Ecosystem resilience and its practical implications in contemporary environmental management

Summary

- Resilience is the situation where environmental forcing causes a deviation in structure, but the system naturally reverts to its original condition
- Resilience applies equally to natural ecosystems and social-ecological systems (SESs)
- Resilience affects the stability of a system and is related to resistance to changes and vulnerability to stressors
- Resilience is a source of change that can either
  - ✓ trigger the establishment of a new stable state for the system when a tipping point is reached, or
  - ✓ that can prevent such state shift
- Under a management perspective, and depending on the specific situation, resilience can therefore be desirable and beneficial, or thwart management actions
- Resilience is related to biodiversity, that is the number of species (richness) and their relative abundance (evenness)
- Resilience is related to functional redundancy, that is the number of species that perform a specific ecological function
- Measuring resilience is challenging and resilience lacks a universal definition
- Resilience is the focus of contemporary management approaches. Policies have become more centred towards managing resilience, rather than removing stressors

Introduction

Historically, the conceptual framework used to study ecosystems relies on how ecosystem dynamics are unidirectionally affected by human activities on one side, and biogeophysical drivers on the other. This allegedly outdated approach ignores more complex interplays and feedbacks, and has been gradually replaced by a more inclusive framework that explicitly includes human decisions, cultural institutions, and economic systems (social drivers) (McGinnis and Ostrom, 2014).

The extended framework (integrated ecology) reflects the resilient and sustained regular interactions between social and biophysical factors, within several spatial, temporal and organisational scales (possibly hierarchically linked). System functioning depends on critical natural, socioeconomic, and cultural resources, that flow, are shared, recycled, and consumed, under the influences of the social and biogeophysical drivers and systems. According to Redman et al. (2004) this perpetually dynamic, complex system with continuous adaptation, is a Social-Ecological System (SES)

SESs are a major focus of contemporary approaches to environmental management (Lade et al., 2013) and paradigm shifts have become commonplace (Gonzalez et al., 2008). An emerging property of SESs is their stability, whose dynamics depend on three complementary attributes: i) resilience, ii) adaptability, and iii) transformability (Fig. 1) (Walker et al., 2004).

