instrument, and satellite-image data. An extended, quantitative temporal dimension drawn from environmental history and palaeodata

Fig. 1. Slow and fast processes.

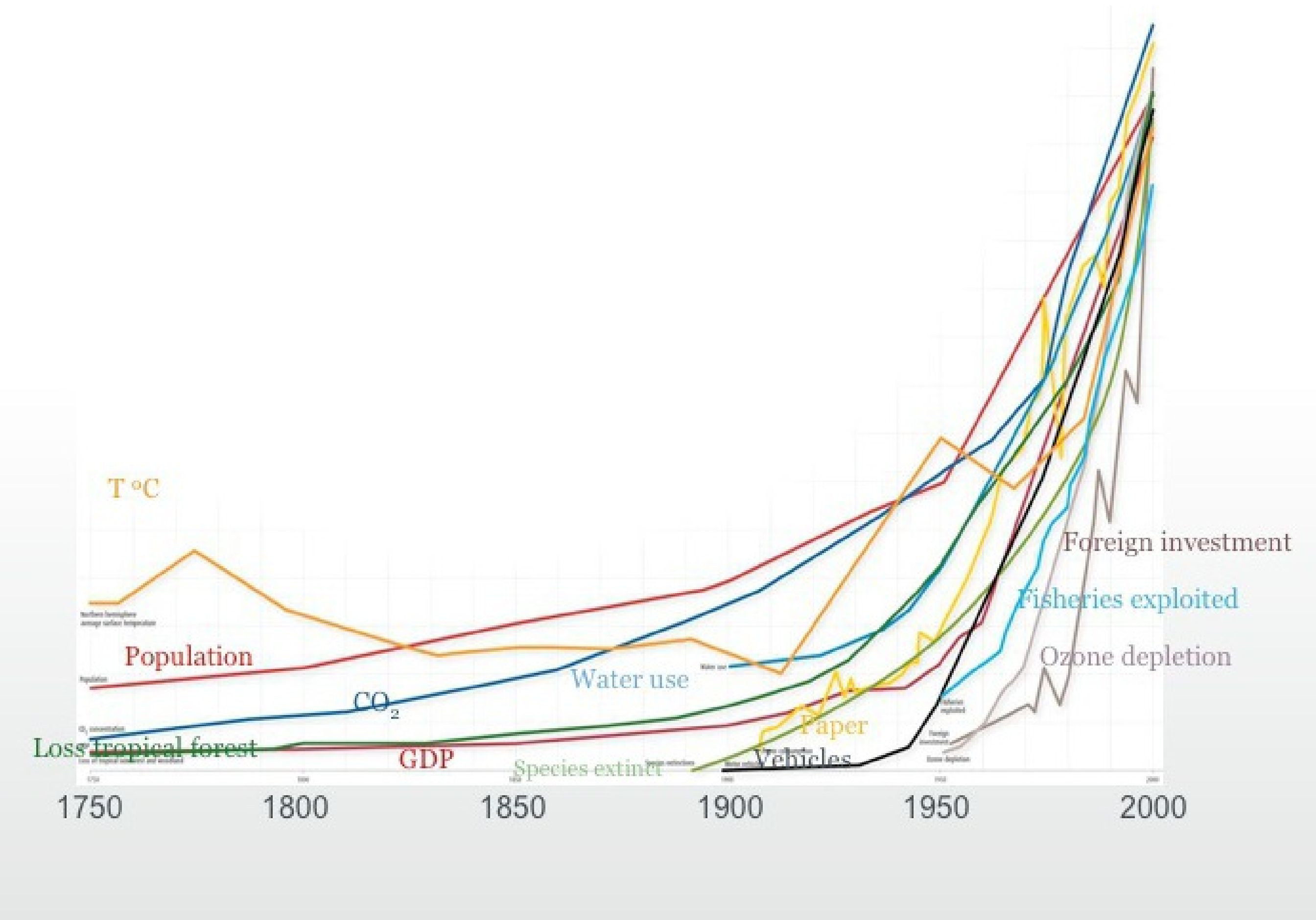


Note: Timescales for a range of biophysical and socioeconomic phenomena range from “fast” subannual events (e.g., floods, fire) to “slow” multidecadal and centennial changes (e.g., culture). Understanding contemporary socioecological systems may require information from a similar range of timescales, but sources of information become more limited for longer timescales. The sources of information available for each segment of timescale with respect to the present are depicted by the lower horizontal bars. Observations and measurements (e.g., instruments, remote sensing, censuses, economic statistics), and documents (e.g., diaries, gazetteers, land use descriptions) may only be available for relatively short timescales. Changes over longer timescales of change that are essential for assessing the role of “slow” processes (the thick vertical bar) may need to be reconstructed. Reconstruction covers all the palaeoenvironmental fields, including archaeology, palaeoecology, palaeoclimatology, and palaeohydrology, that interpret artifacts and natural sediment archives (e.g., lake sediments, stalagmites, peat) in terms of past environment and society. After Oldfield (1983) and Brand (1999).

provides a more robust basis for examining the trajectories (e.g., Dodson and Mooney 2002) of relatively slow processes, such as changes in water quality, rates of geomorphic instability, or the evolving nature of socioenvironment interactions (e.g., Geist and Lambin 2002, Parton et al. 2007, Stafford Smith et al. 2007). The ecological processes and human activities of land systems can be strongly interdependent across spatial and temporal scales (Kasperson et al. 1995). Thus, integrating a range of different types of long-term records can provide comprehensive environmental profiles of that interdependency (e.g., Olson et al. 2008).

Trends may also signify emergence: evidence for bottom-up processes interacting at a local scale producing higher-level structures that are both qualitatively different from their lower-level constituents and not obtainable through simple

Fig. 2. Trends and trajectories.



Note: Changes in global states and processes since AD 1750, including ecological services, climate variables and economic data, show systematic acceleration in rates from the mid-20th century: the Great Acceleration. After Steffen et al. (2004), redrafted at http://rs.resalliance.org/2008/12/04/visualizing-the-great-acceleration-part-ii/.

