Navigating the Perfect Storm: research strategies for social-ecological systems in a rapidly evolving world

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Abstract:	The 'Perfect Storm' metaphor describes a combination of events that causes a surprising or dramatic impact. It lends an evolutionary perspective to how social-ecological interactions change. Thus, we argue that an improved understanding of how social-ecological systems have evolved up to the present is necessary for the modelling, understanding and anticipation of current and future social-ecological systems. Here we consider the implications of an evolutionary perspective for designing research approaches. One desirable approach is the creation of multi-decadal records produced by integrating palaeoenvironmental, instrument and documentary sources at multiple spatial scales. We also consider the potential for improved analytical and modelling approaches by developing system dynamical, cellular and agent-based models, observing complex behaviour in social-ecological systems against which to test systems dynamical theory, and drawing better lessons from history. Alongside these is the need to find more appropriate ways to communicate complex systems, risk and uncertainty to the public and to policy-makers.

Abstract

The ‘Perfect Storm’ metaphor describes a combination of events that causes a surprising or dramatic impact. It lends an evolutionary perspective to how social-ecological interactions change. Thus, we argue that an improved understanding of how social-ecological systems have evolved up to the present is necessary for the modelling, understanding and anticipation of current and future social-ecological systems. Here we consider the implications of an evolutionary perspective for designing research approaches. One desirable approach is the creation of multi-decadal records produced by integrating palaeoenvironmental, instrument and documentary sources at multiple spatial scales. We also consider the potential for improved analytical and modelling approaches by developing system dynamical, cellular and agent-based models, observing complex behaviour in social-ecological systems against which to test systems dynamical theory, and drawing better lessons from history. Alongside these is the need to find more appropriate ways to communicate complex systems, risk and uncertainty to the public and to policy-makers.

Key words: social-ecological system; evolutionary perspectives; management strategy; ecosystem service; multi-decadal; paleoenvironmental records; dynamic modeling

Perfect Storms

No matter how the political deliberations at recent global summits (UN Climate Change Conference 2009; UN Convention on Biodiversity 2010; UN Conference on Sustainable Development 2012) play out, the sustainable management of the world’s social-ecological systems will continue to remain a standing item on the global change agenda. While it is generally accepted that all nations implement appropriate environmental management strategies (e.g. UNEP Medium Term Strategy 2010-2013) their formulation for specific nations and regions poses a significant challenge to scientists and policy-makers alike. At their heart exist frameworks that bring together the concepts of ecosystem services and social wellbeing via a flow of benefit (Millennium Ecosystem Assessment 2005; UK National Ecosystem Assessment 2010). While there is evidence of the interdependent roles played by frameworks, scenario generation, heuristics, qualitative relationships and computational models in the policy process (Carpenter et al. 2009), the last two years have seen a rise in publications in sustainability and adaptation science arguing that in many cases these tools fail to capture relevant complexities of the real world. In this paper, we consider the background to this perceived failure before assessing alternative approaches to observing, modelling, and communicating the complexities of the real world.

Two sets of arguments define the background to this problem. First, that a greater level of understanding of interactions between social and ecological systems can be achieved by using complex systems theory (Nicholson et al. 2009), a view strengthened by the empirical evidence for the rapidity of global environmental change (Steffen et al. 2004). Boundary conditions may be changing so quickly as to negate the usefulness of equilibrium models, for example, with regards to water resources (Milly et al. 2008), even though such models were previously considered fit for purpose. The problem is vividly expressed in John Beddington's (2009) use of a Perfect Storm image to describe the multi-decadal interactions of several drivers culminating in dramatic, and often unanticipated, responses. As more information about past global trends (Steffen et al. 2004) and future projections (Millennium Ecosystem Assessment 2005; United Nations 2006; Intergovernmental Panel on Climate Change 2007; United Nations 2008) become available for an array of social, economic and environmental phenomena it is clear that management policies have to recognize and incorporate the impacts on ecosystem services of multiple interacting drivers and pressures (Fig. 1). Beddington (2009) drew on projections of population growth, food security and water demands, in addition to the direct impacts of climate change, to speculate about abrupt change in the future. But it is a metaphor that can just as well be applied to crises that we have already observed in quite different domains: from regional fire risk to global financial collapse (Fig.1). Building on earlier arguments for an evolutionary understanding of people and nature (Costanza et al 1993), the metaphor emphasizes the need for new approaches that can *explicitly* handle emergent behaviour, 'fast' and 'slow' processes, feedback loops, critical transitions, thresholds and tipping points, and network interactions– in the real world.

