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ORIGINAL PAPER

Dynamic properties of complex adaptive ecosystems: implications for the sustainability of service provision

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Abstract Predicting environmental change and its impacts on ecosystem goods and services at local to global scales remains a significant challenge for the international scientific community. This is due largely to the fact that the Earth is made up of open, coupled, complex, interactive and non-linear dynamic systems that are inherently unpredictable. Uncertainties over interactions and feedbacks between natural and human drivers of environmental change (operating at different spatial and temporal scales) can compound intrinsic intractable difficulties faced by plural societies aiming at sustainable management of ecosystems. Social-Ecological Systems (SES) theory addresses these strongly coupled and complex characteristics of social and ecological systems. It can provide a useful framework for articulating contrasting drivers and pressures on ecosystems and associated service provision, spanning different temporalities and provenances. Here, system vulnerabilities (defined as exposure to threats affecting ability of an SES to cope in delivering relevant functions), can arise from both endogenous and exogenous factors across multiple time-scales. Vulnerabilities may also take contrasting forms, ranging from transient shocks or disruptions, through to chronic or enduring pressures. Recognising these diverse conditions, four distinct dynamic properties emerge (*resilience*, *stability*, *durability* and *robustness*), under which it is possible to maintain system function and, hence, achieve sustainability.

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Introduction

Throughout history, the establishment, development, interaction and migration of civilizations have been significantly shaped by availability of appropriate climate and natural resources. However, since the industrial revolution human societies increasingly impact and—in many cases—effectively dominate (and often diminish) capacities to regulate climate, biogeochemical cycles and biodiversity in ways that are essential to human life itself. This has recently raised considerable concerns relating to sustainable use and conservation of natural resources. These can be attributed to: (i) insufficient understanding of essential ecological processes acting across multiple time- and spatial scales—which can result in a disparity between those scales of ecological processes and scales of human resource use (Cumming et al. 2006); and (ii) the fact that human behaviour is traditionally based on narrow and conflicting short-term interests and goals, resulting (*inter alia*) in high discount rates for future environmental costs and temporal mismatches and disruptions between ecological, social and economic processes (Galaz et al. 2007).

Human societies and their constitutive economic, legal and political institutions drive (both directly and indirectly) changes in biodiversity patterns, wider ecosystem structures, and the services these ecosystems provide (Millenium Ecosystem Assessment 2005). However, the linkages and feedback mechanisms are not always well defined. Whilst there are ways in which it is possible to identify declines in ecosystem health and service provision through monitoring—for example through the Drivers-Pressures-State-Impact-Response (DPSIR) framework widely adopted by the European Environment Agency and other policy-makers (EEA 1995, 1999)—there are insufficient tools for identifying and predicting abrupt loss, or potential catastrophic failure, in service delivery. The DPSIR framework describes a configuration whereby a chain of causal links starting with ‘driving forces’ (e.g. population, energy demands) through ‘pressures’ (climate change, pollution) to ‘states’ (physical, chemical and biological) and ‘impacts’ on ecosystems, human health and functions, eventually leading to policy ‘responses’ (mitigation, adaptation). However, the connectivity between drivers, pressures and responses are much more complex than the sequential causes and effects relationships as described in the DPSIR schema. These complexities arise due to (i) positive and negative feedback responses existing between different activities and mechanisms; (ii) economic and social processes; and (iii) the multiple dynamics of policy, knowledge flows, intentions and responses, etc. (Fusco 2001). The socio-ecological adaptation of the DPSIR framework (Rounsevell et al. 2010) elegantly describes the linkages between drivers and pressures on ecological systems, their services and the beneficiaries of the system.