aggregation of microlevel components (Auyang 1998). Many, if not most, high-level forms and structures in land systems are emergent, (e.g., Lansing and Kremer 1993, Ostrom 2009), including land-tenure patterns, governance structures, trading agreements, agricultural ecosystems, irrigation systems, and river patterns. The importance of emergent forms is less with their identification than with the elucidation of how they have evolved. For instance, collective action is shown to influence land use in ways different from the effect of individual households (e.g., Bousquet et al. 1998, Rouchier et al. 2001, Nagendra 2007), and the totality of individual land-use decisions may trigger regional changes in precipitation (e.g., Pielke et al. 1999, Malhi et al. 2007). Such examples are extensively documented for recent decades, but two studies demonstrate the increasing realization that longer multidecadal and even centennial perspectives may be important.

The first study integrates environmental history, geomorphological investigations, and lake-sediment records from the English Lake District stretching back several centuries (Chiverrell 2006). It makes a compelling case for landscape instability being the result of major changes in land use rather than climate, particularly overgrazing and rapid reductions in woodland/shrub cover. This implies that the recent ending of the European Union Sheep Annual Payment Scheme, where payments are scaled to stock levels, should have beneficial effects in terms of reducing overgrazing and encouraging land stewardship. However, managers who address the objectives of the Lake District Environmental Sensitive Area plan also need to be aware of the likely sensitivity of soil degradation to future clearance or burning of secondary woodland/scrub.

The second study contrasts in scale and context, but the approach taken is similar. The Murray-Darling basin is possibly Australia's most critical resource management issue, with 95% of its river length degraded (Gell 2007). The Murray lakes and lagoons are under pressure from different stressors, with the Coorong coastal wetlands, an internationally significant site (Ramsar Wetland Convention), a particular concern. An integration of decadal–millennial reconstructions of water quality (diatoms) and land cover (pollen) at many sites with land-use histories and hydrological modeling allows reconstruction of interactions and feedback through space and time (Gell et al. 2007). The diatom studies show that many wetlands have been degraded for over 100 yrs as a result of land clearance that started more than 200 yrs ago. This means that restoration of the Coorong system is a greater task than was expected in a government decision to use 1985 as a baseline target. Revegetation initiatives to combat soil erosion and soil salinity are planned, but these may reduce river flows at a time when climate change is projected to drive down runoff by as much as 25% already by 2030 (Gell et al. 2007). A 200-yr trajectory has now left managers with very few options that can satisfy international agreements for conservation as well as the needs of agriculture and water-resource users.