Second, that the management of ecosystem services demands place-based and comparative research, with the emphasis on constructing modelling tools that address policy-making at local and regional scales (e.g. Grimm et al. 2008; Carpenter et al. 2009). At regional scales, impact assessment models (IAMs) are the main tools for agencies to engage with impacts, vulnerability, adaptation and sustainable management. Abundant computing power enables modeling that is cheap and fast (by comparison with empirical studies), but the question remains: will these models deliver what is required? Underlining the connection with complex systems, the argument has been made (e.g. Tallis and Kareiva 2006) that IAMs frequently lack key feedbacks, are unable to predict critical thresholds and tipping points, and may fail to couple ecosystems and their associated services to societal wellbeing. Nicholson et al. (2009) take a stronger line, arguing that modeling approaches that do not consider feedbacks have the potential to produce *dangerous policy recommendations*: they should not be used to predict causality. IAMs may also be compromised as regards their spatial scale. For example, modeled future species distributions using bioclimatic envelopes often use the wrong spatial scale to define species niches (Trivedi et al. 2008). Ignoring fine-scale environmental heterogeneity (Willis and Bhagwat, 2009) and failing to account for adaptive phenotypic plasticity, IAMs may exaggerate the loss of ecological niches and extinction rates (Dawson et al. 2011). Each ecosystem process or service operates over a specific range of spatial and temporal scales (Costanza 2008). Without knowing what these scales are and how the services interact within a social-ecological network the high likelihood of being misled by non-causative correlations make valid assessments difficult. This is because in complex unbounded systems, such social-ecological systems, equifinality results in a system state (or set of states) that can be reached through many different pathways, processes and initial conditions of individual system components (von Bertalanffy 1969). In this sense, Oldfield (2005) notes the lack of rigorous testing of IAM outputs against past data. Despite the problematic notions of validity and verification in complex domains (Oreskas et al. 1994) the close correlation of past global and regional temperature simulations with long-term instrument records (IPCC 2007) has perhaps made the most compelling argument for the acceptance of future climate-model projections. Oldfield (2005) speculates that some modellers prefer not to attempt such model validation against the past because failure may constrain the development of *engaging scenarios* of the future, which allow for a wide variation in the set of coherent, internally consistent and plausible descriptions of a possible future state of the world.

Arguments for new and improved conceptual insights and associated modeling tools that capture complexity belie the difficulty in creating them, but some recent developments are promising.

Improvements to conventional impact assessments, such as Driver-Pressure-Stress-Impact-Response frameworks (Spangenberg et al., 2009), offer new means for dealing explicitly with resilience and other dynamic properties of social-ecological systems (Dawson et al. 2010) by the incorporation of both autonomous and top-down (command-and-control) feedback processes (Rounsevell et al. 2010). Press-Pulse Dynamic frameworks (Collins et al. 2011) would seem to accommodate the interaction of slow and fast processes over the long term, and self-organizational processes are at the heart of Ostrom's (2009) framework for analyzing human-environment interactions in social-ecological systems. Stakeholder participation is an essential component in developing these frameworks and models (Walker et al. 2009). Typically a risk-assessment is involved. While it has been argued that any risk determination—essentially a trade-off between costs and benefits— may be viewed as a non-scientific threshold decision (NRC 1983), Johnson et al. (2007) argue that in regulatory decision-making the roles of scientists and of wider society are commonly confused. Their view is that scientists engaged in risk assessment should ensure they test well-defined hypotheses and that greater efforts are then made to integrate scientific risk assessment and risk analysis so that *non-scientific* questions, such as economic and social acceptance, can be considered within the decision-making process (Graham 1991; Sexton 1995). Thus, as the interactions between major drivers of global change create increasingly complex effects it is now becoming recognized (e.g. Beddoe et al. 2009; Walker et al. 2009) that co-evolving regulatory and institutional reform is a major international priority.