Social-Ecological Systems (SES) theory adopts the concept that society and nature are innately coupled, where human (including cultural, management, economic, and socio-political) and physical-biological sub-systems or agents are interacting at multiple temporal and spatial scales (Berkes and Folke 1998). SES are a form of Complex Adaptive System (CAS) in which a dynamic network of many agents (which may represent species, people, organisations, nations, etc.) are acting independently and in parallel, constantly responding to their environment and what the other agents are doing (Waldrop 1994). Hence, the control of a CAS tends to be highly dispersed and decentralized. An important characteristic of a CAS is that they can exhibit emergent behaviour and self-organisation, phenomena that cannot be predicted directly from the properties of their component parts (Corning 2002; Kauffman 1993). Self-organisation, the spontaneous configuration of spatial, temporal, spatio-temporal structures or functions in systems, has important implications for ecosystems management and the degree to which policy have to intervene in their governance.

This manuscript explores the dynamics of SES and identifies the properties that are necessary for the SES to remain both functional and be sustainable over multiple time-scales. Sustainability has many dimensions but is now widely defined in human development terms to mean “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs” as quoted in the Report of the Brundtland Commission (WCED 1987). This definition relates to the maintenance of, or improvements to, human well-being and quality of life while living within the carrying capacity of supporting ecosystems. The United Nations subsequently extended this definition to include the “three pillars” of social, environmental and economic sustainability (UN 2005) to reconcile the fact that SES must be socially equitable, economically viable and environmentally bearable to be sustainable. This systematic perspective of sustainability supports the SES framework presented in this manuscript. In this context, a sustainable SES is one that, over the normal cycle of pressures and disturbance events, maintains its characteristic diversity of major functional groups, processes, services and utility thereby ensuring its capacity to endure.

Dynamics of social-ecological systems

Management of SES must be an integrated and interdisciplinary process aiming at interdependencies between institutions and ecosystems dynamics (Rammel et al. 2007; Gatzweiler and Hagedorn 2002). Institutions are social constructs that under the scope of social-ecological systems governance are the means to safeguard ecosystems and their flow of services to society whilst maintaining community well-being through protection (from the negative effects of human practices), regulation and through mitigation and adaptation strategies (Frantzeskaki and Thissen 2009). Institutions consequently have to anticipate the complexity of SES and of SES dynamics over multiple temporal scales to avoid SES collapse, for example of common pool resources such as marine fisheries (Hardin 1968; Beddington et al. 2007). In this context, Acheson (2006) refers to ‘Institutional failures’ which lead to overexploitation of natural resources and subsequent loss of fisheries, forests, and water resources and the ecosystem services they deliver.

The governance of SES to achieve sustainability remains a challenge although a recent study sets out a general framework for analysing SES by identifying a number of subsystem variables that affect the likelihood of self-organization in efforts to achieve sustainability (Ostrom 2009). These variables focus upon the interplay between resource and governance systems, resource units and users to identify policies, rules, monitoring and enforcement strategies needed to enhance the sustainability of complex SES. Complementary to this research, Stirling (2007, 2008a, b) proposes a systematic framework for characterising the temporality and provenance of relevant drivers and pressures acting on an SES, that yields four distinct dynamic properties of resilience, stability, durability and robustness (Fig. 1). Stirling’s framework is developed to address divergent social and disciplinary ‘framings’ of systems and interventions (Scoones et al. 2007; Leach et al.

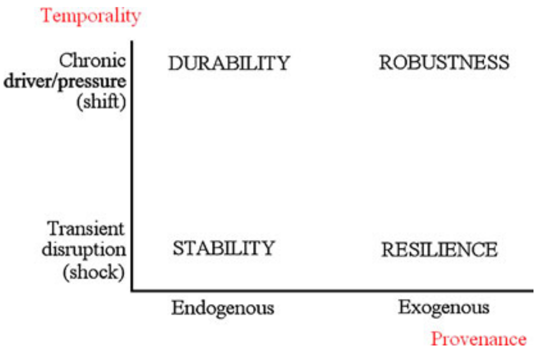

Fig. 1 Dynamic system properties in terms of their temporality, shown on the *vertical axis*, and provenance of drivers and pressures, shown on the *horizontal axis* (adapted from Stirling 2007)

2009). However, this logical scheme may also be adopted within a *particular* integrated interdisciplinary framing of the kind often adopted in analysis of an SES.

