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REVIEW ARTICLE

Resilience thinking: a renewed system approach for sustainability science

Li Xu · Dora Marinova · Xiumei Guo

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Abstract This paper examines the contribution of resilience thinking for social-ecological systems (SESs) in understanding sustainability and the need to preserve natural resources in the face of external perturbations. Through qualitative and quantitative analysis, the literature survey shows the increased importance of resilience and its integration into the interdisciplinary area of sustainability studies. By exploring the links between resilience and sustainability, the analysis finds that these two concepts share some similarities and also highlight the differences. The discussion of resilience indicators, measuring criteria, models and management issues reveals how resilience contributes to sustainability science and in what ways the concept can be used to measure resilience in terms of sustainability. Most existing studies emphasise the ecological aspects of resilience, but only by including human activities in the modelling can resilience thinking inform sustainability in a meaningful way. The paper concludes defining issues requiring further investigation, such as identifying and managing the drivers and key elements of resilience in SESs, exploring the dynamics between critical variables of SESs and the system feedbacks to external perturbations, as well as evaluating policies and engaging stakeholders for building resilience.

Keywords Social-ecological systems (SESs) · Resilience · Sustainability · Literature review · Measurement · Management

Handled by Victor Savage, National University of Singapore, Singapore.

L. Xu · D. Marinova (✉) · X. Guo
Curtin University, Perth, Australia
e-mail: D.Marinova@curtin.edu.au

Introduction

With strong interest in preserving the natural environment, sustainability research is a very complex and highly productive field that brings together scholarship and practice (Clark and Dickson 2003). This "use-inspired basic research" (Clark 2007, p. 1737), also referred to as meta-discipline (Mihelcic et al. 2003), transcends the boundaries of economics, environmental science, climate science, sociology, behavioural and policy studies and many other disciplines.

While sustainability is moving from conceptualisation to the development of analytical tools, human-induced disruptions are resulting in growing environmental shocks. Global problems such as climate change and natural catastrophes are the inevitable truth to which we have to adapt (Barnosky et al. 2012). In the face of such continuing environmental challenges, the context of sustainability thinking changed from questions about avoiding or mitigating climate change to finding out how resilient society is. This reflects the need to integrate the social dimensions in dealing with the abundant empirical observations of ecosystem dynamics (Folke 2006), particularly how people react to changes. Resilience thinking for ecosystems and social-ecological systems (SESs) is asserted to be one of the active focusses within sustainability (Xu and Marinova 2013). It is also regarded as the optimal way in adapting to global environmental change and dealing with human impacts as well as hazards characterised by surprises and unknown risks (Walker et al. 2004; Adger et al. 2005; Berkes 2007; Folke 2006, 2010).

The link between resilience and sustainability thinking, however, is multifaceted and the interpretation of its various dimensions is not always straightforward. What this paper sets to address is: (1) how important is resilience in sustainability studies?; (2) what are the similarities and differences between resilience and sustainability?; (3) in a growingly uncertain future, can resilience help the goal of sustainability?; (4) how can resilience be measured?; and (5) how can resilience be managed? Looking for answers to these questions, the paper conducts a literature survey to provide a better understanding of the place of resilience in sustainability studies.

Methodology

A combination of qualitative and quantitative approaches is used in this investigative review. We first start with conceptually explaining the definitions of resilience. A quantitative analysis of the publications in this area follows with the aim of this bibliometric inquiry being to show the importance of resilience in sustainability science.

Second, we analyse the similarities and differences between resilience and sustainability. The comparison demonstrates the conceptual connections between the two. After this, the contribution of resilience to sustainability is revealed through a discussion of its role in enhancing the main pillars of sustainability, that is, environmental, social and economic sustainability.

A further investigation is undertaken on aspects related to measuring resilience, including indicators, thresholds of different systems and modelling. The last facet of this review is around managing the systems' resilience to achieve sustainability goals which include building up resilience as well as managing resilience in terms of people, social capital and economic means.

Resilience: a prevailing thinking

Resilience thinking shifted the sustainability concept from the early focusses on how to achieve and maintain stability, manage effectively resources, control change, pursue economic growth and increased human wellbeing, to how to deal with changes, disturbances and uncertainties (Berkes 2007; Ahern 2011). In this section, we explain the concept of resilience and then analyse publication trends which show that resilience is becoming an increasingly prevalent thinking for sustainability.

Defining resilience

The term "resilience" originated from the technical area of mechanical and engineering sciences to describe the properties of materials, such as timber or iron, and their ability to withstand severe conditions (Hollnagel et al. 2006). It is now used across many academic fields with different interpretations ranging from engineering to psychology, economics and social sciences to ecology and environmental science (Bhui 2014) with its more recent meaning related to SESs. The conceptual similarities lie in understanding the responses to shocks, surprises, unforseen or hazardous disturbances. The specific lens of the analysis, however, differ (Table 1).

In this review, we examine resilience only in ecologically related contexts with resilience thinking applied to the ecological, social and economic dimensions of change and their integration for future development. The emphasis in social resilience is not just on the time it takes to recover from stress, but most importantly the access community has to critical resources (Langridge et al. 2006), such as water, land, finances and human skills. Economic resilience refers to "the ability of the system to withstand either market or environmental shocks without losing the capacity to allocate resources efficiently… or to deliver essential services" (Perrings 2006, p. 418). Ecological resilience describes the ability of an ecosystem to absorb environmental disturbances as well as its capacity for renewal, reorganisation, learning, adaptation and development, hence reflecting the degree of self-organisation (Berkes et al. 2003; Folke et al. 2004; Folke 2006).

The way in which economic, social and ecological characteristics are integrated is extremely important to permit system dynamics and change. Analysing the resilience of SESs, Le Maitre and O'Farrell (2008, p. 371) point out that human-constructed resilience ultimately fails because of two important reasons: first, it locks social and economic systems in specific states and trajectories (as demonstrated in the use and development of technologies, market mechanisms, or ways of governance) which reduce the overall resilience and capacity to renew and reorganise; and second, it typically also reduces the resilience of the supporting ecological systems, often to the point that they can no longer provide essential services required by society and other populations (as are the cases of climate change and freshwater availability).