These examples underline the need for regional integration of multidecadal data for socioenvironmental processes. This need is particularly important to the development of policies and strategies in regions where successful management of key environmental processes, ecological services, and their interaction is critical: for example, within "wildlands," biodiversity hotspots, areas projected to experience climate change extremes, or socioenvironment systems projected to be particularly vulnerable to combinations of stressors (Dearing et. al. 2006*b*, Past Global Changes 2009). Such regional integration is essential if we are to gauge whether trends leading to the present are divergent or convergent: the former suggesting that we may be able to deal with stress effects of drivers individually; the latter implying that drivers of change may in the future interact to compound their effect. This information helps determine the likely stress levels in the future and, logically, the array of choices that society is able to make.

Frequencies, Thresholds, and Alternate Steady States

Trends provide historical perspective for contemporary land systems, but concern about the future of land systems often focuses on the likelihood of abrupt change, the changing magnitude and frequency of predictable events and the possibility that unpredictable change across a threshold may push the system to a new state. Scheffer et al. (2001) review such changes in ecological systems, emphasizing the idea of a stability landscape that changes its shape through time, while Lenton et al. (2008) have identified a number of potential tipping points in the earth system based on analysis of changes reconstructed from palaeoenvironmental records. They caution against the use of past changes in making projections for the future because the boundary conditions under which they occurred were different from today and anthropogenic forcing is generally more rapid and different in pattern. Nevertheless, the ranking of potential thresholds has made a large contribution to the debate on the possible consequences of global warming.

For socioenvironmental systems, there are already ~270 recorded threshold transgressions of key ecological states and services at regional–local scales (http://www.resalliance.org/183.php), but information is still lacking for key land-system types. New datasets for key land systems would add considerable value to our understanding of the nature and timescales of "typical" threshold transgressions and help gauge the possibilities for recovery from ongoing or projected disturbances. We have many examples of threshold transgressions in ancient land systems (e.g., Redman 2001, Lawrence et al. 2007), and there is scope for more systematic, spatiotemporal analysis of the processes occurring in these instances to provide generic insights about thresholds (e.g., Whitmore et al. 1990). This might help mitigate the paucity of information about threshold transgressions in recent history that directly affects contemporary land systems.

For example, it has been shown that the recent vulnerability of the Sahel to climate is impossible to gauge without an extended temporal perspective. Historically, systemic resilience was created through the diversification of livelihoods, and it seems that systemic thresholds were crossed only recently (Reenberg 2009). The nomadic cultures that developed around pastoralism over the last 5000 yrs became well adapted to the unpredictable resource base (Brooks et al. 2005). However, in the 1950s and 1960s, the Sahel experienced unusually high rainfall that coincided with the independence of the nation states in the region. This concatenation of societal and environmental events created a large incentive to increase the number of settlements that, in turn, had profound implications for the vulnerability of the agricultural system. Cultivation expanded into marginal lands and influenced future vulnerability, essentially driving the land system across an irreversible threshold. In contrast to the times before 1950, the intra-annual and interannual variability of rainfall in the 21st century has lessened the ability of the land system to sustain the significantly increased local population with food in any given year (Reenberg et al. 1998, Nielsen and Reenberg 2009*a, b*).