New methods that provide insight into how governance systems, users and resources interact will be increasingly useful to policy makers (McNie 2007). But inevitably, the extent to which impact assessments are able to inform policy-makers about future thresholds and extreme events, and the basis on whether we can judge them to be 'realistic' outcomes, are questions that society will ask more frequently. So what are the ways forward? Here we consider three areas of study that we believe can contribute to an improved understanding of complex social-ecological changes: observing long-term system dynamics, modeling complex systems, and testing complexity theory against historical reconstructions. The common thread is a greater utilisation of long, multi-decadal records.

Observing long-term system dynamics

Carpenter et al. (2009) contend that management of ecosystem services demands not only place-based but long-term research. Monitored records from instruments and repeat surveys can provide long ecological and social-ecological perspectives (e.g. ILTEN 1993; Singh et al. 2010) but, unlike climate records, datasets are sparse and often cover a relatively short period of a few years. Increasingly, short records are supplemented with environmental reconstructions from historical (e.g Stafford Smith et al. 2007) and paleoecological investigations (e.g. Dearing et al. 2006a). Indeed, there is growing evidence that multi-decadal perspectives are not only useful in providing context. Rather, they may actually represent the true timescales within which a contemporary system operates (Dearing et al. 2010) helping to observe the nature of legacies and contingencies: the changing pattern of magnitude-frequency relationships; 'slow' and 'fast' processes; the existence of thresholds; and the convergence and divergence of system and variable trajectories over these timescales (cf. Fig. 1). As such, these system properties all give crucial insight into the functioning of contemporary social-ecological systems (Foster et al. 2003; Costanza et al. 2007a; Dearing et al. 2008; Froyd and Willis, 2008) and their resilience properties (Walker et al. 2002; Dearing 2008). Without knowing the paths and drivers of social and ecological processes, and their interactions, across all relevant timescales it is doubtful whether 'predictive' simulation models (including agent-based, impact analysis, reduced complexity, and numerical process models) can be accurately created.

Recent studies show that there is a real prospect of reconstructing multi-decadal trends in regions for many ecological services, environmental drivers and impacts (Dearing et al. 2011; Dearing et al. in review). This means that evolutionary perspectives for many real world social-ecological systems are plausible. Whether the current trajectories for social and ecological states are diverging, converging or in coincidental states determines to a large extent the likelihood of abrupt system change in the future. Similar arguments have recently been put forward in explaining the development of modern urban and regional economies (Martin and Sunley 2006; Simmie and Martin 2010). For sustainable management of landscapes and resources over annual-decadal timescales it is desirable to identify the range of potential paths that push the system towards relative stability, threshold-dependent responses, gradual but irreversible changes, lower levels of resilience, or path-dependent 'poverty' traps characterised by low efficiency (e.g. Stafford Smith et al.

2007).

Thus, temporally extended databases of social-ecological systems will make it easier to answer pragmatic questions about regional conditions, for example:

- How rapidly is the whole landscape changing and which social and ecological processes are changing most rapidly? Answers to this question allow policy-makers to prioritize action across the range of ecosystem services and to create simple aggregated, indices of change for communication (cf. IGBP Climate Change Index 2009).

- What are the appropriate pre-impact target conditions for management or restoration of key ecological processes and services that would give long-term sustainable use? In some policy arenas (e.g. EU Water Framework Directive 2002) target conditions for restoration are already based on analyses of past conditions. For other ecosystem processes/services, like soil erosion and biodiversity, policy now lags behind the knowledge base in many regions (Willis et al. 2010).

- How have the various parts of the social-ecological system interacted through time? Long records of ecological services and their drivers allow partial reconstruction of energy, material and information networks through time. (e.g. Dai et al. 2009). Conceptualising how these interactions have changed up to the present enhances our study of the evolutionary processes at work within the system: the mechanisms that drive conditions towards or away from Perfect Storm scenarios; the important feedbacks; the presence of thresholds. But such conceptual models also represent an essential preliminary stage in developing simulation models.