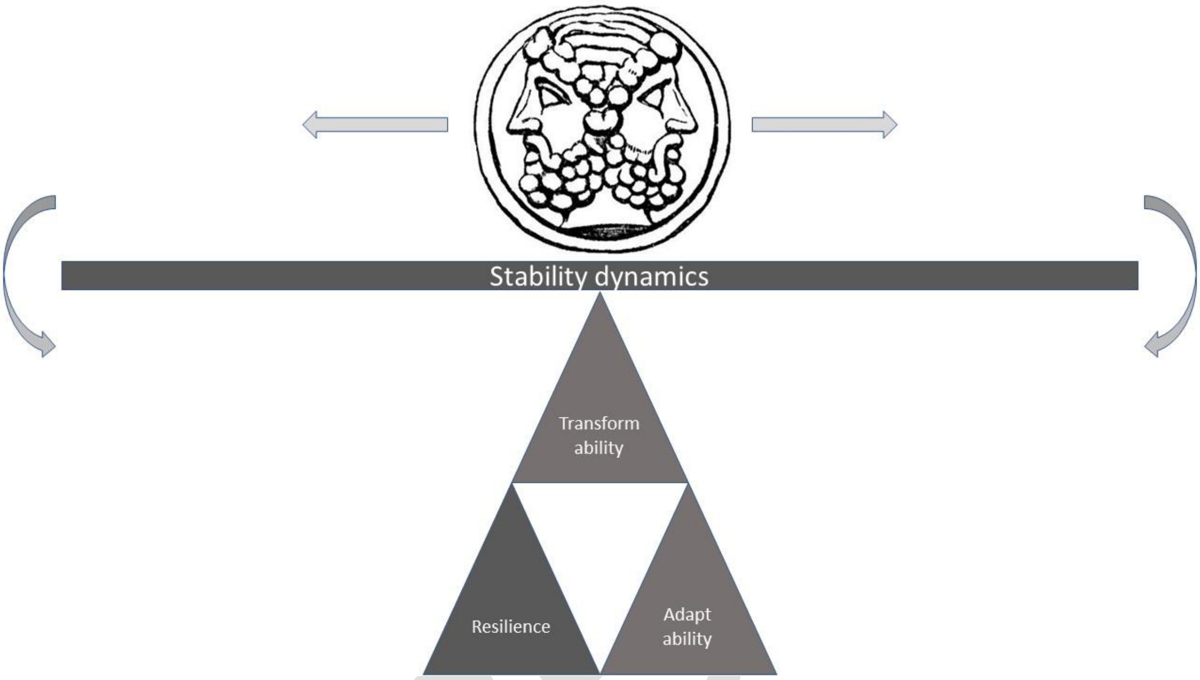

Fig. 1 Conceptual representation of the three attributes affecting the stability dynamics of a social-ecological system (SES). SES is represented by a two-faced Janus marble, in reference to the role of its social- and biogeophysical- drivers. SES stability depends on the complementary states of resilience, adaptability, and transformability.

Resilience (this document's focus) lacks an official/universally accepted definition, as multiple changes/adaptations have been proposed (Gunderson et al., 2002, Walker et al., 2006, Walker et al., 2004) since Holling's 1973 paper (Holling, 1973). Importantly, however, all these definitions revolve around a perturbation event, and the system ability to absorb and recover from this disturbance. Reynolds (2006) summarises this elasticity as the situation where environmental forcing causes a deviation in structure, but the systems reverts to its original condition, and points out how resilience leads to constancy over a long time (rev. in (Reynolds, 2006)).

Many ecosystems are highly dynamic, and spatial and temporal changes are the norm. This dynamicity is often due to large-scale disturbance factors (Elmqvist et al., 2004) and the system intrinsic resilience. As external disturbance is often unavoidable resilience has become the focus of much attention, as a driver of change that has obvious important effects on monitoring- and recovery- strategies (Folke, 2006). The idea of a stable and resilient SES, easily recoverable by environmental managers and eternally able to revert to a pre-disturbance

state, upon removal of anthropogenic stressors is outdated. Under a newer and allegedly more promising resilience-perspective, policies are shifted towards managing the capacity of SESs to deal with unavoidable and unpredictable changes (Folke, 2006). Resilience quantification is challenging and an active research area (Quinlan et al., 2016), but its relationship with SES stability has critical implications for contemporary environmental management approaches. This note presents theoretical and practical examples on these implications.

Environmental management perspective

The classic conceptual view

Fig 2. is a classic "*marble-in-a-cup*" conceptual representation of the alternative stable states of a lake (blue marbles) for various nutrient loads (Scheffer et al., 1993).

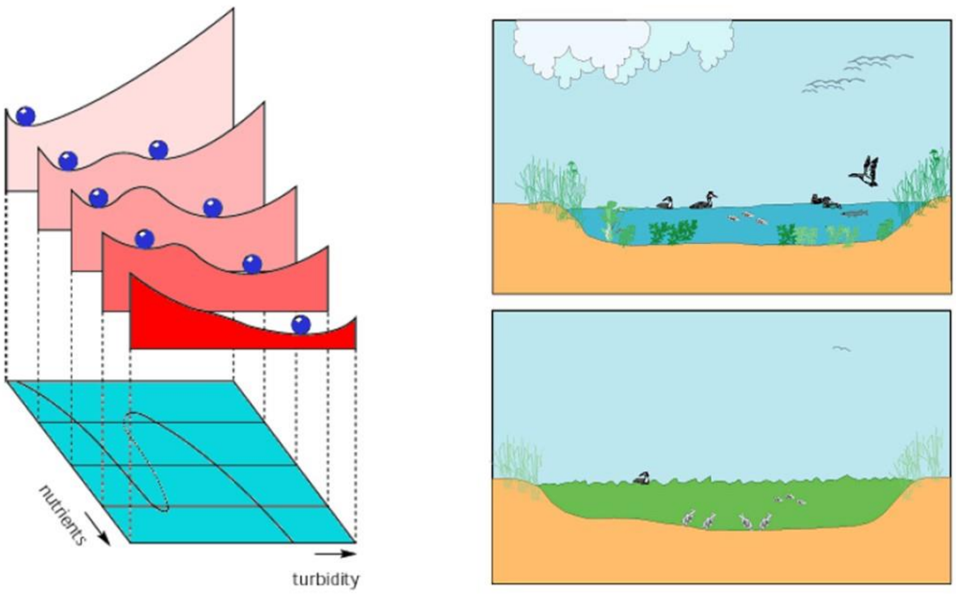

Fig. 2. Conceptual representation of lake stability and turbidity as a function of nutrients (Scheffer et al., 1993).