The need to understand the relationships between people and nature without the barriers and divides created by specific disciplines and knowledge holders led to the establishment of an interdisciplinary network of scientists and practitioners in 1999, the Resilience Alliance. Their explanation and characteristics of resilience are widely accepted and form the basis of the definition adopted by the Intergovernmental Panel on Climate Change (IPCC 2014, p. 5), namely: "The capacity of… systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation". The Resilience Alliance emphasises explicitly that resilience is an

Table 1 Definitions of resilience in different contexts

Term	Definition	Interpretation/example	Reference
Psychological resilience	A set of combined abilities and characteristics that interact dynamically to allow a person (especially children and a family) to bounce back, handle successfully, and function above the norm in spite of significant stress or adversity	Family resilience seeks to identify and foster key processes that enable families to cope more effectively and emerge harder from crises or persistent stresses, whether from within or without the family	Rutter (1993); Tusaie and Dyer (2004); Walsh (1996)
Resilience engineering	The intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions	Refers to the ability to perform without failure; the focus is on expected and unexpected conditions of functioning for a material or system; it is also used as an alternative or a complementary view of safety	Hollnagel et al. (2006), (2011)
Engineering resilience	The ability of systems to anticipate, recognise, adapt to and absorb changes, disturbances, surprises and failures	It focusses on the stability of systems near an equilibrium state and maintaining efficiency of system functions; in this case, resilience can be measured by the stability of the system, i.e. the time the system takes to return to the previous steady state	Holling (1973); Ludwig et al. (1997);
Ecological resilience	The measure of the persistence of systems and their ability to absorb unforeseen changes and disturbances and still maintain the same relationships between populations or state variables as well as essential functions, structures, processes, and feedbacks	It assumes that there exist multiple stable states (equilibria) in ecological systems, thus ecological resilience means the tolerance of the system to perturbations that facilitate transitions among those stable states	Holling (1973); Gunderson (Gunderson and Holling 2002); Walker et al. (2004)
Social resilience	The ability of communities to withstand external shocks, mitigate and recover from hazards	It emphases the time it takes to recover from stress and also most importantly the access community has to critical resources such as water, land, finances and human skills	Adger (2000); Bruneau et al. (2003); Langridge et al. (2006)
Economic resilience	The ability of the system to withstand either market or environmental shocks without losing the capacity to allocate resources efficiently, or to deliver essential services	It emphases the functionality of the market and supporting institutions as well as the production system to recover from shocks	Perrings (2006)
Social-ecological resilience	The capacity of a system to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes	It points out that resilience is an essential property for societies to survive from changes. The system needs to keep this property by retaining its functions, structure, and capacity of self-organisation and learning	Carpenter et al. (2001); Resilience Alliance (2012, p. n.p.)

essential property of the linked SESs (Resilience Alliance 2012) and this is the approach taken here.

Increasing importance of resilience

To present the growing concerns and importance of resilience research, we examined the annual numbers of cited publications from 1973 (when Holling introduced the notion) to 2013. The publications (including books, journal articles, working papers, theses, conference papers and reports) are directly related to the term in the contexts of sustainability, ecological systems, SESs and eco-economic systems, or any combination between them. We opted to examine cited publications rather than just publications as they can better represent the use and prevalence of resilience research among researchers. Further, we did not consider the number of cites as a more informative statistics. The keyword search to identify publications in *Web of Knowledge, Scopus and Google Scholar* is based on the word “resilience” and combinations of “ecological resilience”, “economic resilience”, “social resilience”, “resilience and sustainability”, “resilience and sustainable development”, “resilience and SESs”, “social-ecological resilience”, “resilience and environment”, “resilience and natural resources”, “resilience and assessment” in the title, keywords or abstract.

In total, there are 1765, 1495 and 1560 cited resilience publications in the *Web of Knowledge, Scopus and Google Scholar* databases, respectively (see Fig. 1). There is a clear increase in the annual figures which reached their peak at 269 in 2012. Sharp increases occurred in 1999 and more clearly after 2005. Despite the overall upward trend, numbers for individual years fluctuate. This is not surprising due to the fact that the newer the publications are,

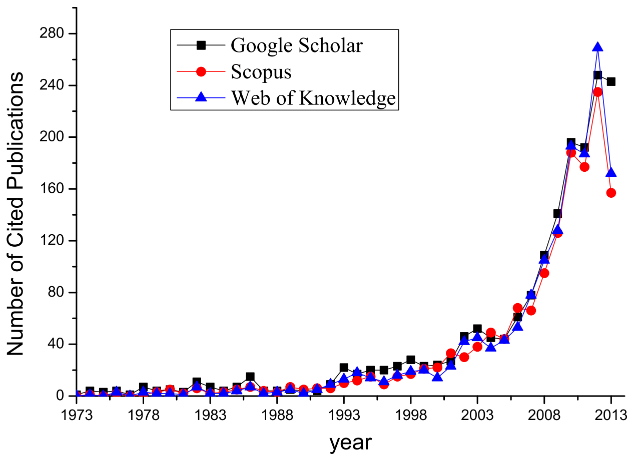

Fig. 1 Number of cited resilience publications per year, 1973–2013

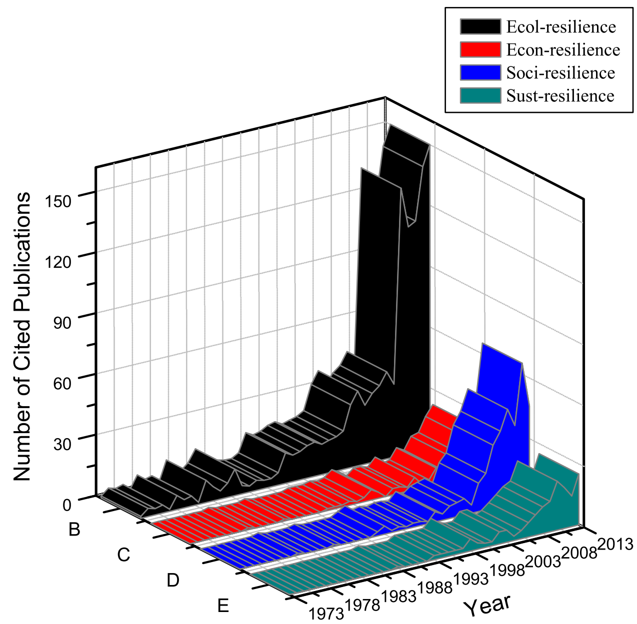

Fig. 2 Cited resilience publications in different contexts, 1973–2013

the less citations they have. The dramatic decrease in 2013 is such an example. The observed trend is consistent with the findings by Janssen et al. (2006) who argue that the sharp increase since 1999 has partly benefited from the establishment of the Resilience Alliance network with its academic journal *Ecology and Society* coupled with the increased interest in global environmental change during 1990s. The active international political arena since 2005, including the release of the Millennium Ecosystem Assessment Reports in 2005, the Stern Review in 2006, the IPCC's 4th Assessment Report in 2007, as well as the continuing regular international climate change meetings and negotiations, all stimulated research interest in resilience.

The trends obtained from the three databases are similar (Fig. 1), which show consistent interest across commercial academic outlets and the freely available *Google Scholar* reference sources. Therefore, we further investigated only *Google Scholar* scrutinising all publications one by one to identify the resilience focus, namely ecological, economic, social or integrated sustainability, each has adopted.

As shown in Fig. 2, all four resilience contexts grew steadily since 1995 with the ecological aspects vastly overshadowing social, economic and sustainability integration. Overall, economic resilience attracted the least number of cited publications. Social resilience and integrated sustainability context publications have become quite important in recent years.

The above analysis is indicative about the trends in resilience research but may contain some deficiencies. First, we made arbitrary judgement and applied our interpretation when classifying the publications into the four context groups to avoid double counting. We also did not use keywords that are considered synonymous, complimentary or characteristic of resilience, such as stability, adaptability, reliability and robustness, and antonyms of resilience, such as vulnerability and susceptibility. Non-English language publications were similarly excluded which maybe under-represents resilience research.