Under any given integrated view then, Stirling's framework distinguishes the provenance of the drivers of environmental change as either endogenous or exogenous to the system in question. An endogenous driver or pressure arises as a process internal to the system while an exogenous driver arises outside of the system. In geographical terms, the scale of the area of interest and the boundaries of the focal system are critical for determining whether a factor is endogenous or exogenous to the system. At the landscape or catchment scale, global climate change and world commodity prices are two examples of exogenous drivers whereas many forms of land-use change would be endogenous to an SES.

The other parameter employed in Stirling's framework (Fig. 1) is the temporality of a driver (or pressure). This is a critical factor in understanding system responses, concerning whether the perturbations in question are chronic or transient. The former is a persistent and lasting driver or pressure, or one that has developed slowly. A transient driver or pressure, by contrast, is one that is short in duration or abrupt—and often correspondingly unexpected. These are also often classified as slow and fast acting variables, respectively). Again, global climate change and world commodity prices provide different examples of drivers that are slow/chronic (climate change) and fast/transient (volatile markets). Clarification of the temporal linkages and pathways in a social-ecological system would facilitate the development of management and policy strategies for maintaining system function in the face of chronic pressure or transient disruption.

The concept of vulnerability has developed from a focus on the human dimensions of environmental change (Adger 2006) and refers to the extent to which a threat or hazard may damage, degrade or harm a system. Vulnerability is therefore contingent on the magnitude of the threat together with the extent to which the system is sensitive to that threat (exposure), and the ability of the system to anticipate, cope with, resist and recover from the threat (adaptive capacity and properties of resilience and robustness) (Smit et al. 1999; Brookes et al. 2005). A crucial factor of SES vulnerability is the level of exposure to threats affecting the ability of the system to cope in delivering key functions such as food production, ecosystem services provision, livelihoods, health, income, etc. These threats may arise from various endogenous and exogenous factors operating across multiple timescales and can range from short transient shocks or disruptions through to long-term chronic or enduring pressures (Gallopin 2006). Within this framework, a highly *resilient* system would be able to maintain or recover key functions through transient and exogenous shocks (Fig. 2). If a stress or disturbance does alter the ecosystem, then it should be

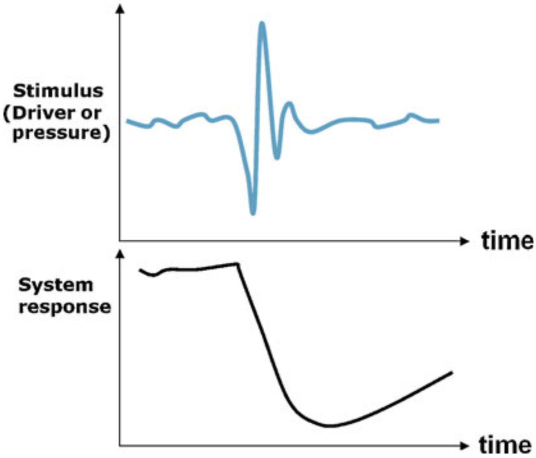

Fig. 2 Example of the effect of a shock or transient event on the response curve of a theoretical system. The lower figure illustrates the systems' ability to 'bounce back' to a prior (steady or dynamic) state after the unexpected stimulus from an exogenous driver or endogenous pressure demonstrating the system properties of resilience and stability respectively