Depending on the level of nutrients (1 to 5), either one or two stable states are possible (left). For instance, for extreme nutrients levels (1 or 5), only one stable state is possible: the vegetation-dominated clear state (right; top panel) or phytoplankton-dominated turbid state (bottom). Turbidity affects light penetration; when there are very little nutrients (oligotrophy), plants won't yield to phytoplankton, even if turbidity increases momentarily (e.g., runoffs). Similarly, in eutrophic lakes phytoplankton will easily outcompete plants, even if turbidity is momentarily decreased (sediments runoff). For intermediate levels of turbidity (2-4) the system shows hysteresis, and different lakes (or the same) may swing between alternative states when perturbed (phase shift).

Fig. 2 draws on the concepts of stability, resistance, and vulnerability, and resilience, transformability, and adaptability (Fig. 1). The depth and width of the cups (AKA basins of attraction) depicts the stability and conceptualise resistance, vulnerability and resilience, whereby despite external forcing the internal structure is either preserved, or first altered and then quickly regained. Decreased resilience makes the system more vulnerable to external pressure (shallow, wide cups in Fig. 2).

Although turbidity is a function of nutrients, there are two possible equations explaining this positive relation. This is called hysteresis and the adoption of one function vs. the other for numerical modelling, depends on the level of critical turbidity which is the ecological threshold that must be exceeded to trigger a phase shift.

For eutrophic lakes (nutrients=5), reducing turbidity won't revert the system to pre-eutrophic conditions. Reducing nutrients from 5 to 4, makes a phase shift possible, but at this nutrients level the vegetation-dominated clear state won't be stable and likely return quickly to the phytoplankton-dominated turbid state. Reducing nutrients from 5 to 2, instead, will increase the chances for the system to more permanently adopt the clear state, as opposed to the turbid state. Finally, at nutrient level 1, only the clear state is possible, and this will be the stable state for the system.

Transformability and adaptability are concepts related to resilience also important to managers (Fig. 1). Allowing for system transformability implies considering i) alternative stable states possible, and ii) shifts unavoidable when conditions make a state unsustainable (Fig. 2). Adaptability is the environmental managers' capacity to influence resilience of SESs (Walker et al., 2004). Adaptable management involves implementing flexible solutions that give latitude to intrinsic resilience to drive changes, and to complex SESs to interact across multiple temporal and spatial scales (panarchy) (Allen et al., 2014).

Importantly, the concept of resilience is not exclusive to natural ecosystems, but also applies to SESs. Examples of studies describing how a variety of stressors have triggered adjustments or transformative actions, thanks to sources of resilience present within the SESs is given in Table 1 (from (Nelson et al., 2007)). In these examples we can identify adjustments that are short-term and reactive (row 1), longer-term and reactive (row 2), and long-term, proactive adjustments (rows 3 and 4).

Adaptation to:	Adjustments or transformative action	Sources of resilience
Drought in Kenya and Tanzania[a]	Switching occupation, selling assets, drought relief	Social networks, remittances
Drought in northeast Brazil[b]	Private actions: livelihood diversification, risk management in agriculture, patron-client relationships Public actions: humanitarian relief, crop insurance, seed distribution, irrigation schemes	Lessons learned from past drought events, e.g., honed emergency relief mechanism, social networks, social security payments
Coral reef stress associated with physical damage, eutrophication, and fisheries decline in Tobago, West Indies[c]	Development of community-based resource comanagement, community monitoring of reef use, consensus building for future zoning and limitations on sewage disposal	High diversity in use between tourism and subsistence activities, heightened awareness of critical thresholds and well-defined user communities, learning through consensus building
Actual and potential disruption from hurricane risk in Cayman Islands, West Indies[d]	Regulatory changes: enhanced building codes and zoning to increase waterfront setback, development of National Hurricane Plan Organization changes: creation of National Hurricane Committee and inclusion of diverse interests within it	Self-efficacy facilitated by high government revenue stability; recent experience of hurricanes (Hurricane Gilbert 1988, Mitch 1998, Michelle 2000, and Ivan 2004) promoted urgent learning from each experience accompanied by a willingness to learn from past mistakes[d]; strong national and international support networks

Table 1. Examples of studies describing how a variety of stressors have triggered adjustments or transformative actions, thanks to sources of resilience present within the SESs (from (Nelson et al., 2007)).