Whether or not rapid change is actually a threshold transgression or part of the natural variability of a system is often only possible to discern with hindsight. Land systems continuously vary in terms of process and state conditions over a range of timescales described in different terms in different fields, for example, as “magnitude and frequency” in hydrogeomorphology (Wolman and Miller 1960) and “risk spectrum” in hazard assessments (Cutter 2001). Sometimes an analysis of long-term variability, that is, changes in the frequency of events, for example, provides important insights into how human activities have modified the probability of extreme events and transgression of thresholds. In the southwest United States, for example, comparison of 400-yr fire-frequency records (fire scars in trees) with land-use histories (Fig. 3) shows that fire suppression measures have been instrumental in reducing the frequency of small-medium sized fires since 1900 (Swetnam et al. 1999). Contemporary statistics show that many sites are now at risk from catastrophic stand-replacing fires as dense scrub thickets fuel non-natural fire patterns. Such long-term studies of variability tend to confirm the view that contemporary human activities tend to push the risk spectrum toward catastrophic events occurring with increasing probability.

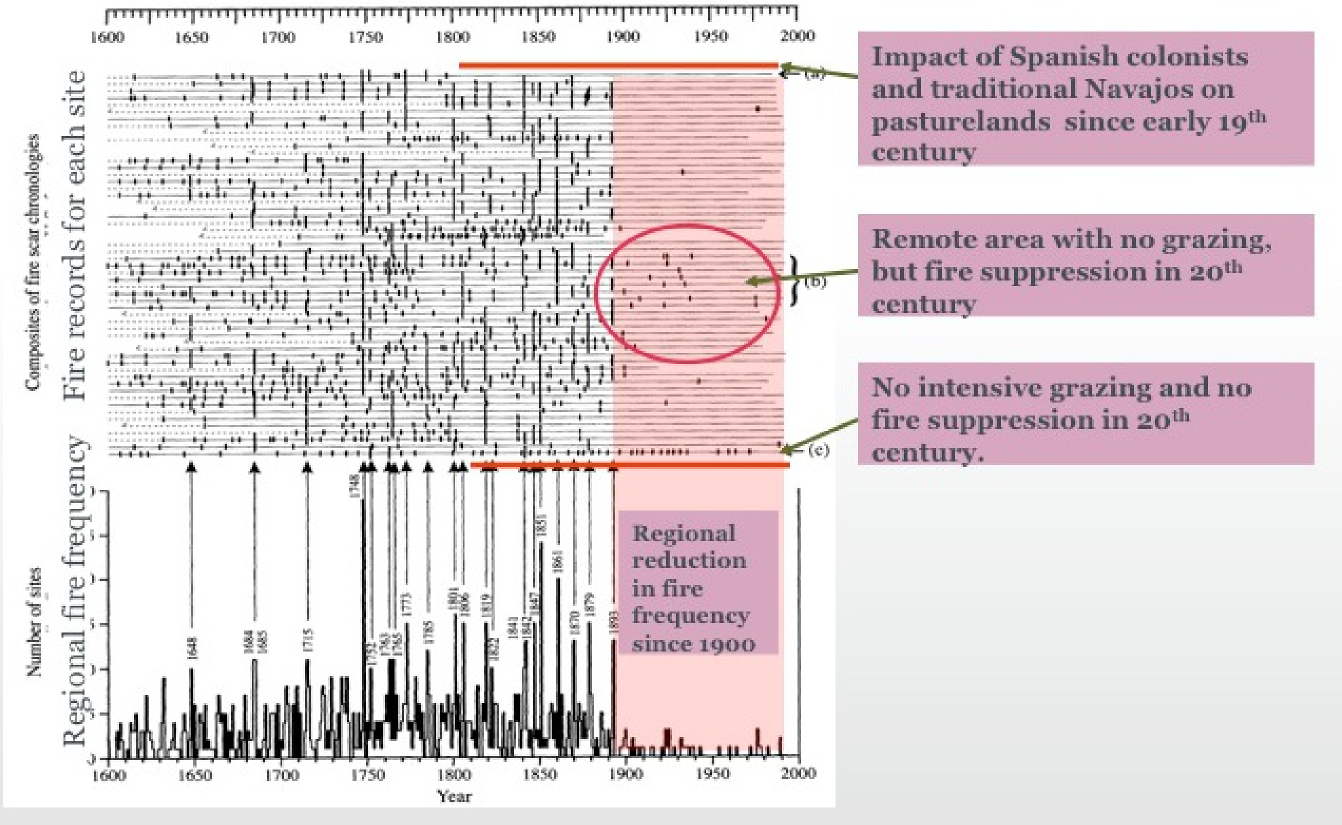
A corollary of abrupt change is that observations of contemporary environmental conditions restrict the number of system states that we can study; a short-term perspective may be unrepresentative of alternative states (e.g., Dearing 2008) that are actually desirable for the goals of management. Where society is bound to choose a reference state as a management target, a short-term perspective is constraining. This is exemplified by actions to implement the 2002 European Union Water Frame work Directive. The Directive requires all Member States to determine reference conditions for aquatic ecosystems that can act as a baseline against which to measure effects of past and present activities. It requires an evaluation of those conditions expected under minimal human impact and has, as a principal goal, to achieve “good ecological quality” by 2015. As Bradshaw et al. (2006) and others have shown, early attempts at gauging conditions associated with minimal human impact were flawed. In Denmark, early suggestions that 1800 levels of phosphorus in lakes could be considered the realistic target for restoration were put into doubt by reconstructions of total phosphorus in lake cores. The core data showed that highest values occurred in the 1950s and, importantly, phosphorus levels have been rising since 300 with an abrupt rise after 1100.