The findings show that resilience analysis experienced significant development and continues to increase. Nevertheless, the strong prevalence of ecological resilience indicates that more work needs to be done in the integration of environmental, social and economic knowledge in order for humanity to understand the occurring changes, self-organise to respond to them and increase its ability to learn and adapt.

Resilience thinking and sustainability

Assessing sustainability in the context of complex systems in the changing world requires a shift in thinking and perspective (Ludwig et al. 2001). The acceleration of human activities is the main external factor affecting the planet's ecosystem. This makes inappropriate the continual separation of ecological, social and economic impacts "even for analytical purposes" (Folke et al. 2010). Resilience represents such a shift in thinking and is described as a change from "fail-safe to safe-to-fail" (Ahern 2011, p. 341) for sustainability management. The review below covers the conceptual connections between resilience and sustainability by discussing what resilience means for sustainability, how resilience contributes to sustainability, how a resilient system can be sustainable, and how to maintain the resilience of SESs to improve their sustainability.

Table 2 Similarities and differences between resilience and sustainability

	Resilience	Sustainability
Similarities		
Objective	A desirable ecological resilience can sustainably supply sufficient resources and keep its functions to meet the demands of social and economic wellbeing without shifting the regimes in the face of perturbations and unforeseen shocks	Strong definition of sustainability includes an important criterion, namely that the stocks of natural capital are maintained at or above existing threshold levels for human wellbeing
Dependency relationship	The basic ecosystem functions should not be affected by human activities or other disturbances beyond their thresholds and socio-economic systems should not collapse because of changes in the states of ecosystems (precondition of sustainability)	The sustainability of a system relies on its own resilience, while such resilience depends on a wide range of properties which affect the system itself (goods and services that ecosystems can provide)
Starting points	The first important thing for applying resilience thinking to practice is to define resilience in terms "of what to what"	The sustainable state of not only social systems but also environmental systems (sustainability of what) to both present and future generations (sustainability to what)
Differences		
Intergeneration equity	Resilience thinking does not conceptually emphasise equity, meaning the resources for next generations are not less than for the current generation	Intergenerational equity is the core concept of sustainability, whose concerns are about previous injustices and the future generations' unreduced accessibility to resources as the current generation has
Desirable state	Resilience thinking does not specify explicitly the desirability of a particular state	Sustainability is interested in the desirability of any state the system is and how it transitions to another more desirable state
Culture emphasis	Culture is considered as part of social mechanisms	A strong body of sustainability research exists that acknowledges culture as the fourth pillar and capital distinctive from the natural, physical and human capital
Methodological approach	Resilience relates to responses to external factors	Sustainability relates to the evolution, and co-evolution, of complex systems that embed natural, social and environmental components and dimensions

What resilience means for sustainability

What resilience means for sustainability is the first step in bridging the conceptual connection between the two. We discuss similarities and differences (Table 2) in their objectives, relationships, starting points, cultural aspects, and in relation to intergenerational equity.

Similarities

Resilience thinking is similar to the objective of sustainability. With a resilience capacity, the system is able to keep its current equilibrium state and endure external perturbations—either from nature or human activities. This equilibrium not only relies on the stock of natural resources but also on the degree of social and economic wellbeing which consists of the three sustainability pillars. The advocated strong definition of sustainability includes an important criterion, namely that the stocks of natural capital are maintained at or above existing threshold levels. This is germane to ecosystem resilience as resilient ecological systems are important for human life and the strong sustainability criterion should be an indispensable guideline for sustainability (Ott 2003).

In other words, the loss of resilience can lead to the loss of adaptive capacity of SESs, thereby the loss of the opportunity during periods of re-organisation and renewal, which will take the systems on an undesirable trajectory termed unsustainability (Folke et al. 2002). By contrast, a desirable resilience of an ecosystem can sustainably supply sufficient resources to meet the demands of social and economic wellbeing without reducing their stock below the thresholds. This desirable resilience is in accord with the goal of sustainability of a harmonious development between nature and human society. Besides, the central aspects of resilience are the "environmental basis for human activity and the temporal dimensions of development and wellbeing" (Adger 1997, p. 3). Consequently, some argue that resilience thinking is equivalent to sustainability, and resilience is the preferred way to consider sustainability in social as well as natural systems (Levin et al. 1998; Derissen et al. 2011).

Second, resilience is a crucial condition for sustainability in that sustainable development requires both ecosystems and socio-economic systems to be resilient (Gunderson and Holling 2002). This is due to the fact that the relationship between ecosystems and human socio-economic systems is complex and interdependent, i.e. a dependency relation (Adger 1997, 2003). The sustainability of a system relies on its own resilience, while such resilience depends on a wide range of properties which affect the system itself (Perrings 1998). Socio-economic development is based on the goods and services (capacity) that ecosystems can provide, whilst such development in turn affects the state of the ecosystems. That is, if those goods and services are able to serve development over extended periods of time, the development does not jeopardise or collapse the functions of the ecosystems, then sustainability can be achieved. What resilience means to sustainability here is that the basic ecosystem functions should not be affected by human activities or other disturbances beyond their thresholds and socio-economic systems would not collapse because of changes in the states of ecosystems. Sustainability management, therefore, needs to be focussed on building resilience (Folke et al. 2002) so as to secure societal development and avoid vulnerability.

It is clear that resilience thinking and sustainability have the same starting point. The first important thing for applying resilience thinking to practice is to define resilience in terms "of what to what" (Carpenter et al. 2001). This can also be interpreted as resilience over what time period, to whom and at what scale. Resilience "of what" can be regarded as what system state is being considered, and resilience "to what" is what perturbations are of interest (Carpenter et al. 2001). For example, the desired resilience of a lake is to be in a clear-water state over a long time period and the perturbations are all industrial, water utilities, transport and recreational activities around the lake combined with climatic, environmental, geological and other natural events. Similarly, sustainability emphasises the sustainable state of not only social systems but also environmental systems (sustainability of what) to both present and future generations (sustainability to what), i.e. achieving intergenerational equity.

Although resilience does not directly highlight intergenerational equity, it implies that a resilient system should be able to maintain a desirable configuration over a long time period in the face of external perturbations—a prerequisite for intergenerational equity. The fairness of intergenerational welfare distribution relies on the planet's life-support systems and could be enhanced by resilience management. If a system collapses from external shocks, intergenerational equity would never be reached. Hence, both resilience and sustainability are achieved on the basis of temporal (i.e. present and future generations and long-term functionality) and spatial (i.e. consideration of all connections and feedbacks between systems) integrity. However, while the temporal integration is expected to be homogenous, namely equal opportunities and continuing provision of services, the spatial integration is heterogeneous and highly dependent on the unique circumstances of any particular SES.