- Which parts of the landscape are particularly resilient to current social and biophysical (e.g. climate) drivers, and which are particularly sensitive? Here, there is the scope to analyse the long-term records in terms of evolutionary conceptual models of change, like the adaptive cycle (Gunderson and Holling 2002; Dearing 2008). For example, knowing where the system lies on the adaptive cycle may give insight into its resilience (Holling 2001). But long-term records might also allow a critical reappraisal of the conditions under which we do and do not see the dynamics described by such conceptual models. Recent suggestions that abrupt changes in climate and ecological systems can be anticipated by observing early warning signals is an exciting development (Biggs et al. 2009; Scheffer et al. 2009). But observation of these signals in real world social-ecological systems is difficult with limited observations, underlining the need for multi-decadal records.

Modeling complex systems

Macro-scale dynamical modeling of global social-ecological system started in the 1970s with the Limits to Growth programme, using World3 (Meadows et al. 1972; 2005). More recent integrated global models, like IMAGE, IFS, DICE, TARGETS and GUMBO (see review in Costanza et al. 2007b) attempt to capture complex behaviour that arise through the interaction of social and biophysical processes. In systems' modeling, success is measured by an improved ability to understand the fundamental organisation of a system's dynamical behaviour (e.g. Costanza and Voinov 2003; Low et al. 1999), rather than an apparent ability to predict one particular outcome at one particular time in the future. Turner's (2008) comparison of the Limits to Growth outputs from the 1970s with data sets for key variables measured over the past 30 years shows striking similarities, especially with the 'business-as-usual' scenario. Not only do the findings suggest that World3 captures realistic interaction of feedback mechanisms, but that the modelled trends and interactions into the 21st century resonate with the perceived effects of multiple stressors (Turner 2008 p. 409) as visualised in the Perfect Storm image. Indeed, both World3 and GUMBO (Boumans et al. 2002) indicate declining trends in 'food per capita' before 2050 using 'business-as-usual' scenarios. Given these insights at aggregated, global scales, it is surprising that there have not been more attempts to develop integrated regional dynamic models. One major obstacle may be the perceived lack of data needed for model calibration and testing. World3 and GUMBO outputs were calibrated against global datasets for key variables (e.g. total population) available from 1900 onwards, but multi-decadal data sets (especially for ecological services) are often perceived as unavailable at sub-global scales.

International efforts to compile regional data from documentary, instrumental, remote sensing, environmental history, palaeoenvironmental and archaeological sources show that this perception may be misguided for many regions (Past Global Changes 2010; Dearing et al. 2011). Analytical developments in the paleoenvironmental sciences means that proxy records for regional fire, flooding, soil erosion, carbon flux, nutrient export, water quality, atmospheric pollution, sediment transport, algal levels, fish stocks, terrestrial biodiversity, land cover, land use, climate variables and other variables linked explicitly to ecosystem services can now be routinely obtained from sedimentary archives (Dearing 2006; Dearing et al. in review). There are caveats to note, especially with regards the calibration of paleoecological proxies, their dating and the geographical coverage (Dearing et al in review). But for many regions, quantitative and high resolution reconstructed time-series, which can replace instrument and document records where none exists and extend the timescale of existing time-series, now provide the means for testing model skill (Anderson et al. 2006; Dearing et al. 2006b).

Top-down, aggregated, macroscale system dynamical models may capture feedback mechanisms among major system components and processes, but as generally constituted do not simulate changes in the spatial distribution of phenomena: essentially giving a 2D rather than a 4D representation of change. In contrast, so-called ‘bottom-up’ approaches simulate autonomous change through continuous interaction and feedback within space as well as time, and include reduced complexity cellular automata and agent-based models based on local rules and behaviour (Costanza et al.1990; Costanza and Voinov 2003; Anderson et al. 2006). Application of ‘bottom-up’ models to social-ecological systems so far has included testing hypotheses about past cultural shifts (e.g. Dean et al. 2000), simulating land use change and urbanisation (e.g. Fontaine and Rounsevell 2009), and experimenting with the effects of different weightings of climate and land use on landscape processes (Coulthard and Macklin 2001). A major challenge for these new modelling tools is the creation of frameworks that are able to accommodate both social and physical processes with their very different levels of fundamental laws (Dearing 2007), though recent attempts to do this look promising (Wainwright 2008). Validation against past records is key, and possible (e.g. Welsh et al. 2009), indicating that full compilations of historical data should be central to the design of forward modelling programmes (e.g. Butler et al 2007).