Anticipating when a threshold change will happen is obviously a key concern for policy makers. Some progress in this domain has come from time-series analyses of model output for socioenvironmental systems that show the variance or volatility of the system rising ˜10 yrs before the shift from one steady state to the other (Biggs et al. 2009). Whether the same approach may be applied to empirical data that describe socioenvironmental systems is unclear, although one intriguing analysis of historical macroeconomic data reports a harmful effect of volatility on economic growth (Hnatkovska and Loayza 2004).

Slow and Fast Processes

In a complex system, the interaction of trends and frequencies is essentially the interaction of “slower” and “faster” processes. Of particular importance in

Fig. 3. Frequencies, thresholds, and alternate steady states.



Note: Records of fire scars (moderate surface fires) from many sites in the southwest United States show the effects of different combinations of historical grazing regimes and modern fire suppression. Most show a reduction in fire scars from the end of the 19th century, largely as a result of intensive grazing. Exceptions strengthen this inference, for example: a) Spanish colonists on traditional Navajos pasturelands since the early 19th century; b) remote area with no grazing, but fire suppression in the 20th century; c) no intensive grazing nor fire suppression in the 20th century. Contemporary statistics show that many sites are now at risk from catastrophic “stand-replacing” fires as dense scrub thickets fuel non-natural fire patterns. After Swetnam et al. (1999).

the evolutionary view is the ability to identify the timescales over which each of the major processes in question operates, sometimes stretching over several orders of magnitude (Fig. 1). In effect, identifying the timescales at which the different processes in a land system operate is often a very effective way to separate relevant and irrelevant information about land system vulnerability and resilience (Gunderson and Holling 2002), to decide which of these processes is essential or subordinate to the dynamics of the system (van der Leeuw and Aschan-Leygonie 2005) and, thus, to identify the loci of effective innovation and management. In the Yunnan Mountains in southwest China, for example, phase-space analysis of land-use and environmental-process records suggest that soil erosion and land cover should be considered as slower processes operating over decades–centuries relative to the faster monsoon intensity and flooding (Dearing 2008).

This relationship between process speed, and the resilience and vulnerability of a land system, is evident in the case of the Haut Comtat in France, a region that was hit by two successive agricultural “crises” in the 1870s and the 1970s. The first crisis combined a rapid outbreak of the vine aphid *phylloxera* that affected wine production and the coincidental opening of the railway to Paris. These two events triggered an immediate search for a new agricultural economy. Newly installed irrigation, coupled with small-scale experimentation with horticulture, enabled a rapid response that maintained the land system. In contrast, in the 1970s, the crisis occurred as a result of the agricultural economy becoming slowly undermined by competition from Italy and Spain as a result of greater European union. The regional land system was not able to deal effectively with these changes and the human subsystem suffered a prolonged economic crisis throughout the 1980s and 1990s (van der Leeuw and Aschan-Leygonie, 2005). Systematic comparisons of such cases can help to reveal the character of the slow and fast events and coupled system conditions in which they operate.