Differences

In spite of similarities between resilience and sustainability, they are not identical notions and cannot replace each other. The main difference is that resilience thinking does not emphasise the long-term time dimension and equity, meaning the resources for next generations are not less than for the current generation. By contrast, intergenerational equity is the core concept of sustainability, whose concerns are about previous injustices and the future generations' unreduced accessibility to resources as the current generation has (Golub et al. 2013). Resilience places more focus on the state of a system when facing disturbances. In fact, in some cases, the system remains resilient as long as the critical tipping points are not passed, even though the stock of resources is reduced and less available than previously. Such a system is not sustainable based on the principle of intergenerational equity. In other words, unlike sustainability, resilience does not always stand for the desirable state of SESs; a system could be highly resilient for those systems (especially ecosystems) with multiple equilibriums without achieving the goal of equity that sustainability requires. Carpenter et al. (2001) show that system states that decreased social welfare, such as polluted water supplies or dictatorships, can be highly resilient.

Another difference relates to the approach towards culture. In resilience, culture is considered as part of social mechanisms, covering social belief, values, knowledge, and behaviours as well as social norms formed in relation to ecological health (Folke et al. 2000; Berkes et al. 2000; Walker and Salt 2012). In sustainability, however, there is a strong body of research that acknowledges culture as the fourth pillar and capital distinctive from the natural, physical and human capital (Throsby 1999, 2009). Throsby (1999) distinguishes between two forms of cultural capital: tangible (e.g. buildings, art works and locations with cultural significance) and intangible (intellectual capital, e.g. social ideas, practices, beliefs and values). Both tangible and intangible capital is inherited from former generations; in terms of equity, sustainability requires us to hand it on to the next generations.

Sustainability is an overarching goal that includes assumptions or preferences about which system states are desirable. Hence, when applying resilience in sustainability research, it needs to make sure that the system does not flip from a desirable into an undesirable state, or alternatively moves from one undesirable into another undesirable state (Carpenter et al. 2001; Derissen et al. 2011). Critics of resilience, such as Nadasdy (2007) and Hornborg (2009), even argue that maintaining capitalist social-ecological relations as a goal for resilience is undesirable as it means continuing the exploitative economic imperatives of modern extractive and agricultural industries. Similarly, the resilience of outdated technological systems could represent barriers to the introduction of better innovations as is the case of fossil fuel-based energy systems. According to Jerneck and Olsson (2008, p. 170), resilience "depicts incremental changes and capacity to preserve systems within given frames but does not recognise that social change mainly implies transitions to renewed forms of production, consumption and distribution with new combinations of organisation, institutions and technology" which represent important areas of research in sustainability.

There are also methodological differences in the way the two notions are conceptualised. Resilience relates to responses to external factors, while sustainability is associated with the evolution, and co-evolution, of complex systems that embed natural, social and environmental components and dimensions (Todorov and Marinova 2011). Hence, resilience thinking is not sufficient for sustainability and cannot be used to totally replace sustainability as the final objective.

How resilience contributes to sustainability

Sustainability is not a perpetual state of a system but evolves through reacting with external and internal factors, thus "sustainability implies not only an enhanced capacity to adapt in the face of changes, but also cope with unexpected events" (Milestad and Darnhofer 2003, p. 83). Building resilience for SESs is the vital pathway to achieve such long-term sustainability as a way to deal with changes and uncertainties (Folke et al. 2002; Milestad and Darnhofer 2003; Quinlan 2003; Berkes 2007). Ecosystem resilience can be regarded as a clear and operational concept of sustainability (Perrings 1998). Human activities can only be seen as sustainable on the condition that the ecosystems where they are occurring and on which these activities rely are resilient (Arrow et al. 1995). Sustainability can be deemed to be the desirable objective of human development, whilst resilience thinking is the way to get to this goal. The greatest contribution of resilience thinking to sustainability, therefore, is its role in linking the visionary and broad theory of sustainability into practices in more specific ways, namely the applications of resilience thinking to different realms for pursuing sustainability.

Resilience contributes to social sustainability. Community resilience is one of the important indicators of social sustainability (Magis 2010); social and ecological resilience have a clear link, in particular for social groups or communities reliant on ecological and environmental resources (capital) for their living (Adger 2000). From a sociological perspective, building resilience for SESs is beneficial for adapting to globalisation, diminishing vulnerability, alleviating poverty and promoting social justice (by accounting for resource allocations and policy decisions) thereby for long-term sustainable development (Adger 2003; Quinlan 2003; Berkes and Folke 2000). That is, a resilient SES is able to provide natural capital for human development and is capable of tolerating the stress imposed by environmental change and human activities, which no doubt enhance intra-generational justice in the short term and intergenerational justice in the long run by balancing human demands and natural carrying capacity. This kind of relative balance state (equilibrium) and social justice is the utopian aspiration of sustainability.

On the other hand, as one of the dispensable components of social systems, economic systems similarly have close relations with ecological resilience. Perrings (2006) conceives that two aspects of resilience change might jeopardise the sustainability of economic development. The first is the importance of systems' thresholds, irreversibility and hysteresis for resilience on the grounds that the loss of resilience in ecological-economic systems implies a change in the range of socio-economic or environmental conditions over which the system can maintain the flow of services. The second aspect is the role of heterogeneity or diversity. Perrings (2006, p. 418–419) explains that the resilience of ecological systems in any state is dependent on "the economic use of the system… the connection between economic usage and resilience lies in the impact of either extraction (habitat destruction, harvesting, pest control) or waste disposal (pollution of air, soils and water) on the composition of the species that support ecosystem functioning and process". In this sense, market-based management can be the effective way to ensure ecological resilience for economic sustainability but some missing markets for properties of the system such as carbon pollution or species preservation must be taken into consideration carefully because they may affect resilience (Perrings 2006). Hence, the use of price mechanisms alone may push the system to undesirable states and closer to thresholds invisible for the market. While ecological resilience improves economic sustainability, the reverse is rarely the case.

The studies applying resilience thinking to global issues at multiple scales, in particular in interdisciplinary analysis, are also paving the way for sustainability research and practice. For instance, studies on resilience of ecosystems have been widely carried out on lakes and aquatic systems that can flip from clear water to turbid water (Scheffer 1993; Carpenter et al. 1999; Scheffer et al. 2001; Gunderson et al. 2006; Baudo 2002; Folke 2003), forests (Steneck et al. 2002; Hirota et al. 2011), coral reefs (Nyström et al. 2000; Mumby et al. 2007), fisheries (Bueno and Basurto 2009), agricultural systems (Perrings and Stern 2000; Cabell and Oelofse 2012), and catchment management (Walker et al. 2009). However, these studies lack an integration perspective, and largely adopt ecological points of view. Other research has examined different community systems. For example, Adger et al. (2005) focussed on social-ecological resilience of coastal areas; Newman et al. (2009) used resilience as one of the scenarios to analyse the future of cities; Anderies et al. (2002) developed a stylized mathematical model to explore the effects of physical, ecological and economic factors on the resilience of rangelands; others focussed on urban ecosystems (Muller 2007; White and Stromberg 2011). Analysing the social aspects of systems' resilience is more difficult than examining a single distinctive ecosystem because of the complex interplay between socio-economic and ecological systems. Research led by the Resilience Alliance has stimulated interdisciplinary investigations through using resilience thinking as an overarching framework and focussing more on the socio-economic aspects of the systems. Examples of these are books, such as "Panarchy" (Gunderson and Holling 2002), "Resilience thinking" (Walker and Salt 2006), "Foundations of ecological resilience" (Gunderson et al. 2010), "Principles of ecosystem stewardship", and many articles (Endfield 2011; Adger 2000; Adger et al. 2005; Perrings and Stern 2000). They explore in-depth issues, such as how communities absorb disturbance and maintain function, why social systems are not just ecosystems, how to build resilience for ecological and socio-economic systems, all of them contributing to promoting our understanding of sustainability.