Practical example one

Chesapeake Bay in the US states of Maryland and Virginia is a large estuary whose water quality has dramatically decreased due to anthropogenic activities carried out within the estuary and surrounding catchments (Lotze, 2010). Tropical storm Agnes (1972) caused a massive inflow event, mainly due to deforested catchments, lack of buffering wetlands and lowered aquatic biodiversity. The extensive and prolonged plume of turbid sediments was a major contributor of a state shift of this by-then vulnerable SES.

Current intense restoration efforts are characterized by adaptability and panarchy and focus on resilience: stratifies include change in land use within the catchment, change in agricultural practices, reforestation, nutrients runoff and sewerage input reduction, phosphate sequestration, revitalization of bivalve and fish populations (Gottlieb and Schweighofer, 1996, Kerr et al., 2010).

These efforts may have successfully increased the Bay's resilience and eventually promoted the regrowth, in the upper bay, of an extensive plant benthic system that disappeared after the 1972 storm (Gurbisz and Kemp, 2014). Gurbisz et al. (2014) attribute plant disappearance/resurgence to state shifts triggered by synergistic forces of river discharge extremes and water quality changes. Negative feedbacks in the system that dampen change were likely responsible for reinforcing pre-and post- shift system states. In accordance to others, this study emphasises the importance of resilience maximization by minimization of chronic anthropogenic stressors during conservation efforts (Gurbisz and Kemp, 2014).

Promoting resilience rather than preserving stability, may be essential in ensuring that a desirable alternative stable state is reached, once the ecological threshold is overcome due to active management actions or stochastic events (Fig. 2). To this end is also important to discuss how positive and negative feedbacks can reinforce or weaken the resilience of stable state. If a perturbation creates a feedback switch (to positive) the disturbance is not dampened by the resilience, the threshold is overcome and a new stable state is reached (Fig. 3) (Briske et al., 2006). A conceptual model like this may explain some of the discussed dynamics in Chesapeake Bay.