Identifying the relatively slow processes may shed light on the processes that determine system resilience (Gunderson and Holling 2002). Resilience is related to stability, often portrayed as a target property for management, but not always. For example, in development terms, Stafford Smith et al. (2009) note that for some dryland regions, the main issue is not to increase resilience. They portray the development of resilient socioenvironmental systems that are undesirable in terms of vulnerability to drought and low carrying capacity. For these land systems, they argue that the key issue is how to increase transformability to enable change from the current type of system to a more preferable system. This may entail modifying livelihoods, developing new goods and services, and operating at different scales (Reenberg 2009). Again, systematic comparison of land-system histories may prove useful in identifying the nature of resilience in undesirable land systems as well as the levers that may transform them.

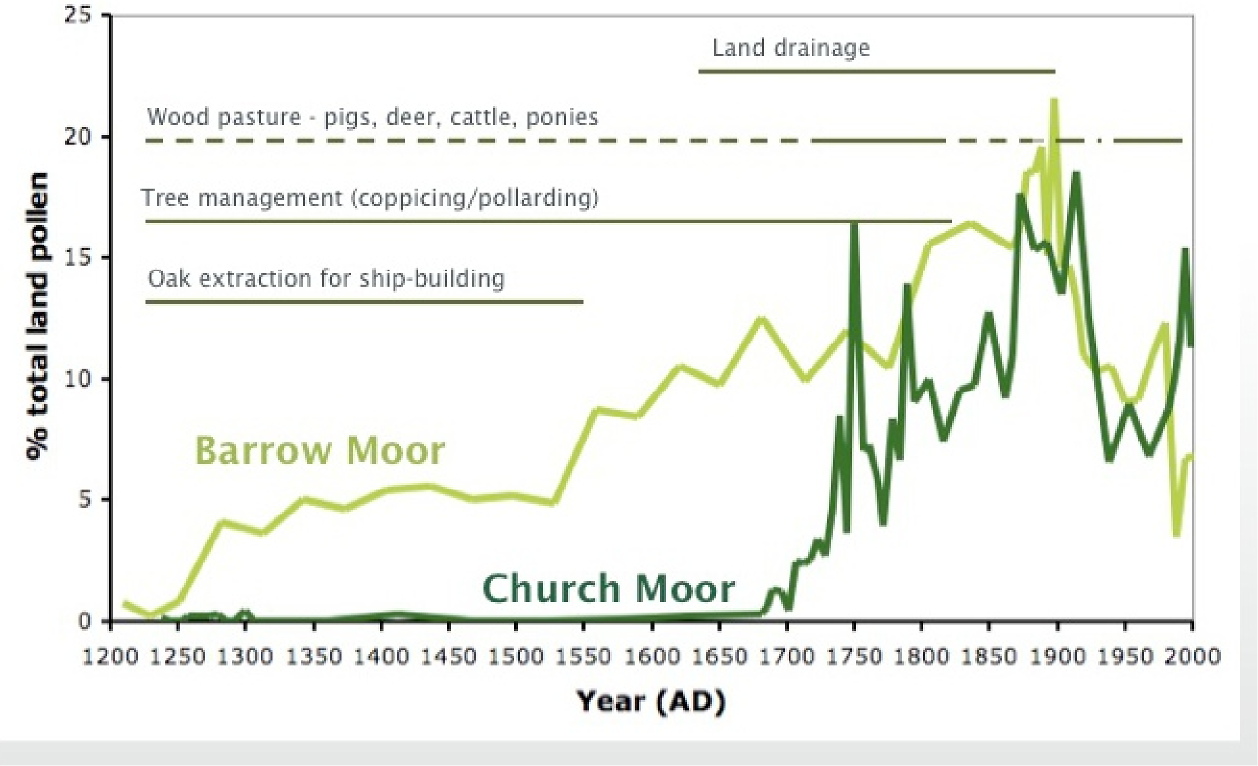
Legacies and Contingencies

Long timescales are necessary to observe the changing nature of interactions among system components. As the land system of interest becomes more affected by human activities, the interactions may extend further across time and space. In systems terms, the hierarchy of organization may increase with far-reaching cross-scale effects (Westley et al. 2002). In the temporal domain, this means that contemporary system behavior may be subject to legacies and contingencies (Foster et al. 2003): that there is “memory” within the contemporary system. One approach to examining these phenomena is to compile parallel and independent time-series of data and information so that the evolution of interactions may be analyzed through time.

In the New Forest National Park (UK), recent observations suggest that the beech woodland is declining (Fig. 4). Various causes of the decline have been put forward, including recent grazing pressure and climate change, pointing to possible policy solutions for the land system. However, reconstruction of past forest dynamics and land-use history over the last 800 yrs shows that the development of beech woodland as it appears today has been dependent, or contingent, on a long history of past land practices stretching back several centuries (Grant and Edwards 2007). From a management perspective, the importance of understanding the extent to which contemporary system functions are contingent on past events is often essential to making accurate decisions about the land system.