How can a resilient system be sustainable?

The first thing in exploring how a resilient system can be sustainable, particularly for SESs, is to measure its resilience. Below, we briefly discuss indicators, criteria and models to this end.

Indicators for social-ecological resilience

Measuring resilience in SESs ought to start with thinking about the abilities of reorganisation, learning, and adaptation of the systems combined with adaptive cycle analysis (Carpenter et al. 2001; Walker et al. 2002) or with systems' capacity of motivation, knowledge (information, knowledge and creativity) and capacity (Lambin 2005; Pierce et al. 2011); for example, the indicators developed for SESs' resilience of river basins on the basis of key subsystems that include biophysical (surface hydrology, climate, groundwater, native vegetation, river channels, wetlands and floodplains), economic (market values, non-marketed values, intrinsic values, bequest values and option values) and social (governance system, social networks, organisations and human capital) aspects (Walker et al. 2009). For SESs in agricultural regions, productive land use, agricultural establishments, farmer age, farmer terms of trade and wheat yield were selected (Allison and Hobbs 2004) and 13 behaviour-based indicators around aspects of the ability to meet food, fuel and fibre needs of humans in the future (Cabell and Oelofse 2012) were developed to diagnose agro-ecosystems' resilience. From a sociological perspective, resilience should be captured by social and ecological aspects with empirical indicators, such as institutional structures, population displacement, migration and mobility which may be affected by environmental variability such as extreme events and resource dependency (Adger 2000).

Yet, the indicators of SESs' resilience have not reached common usage partly because the data are usually hard to collect. Some social ecologists (Carpenter et al. 2001, 2005; Scheffer et al. 2000; Walker and Salt 2006; Darnhofer et al. 2010) suggest that the insights of measuring resilience can be transferred to identify "surrogate indicators" which are inversely related to the resilience of the system. For instance, the desirable resilience of lake systems (a clean water state) can be measured by indicators, such as the ability of farmers to reduce nonpoint pollution from their lands, if they can afford to leave wetlands undisturbed; public support for controlling pollution; economic indicators, including externalities captured by market means such as phosphorus or quotas determined by the market, phosphorus pollution costs in the market; social indicators, including social networks or groups that facilitate collaborative actions.

Existing sustainability indicators lack the propensity to present information about the ability of systems to improve their current state to become sustainable over time in the face of growing uncertainties. To fills this gap, research endeavoured to incorporate resilience directly into sustainability with the purpose of measurement (Milman and Short 2008; Walker et al. 2010b; Mäler and Li 2010). As one example, Milman and Short (2008) developed a Water Provision Resilience index to improve the deficiency of the existing indicators, which can only measure the current state of human wellbeing rather than the capacity of maintaining water accessibility over time and absorbing external stresses, for sustainable water provision in cities. Despite the contribution of this study in linking resilience thinking to sustainability assessment, there is still room for new knowledge. For example, the assessment of this study was conducted by way of expert participation and the data were based on qualitative analysis. However, quantitative data may prove more reliable for any sustainability assessment but data about natural systems are difficult to gather (even non-observable) in many cases. Appropriate surrogate indicators, which may be easier to collect in terms of data, thus need to be explored. Also, limitations of resilience indicators are that they are unpredictable and there are still gaps in our understanding of how they would behave in more complex situations. Indicators should allow to be used as early warning signals in future stochastic shocks (Scheffer et al. 2012). The work has begun but much more needs to be achieved.

Measuring criteria

It is an important question to recognise whether the resilience of SESs is increasing or decreasing thereby determining how far it is to sustainability. A well-defined threshold (or a magnitude that a system can absorb before it flips to another state; or a breakpoint between different regimes) can be used to achieve this goal (Walker and Meyers 2004; Walker et al. 2010a). Because of the complexity of SESs, the thresholds of their components are influenced by many factors. It is important to identify the crucial variables or drivers (fast and slow) together with their thresholds which determine the dynamics of the system as well as the interacting processes evidenced in the SESs (Walker et al. 2002; Walker and Meyers 2004; Kinzig et al. 2006; Walker et al. 2009). When the critical threshold level of an underlying variable is crossed, a regime shift happens. Such a shift can occur in four situations (see Fig. 3).

There is no discontinuity happening in Fig. 3a where the state of the system changes continuously with the change in the critical variable; this situation depicts how the system state changes without the effect of thresholds. In Fig. 3b, a dramatic change happens to the state of the system; however, this is reversible as there is no completely different configuration for the system. Critical thresholds exist for the underlying variables of the system in both Fig. 3c, d and they have important effects which trigger discontinuous changes on the state of the system. Both (c) and (d) have hysteretic responses to the changes in the underlying variables under the effects of thresholds. In (c), the change is reversible, while (d) is irreversible (Walker et al. 2010a, b). In this case, social-ecological resilience can be explained as how much disturbance SESs can absorb. For example, a contraction below the threshold level leads to loss of jobs and decline of social networks for the dairy and fruit processing sectors; a tipping point effect exists in terms of costs and benefits from maintenance investment; tree cover affects the water table depth and also native biodiversity; and water table depth and salinized area depend on rainfall, thus on climate, water allocation, energy cost, infrastructure and tree cover.

For management purposes, we need to recognise in which resilient regime the SESs should be, what variables determine the change of the system state, and whether there are thresholds and, if so what thresholds need to be identified to avoid the system flipping into an undesirable regime. Some thresholds can be quantitatively identified, while others are not accessible or unidentifiable, in particular for slow variables. Accordingly, research on thresholds typology is advocated as a priority topic in sustainability (Walker and Meyers 2004). This requires considering which thresholds are fixed, where they come from and how they are bundled through understanding ecosystem services, and which can be changed and categorising thresholds according to various uncertain drivers of resilience, e.g. known (known to exist or fairly certain), strongly suspected, and possible (with a fair degree of uncertainty) (Walker et al. 2009; Walker and Salt 2012). For example, there are two regimes in most freshwater lakes: desired—clear water, submerged vegetation and preferred fish species, and undesired—eutrophic, turbid and few fish, state. The state is dependent on variables such as vegetation and fish composition, water oxygen levels, and phosphorus and nitrogen input from agricultural land (the main external disturbance). Water clarity is hardly affected by increased human-induced nutrient loading until its concentration is over a critical threshold. Effective policy for preventing regime shifts can be focussing on strategies aimed at reducing nutrient loading at source, such as regulation of fertiliser use and promotion of phosphorus-free detergents. Unknown thresholds (suspected and possible), also called potential concern thresholds (Walker and Salt 2012), are more likely present in social and economic domains that are context dependent and require identifying ways of looking for them, especially critical ones, in similar systems. For instance, unknown thresholds in economic systems of a river basin include farm income (debt ratios), state of infrastructure and presence of high-multiplier economic sectors. The explanation is that the increased cost of water use will enhance on-farm innovation and water use efficiency, but will require increased capital investment (Walker et al. 2009). Thresholds in social systems include mainly balance of values held by individuals, which can be influenced by communication, policy or management. Thus, policy for enhancing socio-economic resilience could be focussed on these influencing aspects. For systems with no thresholds, for example, cultural capital (e.g. a heritage building is ruined if a fire happens), policy arrangements should focus on avoiding disturbance in the system.