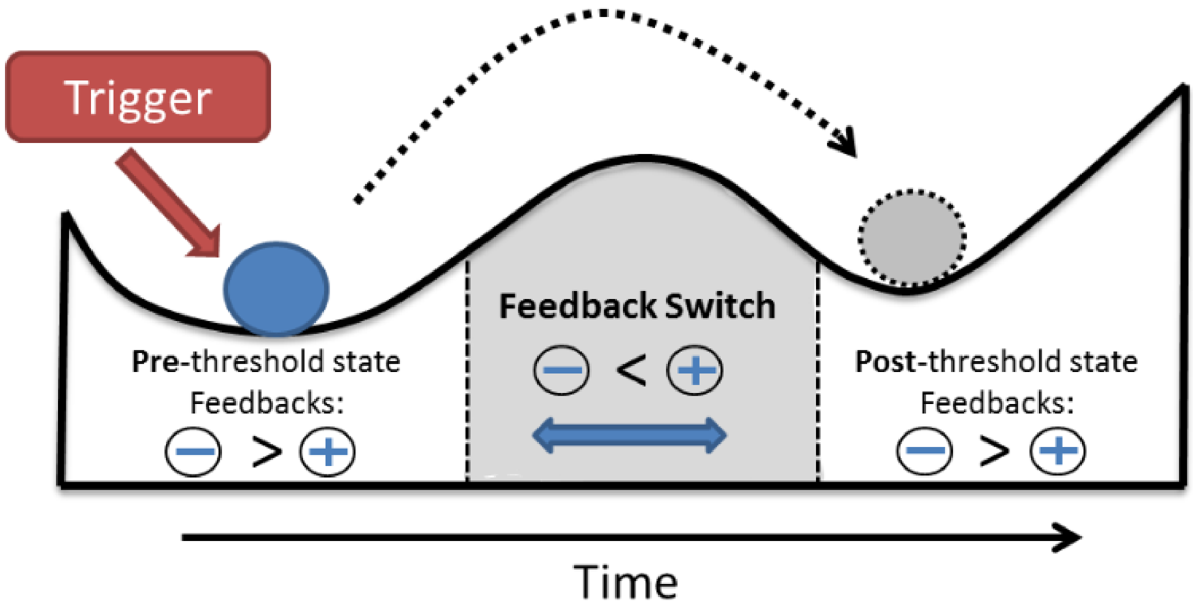

Fig. 3. Relationship between positive and negative feedbacks and resilience. System stability is connected to resilience, which can be strengthen or weakened by a positive or negative feedback. An external perturbation can cause a transitory feedback switch and the shift to a new alternative state (Briske et al., 2006).

Practical example two

It is widely accepted that changes in biodiversity alter ecosystem processes and SES resilience to environmental change (Chapin et al., 2000). Species richness and evenness are related to the important concept of functional redundancy: when multiple species can perform the same ecological role, the function is more likely to be preserved, even if some species are lost due to lethal stressors.

A stimulating study on climate change and coral reefs illustrates conventional and alternative views of resilience, as in Fig 4 (Côté and Darling, 2010).

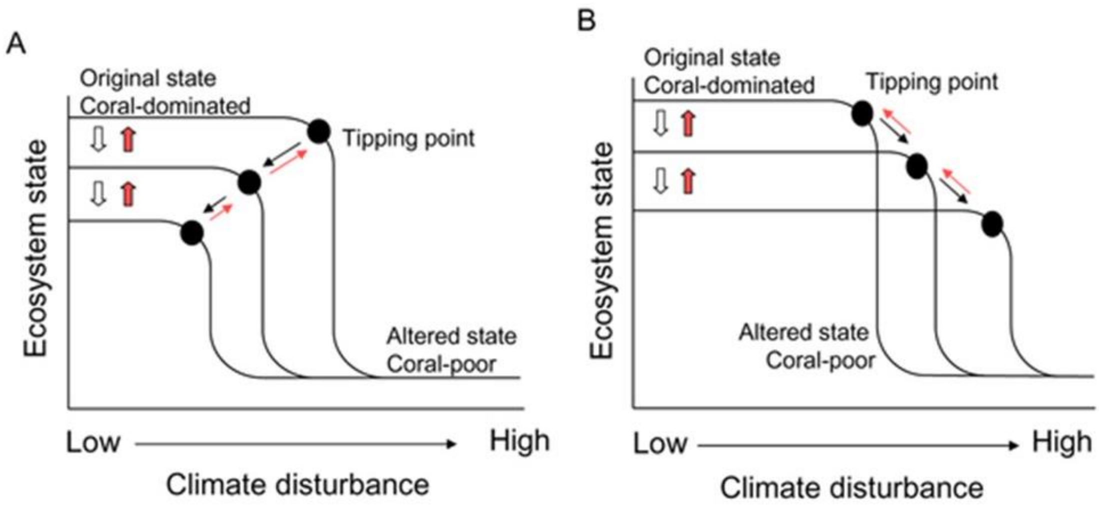

Fig. 4. The conventional view of coral-reefs resilience and climate disturbance (A). An alternative view (B). Disturbance and state could be measured as temperature and biodiversity, respectively (Côté and Darling, 2010).

The conventional view assumes that biodiverse, undisturbed coral-dominated ecosystems (higher ecosystem state) are more resilient to climate disturbance than stressed ones (Fig. 4A). Management actions increasing the ecosystem state (red block arrows), increase also biodiversity and resilience, thus promoting self-recovery and moving the tipping point further to the right. Non-climatic local stressors (open block arrows) move the tipping point further to the left and the altered coral-poor state is reached at lower levels of climatic disturbance.

Under the alternative view (Fig 4B), it is proposed that chronic anthropogenic stressors degrading the ecosystem state (open block arrows) have the potential to selectively remove species more sensitive to disturbance. This pushes the tipping point in response to climate change to the right, and makes the reef more resilient to climate disturbance. Under this view, management that seeks to control local anthropogenic disturbances by increasing the state will have counterproductive effects (Côté and Darling, 2010).