able to bounce back quickly to resume its former ability to yield a service or utility rather than transform into a qualitatively different state that is controlled by a different set of processes. In order for ecosystem resilience to be defined, the ecosystem must have a degree of stability prior to the perturbation. Resilience relates to return to stability following perturbation (Holling 1973). *Stability* refers to a system's tolerance to transient and endogenous shocks or disruptions (Fig. 2). Note that under certain circumstances, a system may become stable in the sense of a steady or dynamic equilibrium state (Fig. 3), evidenced, for example, in predator–prey relationships. A system has stability, for example, when it is able to adapt autonomously to endogenous perturbations. In this sense, the system adapts through automatic (usually negative) feedback mechanisms or through managed policy/response interventions. The system need not be in a static 'steady state', but also, itself, be dynamic, where endogenous perturbations are defined in relation to an equilibrium trajectory. *Robustness* represents a system's ability to recover or maintain its social-ecological functions in the face of an external and chronic driver (Fig. 4). An ecosystem is robust when it is capable of resisting changes caused by long-term drivers or pressures that are external to the ecosystem, such as global warming, nutrient loading or hunting pressure for example. Robust ecosystems demonstrate adaptability to external forces, for example if a keystone species goes extinct, surviving species can compensate for the loss of function over physiological, demographic, or evolutionary time scales

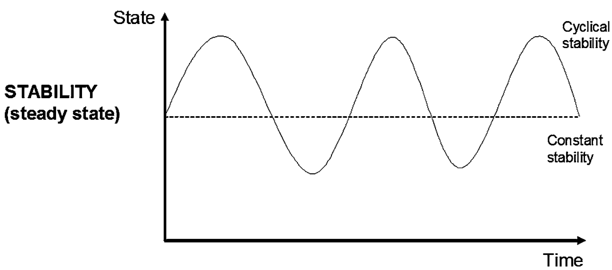

Fig. 3 A systems' autonomous response to endogenous pressures can exhibit a steady or dynamic equilibrium system state, as in predator–prey relationships, for example

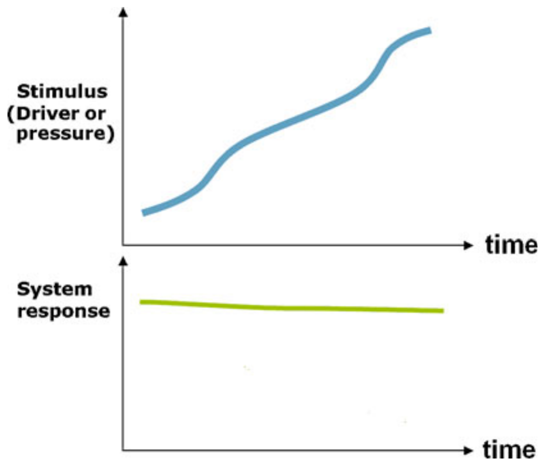

Fig. 4 Properties of Durability (endogenous) and Robustness (exogenous) arise from a systems response to a chronic or enduring driver or pressure, which can be exogenous or endogenous. Examples are climate change (exogenous) and biological evolution (endogenous)

(Lenski et al. 2006). Similarly, *durability* is the property expressed when a system is able to cope with a chronic stress, but the source of this stress is endogenous. Durability of an ecosystem pertains to its ability to continue to yield a service or utility, for example capacity to support human or other life, over relatively long time-scales or indefinitely without any degradation or loss of the important biotic or abiotic components that make up the ecosystem. Evolution is an example of an endogenous pressure which acts on the species that make up an ecosystem.

As Stirling (2008a) states, each property is individually necessary and collectively sufficient for achieving sustainability. If these system capacities have been eroded, a disturbance may be more likely to push the system beyond a threshold state (Kinzi et al. 2006), from which it may not recover—or may take many years to return to its previous state through natural processes. This type of shift from one state to another has been called a 'regime shift' (Scheffer et al. 2001, Carpenter 2003) and may be desirable or undesirable.

Agriculture and food production is a useful ecosystem service which can be used to exemplify these properties. Over thousands of years, humans have engaged in thinking and learning experiences which have shaped the processes underpinning modern agricultural practices, addressing multiple factors and tradeoffs. Contemporary intensive industrial agricultural practices emphasise the property of stability—seeking to optimise input/output ratios in the face of parameters that are effectively assumed to be subject to endogenous control. Here, the growing of crops or rearing of livestock has been adapted and 'tuned' over time (for instance) to increase productivity per hectare. This has involved the modification of plants and animals (through hybridisation and, more recently, genetic modification) to enhance useful biological traits (e.g. pest resistance or higher yields) or through improving technology and adding energy to increase productivity (use of fertilizers and pesticides). As cumulative effects arise from these practices (such as nutrient depletion or soil erosion), so measures are required to build the property of durability. But this again tends to be addressed as a matter of endogenous control.