However, how to measure thresholds for SESs still remains a challenge for researchers. The urgent issue is not only to know what they are or which systems have thresholds but also to gauge where the system thresholds are and how to measure them. Many studies have attempted to address such questions. Among them "Planetary Boundaries" (Rockström et al. 2009) made the contribution of identifying and defining the thresholds for our planet. In it, the thresholds were defined by controlling

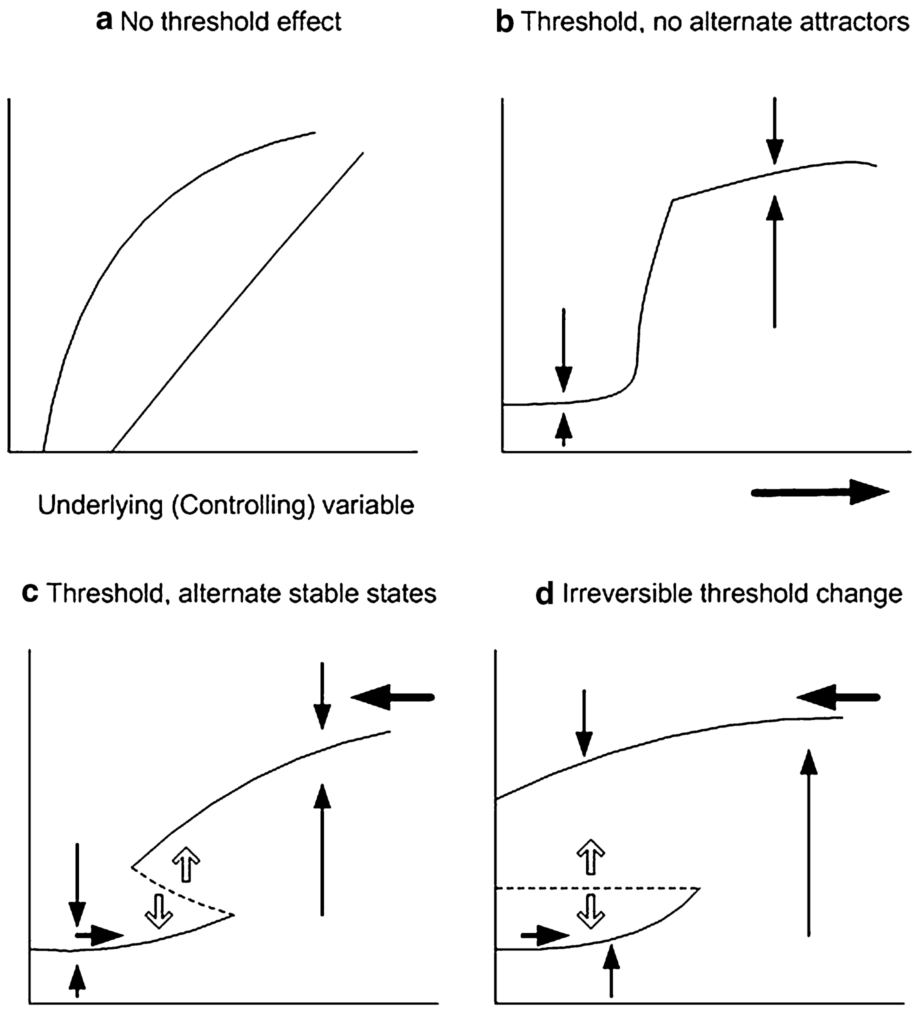

Fig. 3 Relationships between possible equilibrium state of a system and underlying variable. The *x*-axis denotes the state of the underlying (critical) variable/s and the *y*-axis represents the state of the system, with the units of measurement depending on the respective variables. The *lateral arrows* in **c** and **d** represent the direction of change

variables (parameters), such as carbon dioxide concentration for climate change, in the Earth-system process (Rockström et al. 2009). The authors used a risk-averse approach to quantifying the planetary boundaries but considerable uncertainties remain in relation to the true position for many thresholds, such as for atmospheric aerosol loading and chemical pollution. Also, the thresholds defined in the "Planetary Boundaries" study may be conservative due to the fact that in places which are particularly vulnerable they would be much lower.

In cases when we know what the thresholds are, empirical data are useful for measuring the position of a system. However, if critical variables (typically for linked social systems) are not yet evidenced or hard to identify, what other options could be is another issue. One of the key reasons why thresholds are difficult to measure is that often they are not constant and can change along a determining variable or with scale or with changes in system feedbacks (Conway 1997; Walker 1993; Walker and Meyers 2004). The rangelands system is such a good example—if the grass layer consists of all perennials, the threshold ratio of shrubs to grass is higher than if the grass layer embraces only annuals (cited in Walker and Meyers 2004). To deal with unknown thresholds and those that have not yet been crossed as well as with those that cannot be quantified, Walker and Meyers (2004) recommend extrapolation from related systems whose thresholds have been observed. Further examples and empirical data are freely available in the regularly updating database developed by the Resilience Alliance (http://www.resalliance.org/).

Another option is to use a broad-scale indicator as the signal for the measurements, such as microbial indicators for showing the dynamic nature of nutrient-production linkages and thresholds between water bodies (Paerl et al. 2003). For large spatial and temporal scales, approaches include surveys, experimental manipulations, paleo-ecological reconstructions and models (Groffman et al. 2006). For some complex SESs, it is advised to develop surrogates as an effective way to measure thresholds (Carpenter et al. 2005). This requires describing the system's identity of interest in a way that the potential thresholds can be analytically described. The study by Blythe (2014) is a good example of this. It explored the social thresholds in two coastal fishing communities in Mozambique using stakeholder engagement and developed future scenarios to describe potential social responses to crossing a system threshold.

Overall, it is easier to identify thresholds that have been passed than those that may occur in the future. Yet, the goal of sustainability is to avoid passing thresholds. Thus, the most urgent but also challenging task for sustainability is to identify and quantify critical social-ecological thresholds in SESs. Since some thresholds in SESs may not be directly observable, possible approaches include scenarios (Walker et al. 2002; Folke et al. 2002), surrogate indicators combined with assessment modelling (Carpenter et al. 2005) and generic empirical indicators (Scheffer et al. 2012). As well, to better determine them, in-depth understanding of the complex dynamics between different thresholds is needed as cross effects and a delicate balance (Rockström et al. 2009) exist among them in our planetary system.