An extension of this approach can help determine path dependency, the term given to describe a human–environment system that follows a self-reinforcing trajectory or path through continuous feedback mechanisms. Stafford Smith et al. (2007) illustrate this in their review of historical desertification events in Australia that elegantly combines analog and evolutionary approaches. They compile information for individual drought episodes in different locations since 1898 to help understand the reasons why land degradation repeats and intensifies, revealing a number of self-reinforcing steps in each case. Increasing commodity prices before a drought encouraged heavier stocking that, in turn, increased grazing pressure and reduced pasture quality. Each such episode accelerated arid land degradation. Overexpectations of stocking levels were based on moderate land conditions emerging between droughts. These conditions existed longer than the lifetimes of pastoralists, inhibiting learning and adaptation measures. Over time, the socioenvironment system became increasingly highly connected, maladaptive and “locked-in,” limiting its freedom of choice, so that ultimately it was driven over existing environmental thresholds.

Fig. 4. Legacies and contingency.



Note: The ecological structure of the Ancient and Ornamental Woodlands in the New Forest National Park, UK, is in part the legacy of long-term effects of land use since AD 1200. The two curves represent the growth and decline of beech trees (*Fagus sylvatica*), plotted as percentages of beech pollen in total pollen sum observed in two peat basins (Church Moor and Barrow Moor) within the forest. Although the two curves show similar trends, the different timings for the rise of beech suggest that beech is a relatively recent species contingent on local conditions that vary over short distances. The horizontal lines show the duration of several important land-use practices, including using the forest for pasturing animals, coppicing and pollarding, timber extraction for local ship-building, and land drainage. The rise of beech in the 18th and 19th century is most likely a legacy of the decline in other tree species such as the oak used in ship-building. Declining trends during the 20th century are a result of the decline in traditional land-use practices coupled with greater vulnerability to wind-throw as the trees become taller and larger. Adapted from Grant and Edwards (2007).

TOWARD NEW LAND SYSTEM MODELS

At the global scale, outputs from climate models for a range of scenarios continue to dominate our view of the future of the earth system and to drive the political agenda for mitigation (IPCC 2007). At regional scales, impact assessment models (IAMs) are the main tools for agencies to engage with the questions of impacts, vulnerability, adaptation, and sustainable management (Grimm et al. 2008). But IAMS, such as those based on Driver–Process–State–Impact–Response frameworks (e.g., Spangenberg et. al. 2009) are not beyond criticism.