Testing complexity theory against historical reconstructions

We usually learn from history by drawing generalizations from historical events that represent credible analogues with the present (Dearing et al. 2010). For example, it seems that monetary policy for handling the recent global financial crisis drew as much on analyses of the socio-economic interactions in the early 1930s as from contemporary economic models. The literature is replete with historical case studies of social-ecological change that potentially provide lessons for the future (see Dearing 2006). But criticisms of an analogue approach are long-standing and many. They include the difficulty of matching modern political and technological conditions with those in the past, and the possible bias towards the examination of disasters and social collapses, as in the history of Easter Island. However, new, imaginative developments suggest that far from being simplistic analogues for the present, historical case studies can provide important heuristic typologies of social-ecological system behaviour (Costanza et al. 2007a; Tainter and Crumley 2007; Dearing et al. 2010) and decision-making (Diamond 2005). For example, historical reconstructions of repeated drought-led agricultural collapse in Australia show that the phenomenon was characterized by a distinct set of social and ecological interactions that varied in local detail but had a common pattern (Stafford Smith et al. 2007). Other global zones vulnerable to drought may also have their own unique properties that, through the historical record, are amenable to description and analysis at a level of general system behavior. Such a typological approach that compresses system complexity into an easily understood narrative of system behaviour adds important qualitative details to classifications of modern social-ecological systems (Lüdeke et al. 2004) and provides an attractive option for communicating findings to policy makers.

However, typologies of social-ecological change are not the same as theories of change. It can be argued that a major barrier to designing adaptation strategies for complex systems is the lack of a formal theoretical basis. Over the past six decades many theories have been advanced that are relevant to explaining social-ecological changes, for example: ecological theory for complexity and stability (MacArthur 1955; May 1974); the ‘tragedy of the commons’ (Hardin 1960; Ostrom 2001); self-organised critical states (Bak 1966); network theory (Barabásí and Albert 1999; Janssen et al. 2006); heterarchical versus hierarchical structures (Crumley 1995); resilience theory and panarchy (Gunderson and Holling

2002); and early warning signals of critical transitions (e.g. Scheffer et al. 2009). But there is incomplete rationalization of theory and principles, and insufficient comparisons between mathematical and real world systems. As a result, there are apparent contradictions: common theoretical elements seem to exist in apparently unconnected fields, and the potential value of linking across theories has yet to be realized. One of the latest developments in complex systems science uses information theory. Ulanowicz et al's (2009) mathematical studies of ecological food webs allow quantification of the size, efficiency and resilience of networks. Their results show that natural ecosystems have a small space of stability, a *window of vitality*, which they extend to a general model for the sustainability of all networks in terms of diversity and connectivity. Networks that are too efficient, with too little diversity become 'brittle' and lack resilience, whereas those with insufficient efficiency create stagnation. These findings not only resonate strongly with current resilience theory and the adaptive cycle (Gunderson and Holling 2002), but also with observations of modern socio-economic systems (Goerner et al. 2009) and cascading social and ecological crises (e.g. Adger et al 2009; Galaz et al 2010), and the detailed analysis of past societal collapses, such as the Roman Empire (Tainter and Crumley, 2007). But systematic analysis of these potential connections between mathematical theory, heuristics and observations remains undone.

Thus, there is the exciting possibility that historical case studies can play a key role in testing current complexity theory in order to help develop new social-ecological theory. The approach would be to compare mathematical system behaviour drawn from ecology and complexity science against historical, empirical records from the real world. Past records not only provide longer timescales than are conventionally available for modern observations but provide a larger array of social-ecological systems than currently exist. A strong theoretical basis would help sharpen the design focus for adaptation strategies and give an enhanced level of confidence in their deployment.