Measuring models

The widely applied conceptual model for measuring resilience is Panarchy which is used to analyse the source and role of change in systems—the interplay between change and persistence, the predictable and unpredictable and between different phases (exploitation, reorganisation, conservation, and release) by means of an adaptive cycle (Gunderson and Holling 2002), including relationships between long-term environmental change and economic development (Allison and Hobbs 2004). Panarchy explains well the rules of how changes happen in nature taking place and interacting at various scales from local to global (Allen et al. 2014). As there already exists detailed discussions and reviews of this theory (Gotts 2007; Holdschlag and Ratter 2013; Allen et al. 2014), we examine the mathematical models which have attracted less attention.

Most of the existing models which attempt to assess resilience for sustainability are developed from an economic perspective. They tend to cover economic costs (Anderies et al. 2002), resource stock and environmental accounting with a pricing approach (Perrings 1998; Perrings and Stern 2000; Walker et al. 2010a; Mäler and Li 2010; Derissen et al. 2011; Scheufele and Bennett 2012). For instance, a Markov model was employed to analyse the dynamics of economic-environmental systems in terms of resilience by Perrings (1998), while Walker et al. (2010b) and Mäler and Li (2010) priced resilience on the basis of a probabilistic approach. We take the inclusive wealth (IW) model as an example in this review because of its implementation for policy makers and closer connections to the typologies of thresholds (known and unknown) which we discussed before.

The IW model aims to evaluate inevitable trade-offs and resilience by the way of environmental accounting and by taking consideration of known or suspected thresholds (Walker et al. 2010b). According to the IW approach, intertemporal social welfare is defined on a vector of consumption flows, i.e. goods and services. The social welfare function can be given by (1) which is assumed as a monotonically increasing and strictly concave function (cited in Walker et al. 2010b).

$$W_t = \int_t^{\infty} U(C_\tau) e^{-\delta(\tau - t)} \mathrm{d}\tau \tag{1}$$

where W_t represents social welfare, δ is a positive constant which stands for the utility discount rate, to which W_t is subject, and $U(C_\tau)$ is the function of consumption flows (utility of goods and services).

Based on the IW model, Walker et al. (2010b) define sustainable development as non-decreasing social welfare in the long term, namely the present value of any future utilities must be maintained over time, and short-term declines in instantaneous consumptions are allowed but need to be offset. Accordingly, they use capital stocks, time and the resource allocation mechanism to describe social welfare. Social welfare is then measurable in terms of the value of capital stocks through shadow prices of capital assets. The change in welfare over an infinitesimal period of time can be measured, as it is equivalent to the change in the capital stocks. The welfare change is given by Eq. (2).

$$V_T - V_0 = \sum_i (p_{iT} K_{iT} - p_{i0} K_{i0}) - \int_0^T \left(\sum_i K_{i\tau} \frac{\mathrm{d}p_{i\tau}}{\mathrm{d}\tau} \right) \mathrm{d}\tau \tag{2}$$

where the first part is capital gains and the second part is endogenous price changes; V_T is the value of the capital stocks at time T, V_0 is the initial value of the capital stocks, K represents capital stocks. If K_i does not change between two times, there has been no change in IW. If $V_T - V_0 \geq 0$, then the system can be viewed as sustainable as social welfare is non-decreasing over this period.

In incorporating resilience into the assessment of sustainability, Walker et al. (2010b) quantify resilience using the critical thresholds (distance to threshold) and measuring the shadow price, which reflects the future change in social welfare from a marginal change in current resilience (capital stocks) in terms of welfare. After introducing cumulative probability distribution and net benefit, the price of one more unit of resilience at time 0 can be estimated by Eq. (3).

$$q(0) = \frac{\partial E(W_0)}{\partial X_0} = \int_0^{\infty} \frac{\partial S(X_0, t)}{\partial X_0} [U_1(t) - U_2(t)] e^{-\delta t} \mathrm{d}t \tag{3}$$

where $E(W_0)$ is the expected intertemporal welfare, i.e. the expected present value of future utilities from the initial time 0. $S(X_0, t)$, called the survival function, represents the probability that the system has not flipped before time t and equals to $1 - F(X_0, t)$; $F(X_0, t)$ represents the cumulative probability of a flip up to time t and X_0 is the initial resilience stocks; $U_1(t)$ and $U_2(t)$ is the net benefit at time t in the situation that the system has not bifurcated and the net benefit if the system has bifurcated before (or at) time t, respectively.

How can the IW model contribute to policy making? As an example, the IW model was used in the Goulburn-Broken Catchment management project to assess the value of different policy options (Walker et al. 2010b). Whether the enhanced pumping policy, aiming to control water flows for regulating the water table, is feasible or socially profitable can be evaluated with the model by comparing welfare using accounting prices. Accordingly, the estimated values of IW are calculated to be \$46 and \$57 million in normal climate and dry climate scenarios, respectively. Accepting that the value of the enhanced pumping capacity is equal to the value of the enhanced resilience enabled by it, whether the policy is socially profitable can be evaluated by comparing whether the cost of the policy to reduce the initial water table by 1 m is less than the estimated value (i.e. \$46 and \$57 million).

Economic accounting of resilience for the assessment of sustainability is a direct way to analyse how resilience in SESs interacts with different variables. However, to implement this approach requires information about the probability of an ecosystem shift, which in many cases is unpredictable and unobservable. Despite the IW model being a good theory for evaluating projects and policy options, it relies heavily on estimates of parameters, such as capital stock and shadow prices which in many markets are hard to calculate, and expectations about the future, such as related to climate, which are unforeseeable. The estimation of parameters in the model thus needs to be analysed according to the specific situation (Walker et al. 2010b). Likewise, the existing models do not put enough emphasis on the impacts of human activities on the resilience of SESs, while in reality these are becoming an increasingly detrimental driving force in pursuing sustainability. Any future research on resilience modelling for sustainability needs to integrate environmental and social disturbance variables to provide more meaningful insights.

How to manage resilience for sustainability?

Sustainable management requires effective and efficient management strategies for social-ecological resilience (Scheffer et al. 2001). Folke et al. (2000) suggested seven general principles for building resilience for sustainability management: (1) using management practices based on local traditional ecological knowledge; (2) designing management systems that 'flow with nature'; (3) developing local ecological knowledge for understanding cycles of natural and unpredictable events; (4) enhancing social mechanisms; (5) promoting conditions for self-organisation and intuitional learning; (6) rediscovering adaptive management and (7) developing values consistent with resilient and sustainable SESs.

From this perspective, management practices fall into three categories (Berkes et al. 2000): (1) practices found in both conventional resource management and some local societies (e.g. monitoring resource abundance and change in ecosystems; species and habitat protection); (2) practices abandoned by conventional resource management but still found in some local societies (e.g. multiple species management, resource rotation and succession management); and (3) practices related to the dynamics of SESs seldom found in conventional resource management but existing in some traditional societies (e.g. management of catchments, landscape patchiness and nurturing sources of ecosystem renewal). There are also complex social mechanisms relating to institutions, cultural internalisation, and worldview behind traditional ecological knowledge practices. Institutions, either formal or informal, provide rules for individuals to organise their activities that produce outcomes affecting them and maybe others (Olsson et al. 2004). Worldview shapes cultural values, ethics, basic norms and rules within a society (Berkes et al. 2000).