Tallis and Kareiva (2006) argue that they frequently lack key feedbacks, are unable to predict thresholds, and make poor connections between ecosystem services and human well-being. As valuable as they are as frameworks for the classification of information for policy makers, IAMs should not be used as a causal scheme (Spangenberg et. al. 2009). Projections of some environmental phenomena, such as species distributions through the use of bioclimate envelopes, may use the wrong spatial scale to define species niches (Willis and Bhagwat 2009) and by their nature ignore the fundamental complexity of the systems and the distinct possibility that boundary conditions may be rapidly changing. Oldfield (2005) highlights the lack of rigorous testing of model outputs against past data. Even where long temporal perspectives are valued, such as the historical profiling approach used by the resilience community (Walker et al. 2002), there is a tendency to use historical information to contextualize the system rather than to use it in ways that explicitly embrace an evolutionary approach.

As the sustainability agenda (Kates et al. 2001) grows stronger, thus there is a growing call for modeling tools that can simulate future system states while capturing essential nonlinearities and complex behavior (e.g., Nicholson et al. 2009). In these analyses, success is measured by an ability to understand the fundamental but realistic dynamical behavior of the system, if needs be at the expense of accuracy. This challenge is taken on through the development of relatively new types of system analysis and simulation modeling.

In theory, modeling the complexity of land systems over decadal timescales should be enabled by the use of bottom-up approaches that evolve change and emergent phenomena through continuous interaction and feedback (Dearing et al. 2006*b*, Dearing 2007*b*). These models include reduced complexity cellular automata-type approaches (Coulthard and Macklin 2001) and agent-based models (Bonabeau 2002) based on the operation of rules. The rules for many biophysical processes can be modeled using established, and sometimes universal, low-level mathematical algorithms, for example, water flow. In contrast, the high-level rules for social processes are usually statistical in nature, necessarily based on local surveys of likely human behavior, for example, land preferences, and underlined by the assumption of rationale behavior. These models have been used successfully to simulate land-use decision making (Parker et al. 2003), to test hypotheses about past cultural shifts (e.g., Dean et al. 2000) and to experiment with the effects of different weightings of climate and land use on landscape processes (Coulthard and Macklin 2001), but the field is in its infancy. A major challenge is the creation of frameworks (e.g., Wainwright 2008) that allow these models to accommodate both social and physical processes with very different assumptions, levels of rules, and degrees of uncertainty.

As with the validation of global climate models (IPCC 2007), the most convincing validation of predictive models would be through simulation of past socioenvironmental interactions covering the last few decades and centuries: letting the model run from specified starting conditions in the past and making comparisons with long-term observations or reconstructions of reality. At present, attempts to do this are confined to bottom-up process-based models at local scales where human actions are essentially embodied as switches in land use (e.g., Anderson et al. 2006, Welsh et al. 2009). The development and testing of interactive models that can simulate the evolving nature of interactions among social and environmental states is a major research priority. Such models are predicated on the widespread existence of the four system characteristics identified above.

CONCLUSION

As climate change and sustainability science continue to galvanize the coupling of multiple research arenas, historical change in all its forms (Butzer 1996) must be included in studies of land systems. There is now overwhelming evidence that contemporary socioenvironmental systems are the product of self-organizing, evolutionary changes that cannot be fully understood without recourse to the past: either directly by extending the timescale of observation to capture the relevant timescale of interactions, or by interrogating past socioenvironmental changes to draw analogous lessons. Paleoenvironmental studies can provide long-term perspectives on past ecological conditions and processes, particularly the process responses to human–environment interactions (Dearing et al. 2006*a*). Environmental and human history can bring holistic and interdisciplinary perspectives to the interactions between humans and nature (e.g., Turner et al. 1995, Myllyntaus and Saikku 2001), drawing on a range of theoretical insights (Braudel 1949, Redman and Kinzig 2003). By integrating historical information of changes in human&#8211environment interactions, there is far greater opportunity of engaging with contemporary land systems and their future within a complex socioenvironmental framework (Wardell et al. 2003), a claim long noted (Butzer 2005) and long underemphasized. This integration will be facilitated by sustained, systematic efforts to address land (or coupled human–environment) systems, trends and trajectories, frequencies, thresholds and alternate steady states, slow and fast processes, legacies, and contingencies.

Responses to this article can be read online at: *http://www.ecologyandsociety.org/vol15/iss4/art21/responses/*

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