Traditional and subsistence agricultural methods, on the other hand, tend to a greater extent to embrace the property of resilience. Here, perturbations are acknowledged to lie beyond endogenous control capacities, militating against optimising strategies. The resulting practices are usually low input, satisficing systems involving strategies like slash and burn practices, crop rotation and alternating years of cultivation with periods of fallow to maintain soil fertility. Traditional crop varieties also tend to be more tolerant of local climatic variations, including extreme events, such as drought or flood. This ensures sustainability of production but at the expense of lower crop yields. Due to the globalisation of agricultural trade, current agricultural practices are also showing evidence of a shift from adaptation to environmental disturbances to adaptation to market fluctuation—with oscillations in commodity prices and agricultural subsidies. Many of the modern crop varieties, by contrast, require intensive management and are prone to failure outside of the (sometimes narrow) range of their optimal climate conditions. By adopting an intensive agricultural production system and developing technology-based strategies aiming to eliminate or diminish disturbances, we have committed ourselves to a high-maintenance, high energy-demand stability-based regime, thus compromising on qualities of both durability and resilience. With the advent of large scale chronic global pressures such as climate change, biodiversity loss, demographic stress and economic globalisation, penalties may also become evident in relation to qualities of robustness.

Within SES, a number of organisms or other agents can be identified that play a crucial role in the regulation or control of the availability of resources to other organisms and therefore support the endogenous properties (stability and durability) of the system. For example, in a forest, a tree canopy will affect the availability of light, temperature, precipitation and humidity in the understory and soil layers, resulting in a physical modification, maintenance and creation of habitats (Holling 1992). These diverse ecological effects are not trophic or competitive interactions, but it is likely that more species in the forest ecosystem are affected by them than directly competing with individual trees for resources (sunlight or nutrients) or using the tree for food (Jones et al. 1994). The physical state changes of the localised environment caused by the tree has been termed "physical ecosystem engineering" by Jones et al. (1994, 1997), further defining the plants, animals and microorganisms (and particularly humans) that directly or indirectly control the availability of resources to other organisms through state changes in habitats as "physical ecosystem engineers". Although not inevitable, changes in the physical engineering of habitats can arise through trophic interactions or competition. Jones et al. (1994) provides the example of the kelp forests (*Macrocystis* spp.) off the Pacific coasts of the USA where the kelp engineers modify the environment through the suppression of sediment movement, diminish wave action and maintaining water clarity, providing a number of habitats for species that do not feed on kelp. Urchins (*Strongylocentrotus* spp.) feed on kelp and sea otters (*Enhydra lutris*) predate on urchins, which establishes otters as a keystone species in the structure and functioning of the kelp ecosystem (Estes and Palmisano 1974; Graham 2004). The otters confer stability on the kelp forest ecosystem by dampening the effect of predation by urchins. Over long time periods, the consistent interplay between trophic interactions, competition between species and ecosystem engineers results in a durable ecosystem. The kelp creates and maintains the macro-structure of the ecosystem over large spatial scales, characterising the dominant habitat that supports all the other species. This connectedness has important implications for sustainability. For example, although individual kelp plants may die, or be eaten by urchins, a process which is replicated over multiple time-scales, the overall habitat extent is maintained through rejuvenation processes at the patch level and the role of the otter as top predator, which extends over larger spatial scales.