The above principles are only the start in analysing SESs and sustainability, further identifications and interpretations are needed for specific studies (Berkes et al. 2000). Notwithstanding this, they clearly show that the two main components of management practices are local ecological knowledge and social mechanisms.

People play a key role in the process of managing resilience. The first step is to identify the right people to be involved in the management practices and consideration should be given to users of resources (people from government agencies, industry groups and local stewardship groups) and people who hold the knowledge (individual, community, specialist, organisational and holistic) (Walker and Salt 2012, p. 36). The next step is for local ecological knowledge to contribute to management practices. Views from people can help managers to specify what should be known about what is happening at different scales, their connections and what is important to the system (Walker and Salt 2012, p. 39). Social mechanisms could be enhanced through financial interventions (investments, subsidies or taxes), building up flexible governance or institutions (multilevel and polycentric) and improving education and training to achieve active adaptive management and social-ecological resilience (Adger et al. 2005). Furthermore, resilience policies for sustainable development should: (1) strengthen the perception of humanity and nature as interdependent and stimulate building resilience in SESs; (2) create open institutions for learning and flexible collaboration as well as direct actions towards building adaptive capacity; and (3) stimulate the development of indicators and warning signals of gradual change, loss of resilience and thresholds, and develop friendly technology and economic incentives to enhance resilience, encourage learning and incorporate ecological knowledge into institutional structures (Folke et al. 2002; Adger et al. 2005).

In addition, other studies advocate increasing collective actions, i.e. coordination of efforts among groups of individuals to achieve a common goal, as a way to manage resilience for sustainability (Ostrom 1990; Tompkins and Adger 2004; Olsson et al. 2004; Fiksel 2006). For the collective action to be effective, the interests of different stakeholders should be carefully considered. Smaller groups that consist of diverse stakeholders with similar interests are more likely to be successful than large ones, and members of the group should have equal endowments (Ostrom 1990; Tompkins and Adger 2004). Co-management institutions are put forward as a form to achieve such collective action. Tompkins and Adger (2004) found that expanding the networks of dependence and multilevel engagement (local, regional, national and international) can contribute to building co-management institutions thereby social and ecological resilience. Olsson et al. (2004) argued that institutional and organisational landscapes should be investigated to identify what contributes to the resilience of SESs identifying important aspects of the co-management process, including legislation, leadership and trust, funds for responding to environmental change and remedial action and information flow through social networks.

Some economic means can induce change in the resilience of SESs thereby its sustainability; enhancing the resilience of SESs thus requires identifying and controlling those economic variables. For instance, price shocks to products which may affect environmental conditions can result in changes of the state of systems, and the price has different impact on change and return. A fertiliser price that induces a change of state of the lake is very different from a fertiliser price that induces a return to the original state (Perrings 2006). The ecosystem must be able to provide goods and services continuously for human development, to maintain "manageable levels of government and external debts" and to avoid "extreme sectoral imbalances which damage agricultural or industrial production" (Harris 2000, p. 5–6). To achieve sustainability economically, a market discount rate is advocated for natural resources such as soils, and atmospheric functions should be treated as aspects of natural capital (Daly 1994). Particular economic implications to enhance resilience and sustainability highlighted by Perrings (2006) are to: (1) understand the ecological-economic systems dynamics as any feedback control mechanism, such as the market policy process, may be misdirected; (2) identify the existence of both ecological and economic thresholds (such as price beyond which activities have important consequences for physical conditions) and the consequences of crossing the thresholds; (3) understand the role of natural, financial and produced assets in the management of financial and ecological disturbance; and (4) pay more attention to the trade-off between productivity and resilience.

In summary, increasing co-management by engaging stakeholders, linking social networks and enhancing social mechanisms by emphasising local and scientific ecological knowledge, facilitating social learning and establishing flexible institutions are the key measures for building resilience for sustainability in the foreseeable future. However, further research and efforts are still required to achieve such goals. There is need to explore multi-scale effects, how to evaluate environmental, social and economic trade-offs, how to monitor and evaluate strategies, how to identify and engage with stakeholders. Resilience thinking is still in its infancy, while sustainability imperatives are becoming increasingly pressing for research and people to address.

Concluding remarks

Sustainability is about a harmonious relationship between the natural and human world. It relies largely on SESs being able to withstand the increasing external uncertainties and perturbations. Managing for resilience is the best possible way to enhance the likelihood of sustainability in this uncertain future (Walker et al. 2004; Adger et al. 2005; Berkes 2007; Folke 2006).

The review presented provided some most needed understanding about the connection between resilience and sustainability. What we have been able to identify is:

- Resilience thinking has drawn an increasing number of researchers whose interests have started to guide interdisciplinary efforts with more focus on social and social-ecological contexts. Despite this, research on resilience and sustainability is still in its development stage with more attention required to integrating the abundant ecological evidence with socio-economic aspects and the role of human activities in shaping the planet's ecosystems.
- Despite shared objectives and resilience thinking being essential for sustainability, it is not entirely sufficient

and cannot be used to totally replace sustainability as the final objective. Any studies that try to incorporate resilience into sustainability need to take a long-term perspective from an intergenerational point of view, define what the desirable state of the studied system is and ensure that the system does not flip from a desirable into an undesirable state.

- The important contributions of resilience to sustainability are not only its specific views on dealing with changes and uncertainties for sustainability goals but also its growingly wide applications that are increasingly improving our understanding of sustainability. Despite this, more efforts need to be made to study the uncertain and complex dynamics in particular in SESs.
- Measuring resilience for sustainability is not an easy job and still remains a challenge with the difficulties and uncertainties in identifying thresholds which have not been crossed or are non-observable. There is not enough evidence revealing critical variables that cause regime shifts of systems. This is extremely important as many variables in SESs are tightly linked; exceeding the critical threshold of one may affect others thereby the balance of the whole system. The area of sustainometrics (Todorov and Marinova 2011) will continue to benefit from further research on modelling and measuring sustainability but it is unlikely that any mega single discipline would be able to deliver the knowledge required to properly understand resilience and sustainability.
- Managing resilience requires careful considerations to be given to establishing flexible institutions for social learning and co-management, including stakeholder engagement to improve sustainability practices and enhance local ecological knowledge about the dynamics of SESs.

In conclusion, resilience research for sustainability will need to concentrate on questions such as how to identify and manage the key drivers and elements of resilience of the SESs, what the dynamics between critical variables in SESs of different areas are, how long it will take for feedbacks from a system to cause changes to happen in others (especially hazardous changes in other systems when the thresholds of a system are crossed), how to monitor and evaluate whether the strategies are working towards building resilience, and how to identify and engage with stakeholders when building social-ecological resilience.

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