Navigating the Storm

There is then reason to be optimistic about our ability to improve our understanding of social-ecological systems. However, this in itself does not ensure better policy because there are numerous barriers to effective policy making. Here we confine discussion to the way in which scientists communicate their findings to policy-makers and the general public, and the expectations of scientists on the part of policy-makers and the public. As scientists develop a more refined approach to dealing with complex systems, how should they communicate complex and alternative views of the future? Scientists are under pressure to *predict*, but at some stage the semantics need to change. Policy-makers need to know that large-scale simulations, 'in silico' science, 'virtual labs' and synthetic experiments are not sources of facts about the world that can be acted upon but must be viewed as ways of exploring system sensitivities and the ramifications of theories (Peck 2004; Di Paolo et al. 2000). Policy-makers need to accept and accommodate the fact that the best available scientific understanding may not enable us *to reduce uncertainty* or even *to define uncertainty* but only to define *what we may never know* (Costanza and Cornwell 1992; Makridakis and Taleb, 2009), and to reach consensus on what we currently understand. Easily communicated results may be attractive but have little value to policy makers and society in the long run if they are based on methods that do not adhere to the new complexity paradigm. Scenarios seldom account for emergent properties and behaviours arising from complex system dynamics, which are largely unpredictable. At some point, scenario-driven models alone will be unable to provide the essential depth of understanding or range of realistic options needed to support effective policy-making.

Successful policy decision-making to address the multilevel and multiscale character of today's complex social, political and environmental challenges requires both access to clear accurate scientific information and an effective adaptive governance context to navigate the research-policy linkages effectively (Court and Cotterell 2004). Whilst the arrangement of the appropriate institutional factors for governing complex systems remain poorly understood (Folke et al. 2007; Termeer et al. 2010), the scientific knowledge needs to be communicated through multiple pathways and scales depending on needs of the various stakeholders: government, non-governmental organizations, lobby-groups, epistemic communities, international organizations and others. A major research challenge is to know when to discard simplistic explanations in favour of complex realism, and how this should be communicated. We have to recognize that the credibility of models derives from two distinct sources: (1) the ability of the model to simulate complex reality and (2) the degree of consensus about the model and its assumptions among the stakeholders who might use the model (van den Belt 2004). This 'social capital' component is often overlooked but is essential for creating models that are actually used in policy-making (Brondizio et al. 2009).

In conclusion, we strongly support explanations, narratives and visualisations (cf. Rosling 2009) about how society and the environment have co-evolved and are likely to co-evolve, based on all available empirical evidence and modeling exercises. As we have shown, new approaches are available: validated top down regional dynamical and bottom-up complexity models that incorporate feedback; extended perspectives to observe multi-decadal system behaviour, and learning more effectively about social-ecological dynamics from historical case-studies. These essentially qualitative assessments may be more useful for anticipating change and developing policy than are choices made between equally uncertain futures derived from the current generation of predictive models alone. We are approaching a time when untested IAM assessments of future *impacts* may have less influence on discussions about policy than hitherto because the realism of projections are unacceptably low given the *insights* from complexity science. However, the expectations of science on the part of society and policy makers are still not yet compatible with the existing modeling abilities of the scientific community to capture and relay the complexity of future worlds. Concerted efforts in these methodologies therefore need to develop in parallel with debate and education about the real meanings of complex systems, risk and uncertainty. In addition, new forms of multi-level, polycentric, adaptive, participatory governance institutions will need to be developed that can better incorporate complexity modeling into decision-making.

Model development for adaptation policies and sustainable management is at a crossroads. We are seeing the birth of evolutionary approaches that have the potential to lift us out of an outmoded over-commitment to impact assessment models at the expense of nuanced understanding of system complexity. If we fail to embrace this potential, the prospects for designing meaningful and effective adaptation strategies are low.