In many ecosystems, the removal of the top predator can have devastating consequences on the stability and durability of ecosystem without human intervention. For example, studies have shown that the removal of sharks (superorder *Selachimorpha*) in a coral reef ecosystem by overfishing can result in increases of lesser predators, such as groupers (family *Serranidae*), culminating in significant losses of herbivorous fish causing a 'regime shift' from a coral dominated ecosystem to a macro-algal dominated ecosystem (Bascompte et al. 2005). This is an example of a trophic cascade, predator–prey effects that propagates through the food chain altering the abundance of species across more than one trophic link. The extinction of wolves (*Canis lupus*) in the Scottish highlands from hunting resulted in rapid growth in the population of red deer (*Cervus elaphus*), leading to woodland and grassland degradation through overgrazing pressures (Côté et al. 2004). Human intervention is now required in the form of an annual culling of red deer in order to maintain these highland habitats in perpetuity. Indeed, humans play increasingly important roles as ecosystem engineers in order to maintain stability and durability of natural habitats. Other examples include the regulation of water resources to maintain minimum ecological flows (Richter et al. 2003), and management of habitats that would normally be lost to natural succession, such as reedbeds (Burgess et al. 1995).

Another important consideration in the dynamics of complex social-ecological systems is temporal pathways that are internal to the SES and the potential for a temporal mismatch in the interconnections and associated processes. An external transient shock event, for example, may not have any immediate discernable effect on ecosystem function and service provision, but could trigger an internal (to the system) chronic decline in durability. It is therefore crucial that appropriate indicators are identified within the system that can detect changes that will be acted upon in a timely fashion before a severe loss of service provision or even catastrophic failure (Feld et al. 2010). The inevitability of the latter condition may arise before it is detected due to positive feedbacks in the system whereby a *Tipping point* is reached, a threshold behaviour whereby the subsequent momentum of change becomes inexorable and the system goes into another state. An example of this issue can be demonstrated by a simplistic examination of the ecosystem services performed by keystone species that undertake crucial life support functions in ecosystems, such as seed dispersal, pollination, or pest regulation. Drawing on case in point used by other manuscripts in this volume, Hougner et al. (2006) conducted a replacement cost through human means analysis of the seed dispersal service performed by the Eurasian jay (*Garrulus glandarius*) in the Stockholm National Urban Park, Sweden. The park holds one of the largest populations of giant oaks in Europe, which have both high biodiversity benefits and is a culturally important recreational space for the urban population of Stockholm. They demonstrated that continuous temporal and spatial oak dispersal service provided by jays holds several benefits compared to a man-made replacement of this service, including significant economic gains in particular. The oak trees are the ecosystem service provider in this example, but it would be deficient to have only indicators based upon this species alone for sustainable monitoring of service provision. If the jays became extinct due to a short shock event (e.g. from a disease, introduced predator or extreme climatic event), the effect on service provision (the persistence of mature oak trees) will not be detected for many years after the event even though the seeding and regeneration of oak trees will discontinue. This is because the life-cycle of an oak tree is 20–60 years, and mature oak trees can live for more than 400 years.

Conclusion

The identification of sustainable development trajectories for a SES requires an understanding of the temporality and provenance of diverse drivers and pressures and an understanding of the way in which the system will respond to these. The cross-scale and dynamic nature of both transient and chronic changes that are transforming and taking place within adaptive systems is termed panarchy (Gunderson and Holling 2002). An understanding of these dynamic interactions and the system configurations that they may produce can help guide interventions in social, economic and technological systems, and other forms of human agency, that may enhance adaptation to environmental change.

Since social-ecological systems are dynamic and are shaped by a variety of processes acting across different spatio-temporal scales, human development and natural resource managers need to identify the potential alternative functioning pathways that may exist for a system. These might include strategies for adaptation (Smit and Wandel 2006) or building of functional redundancy (Berkes et al. 2003). The present heuristic distinction between essential dynamic properties of resilience, stability, durability and robustness directs attention at some crucial differences in the conditions under which system functions must be maintained. It is only by attending to all these properties in respect of our priority functions (like food production, ecosystem services, livelihoods, health and income), that we may hope truly to achieve sustainability.

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