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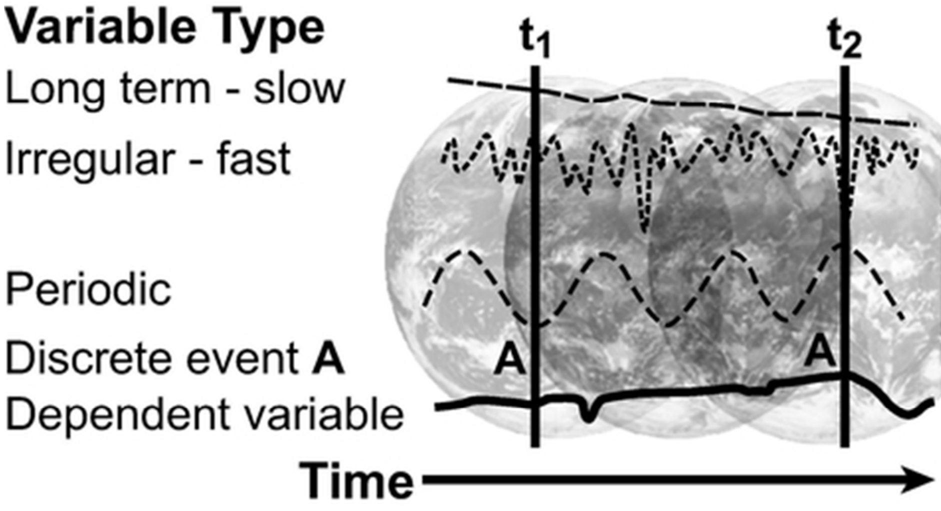
Figure Legends

Figure 1

The Perfect Storm. An evolutionary model of major social-ecological change,showing the complex interaction of multiple driver/pressure variables. The change in the dependent variable is the combined result of several types of influence: long-term-slow, irregular-fast, periodic and unpredictable discrete events. In this example two discrete events in the irregular series (A) occur at t1 and t2 with different responses in the dependent variable. At t2, a significant threshold change in the dependent variable follows the event because it is sensitive to a combination of other variable states that was not present at t1. The dependent variable may be exemplified by numerous environmental and social phenomena. Changes in forest biomass in California occur where long term, irregular, periodic and discrete signals correspond to the frequency of small fires (build-up of fuel), wind strength, seasonal climate and accidental ignition events respectively. The 2008 downturn in global economic growth occurred as a result of interacting long term, irregular, periodic and event variables corresponding to the growth of sub-prime debt, commodity prices, seasonal housing market, and the failure of major banks respectively. The challenge for designing adaptation strategies is to anticipate how these interactions, involving feedback in time and space, are likely to evolve in the future.



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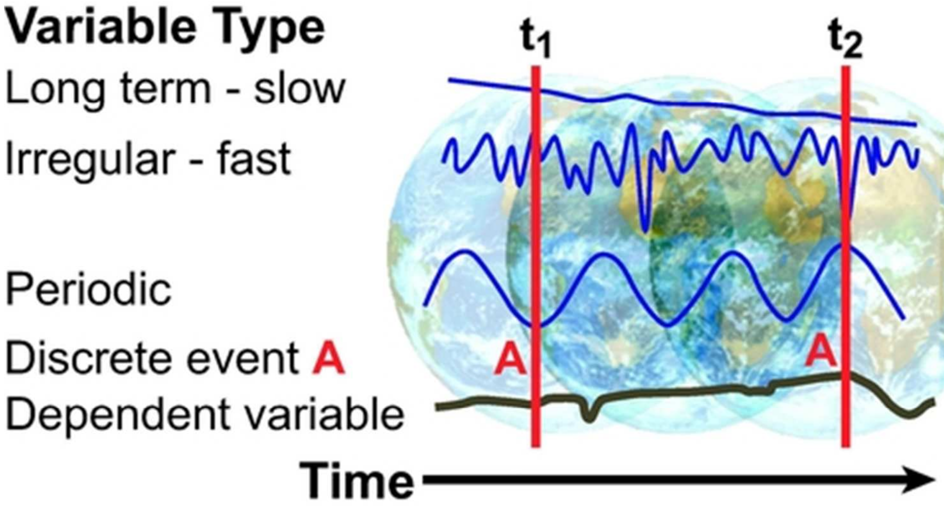

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