The thought-provoking paper by Côté et al. (2010), show how marine reserves do not necessarily reduce frequency/intensity of thermally induced coral bleaching, and suggests that chronic anthropogenic disturbance can make coral communities richer in disturbance-tolerant species or individuals. Arguably, this alternative view is more consistent with the majority of empirical observations from Phoenix Islands, Palmyra reef (Line Islands), American Samoa, Fiji, and the Philippines (Côté and Darling, 2010).

Conclusions

Global population growth and the frequency and amplitude of environmental changes observed since the industrial revolution pose extraordinary challenges that require large scale adaptations and social transformations. The notion that if pressure is removed a (social) ecological system self-heals is outdated. It is also now clear that our ability to actively

manipulate a multitude of interacting stressors is limited, like it is our capacity to anticipate the responses to such manipulations. In this context resilience has drawn much attention and has progressively become the focus of management policies and strategies. Quantifying resilience is fraught with problems. However, resilience can still be responsible for hindering management efforts or induce desirable regime shifts, so universal or system-specific proxies of resilience (e.g., biodiversity, functional diversity etc.) should be tested ad measured.

References

ALLEN, C. R., ANGELER, D. G., GARMESTANI, A. S., GUNDERSON, L. H. & HOLLING, C. S. 2014. Panarchy: Theory and Application. *Ecosystems,* 17**,** 578-589.

BRISKE, D. D., FUHLENDORF, S. D. & SMEINS, F. E. 2006. A Unified Framework for Assessment and Application of Ecological Thresholds. *Rangeland Ecology & Management,* 59**,** 225-236.

CHAPIN, F. S., ZAVALETA, E. S., EVINER, V. T., NAYLOR, R. L., VITOUSEK, P. M., REYNOLDS, H. L., HOOPER, D. U., LAVOREL, S., SALA, O. E., HOBBIE, S. E., MACK, M. C. & DIAZ, S. 2000. Consequences of changing biodiversity. *Nature,* 405**,** 234-242.

CÔTÉ, I. M. & DARLING, E. S. 2010. Rethinking Ecosystem Resilience in the Face of Climate Change. *PLOS Biology,* 8**,** e1000438.

ELMQVIST, T., BERKES, F., FOLKE, C., ANGELSTAM, P., CREPIN, A. S. & NIEMELA, J. 2004. The dynamics of ecosystems, biodiversity management and social institutions at high northern latitudes. *Ambio,* 33**,** 350-5.

FOLKE, C. 2006. Resilience: The emergence of a perspective for social-ecological systems analyses. *Global Environmental Change-Human and Policy Dimensions,* 16**,** 253-267.

GONZALEZ, J. A., MONTES, C., RODRIGUEZ, J. & TAPIA, W. 2008. Rethinking the Galapagos Islands as a Complex Social-Ecological System: Implications for Conservation and Management. *Ecology and Society,* 13**,** 26.

GOTTLIEB, S. J. & SCHWEIGHOFER, M. E. 1996. Oysters and the Chesapeake Bay ecosystem: A case for exotic species introduction to improve environmental quality? *Estuaries,* 19**,** 639-650.

GUNDERSON, L. H., PRITCHARD, L., INTERNATIONAL COUNCIL OF SCIENTIFIC, U. & SCIENTIFIC COMMITTEE ON PROBLEMS OF THE, E. 2002. *Resilience and the behavior of large scale systems,* Washington, D.C., Island Press.

GURBISZ, C. & KEMP, W. M. 2014. Unexpected resurgence of a large submersed plant bed in Chesapeake Bay: Analysis of time series data. *Limnology and Oceanography,* 59**,** 482-494.

HOLLING, C. S. 1973. Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics,* 4**,** 1-23.

KERR, L. A., CADRIN, S. X. & SECOR, D. H. 2010. The role of spatial dynamics in the stability, resilience, and productivity of an estuarine fish population. *Ecological Applications,* 20**,** 497-507.

LADE, S. J., TAVONI, A., LEVIN, S. A. & SCHLUTER, M. 2013. Regime shifts in a social-ecological system. *Theoretical Ecology,* 6**,** 359-372.

LOTZE, H. K. 2010. Historical Reconstruction of Human-Induced Changes in US Estuaries. *In:* GIBSON, R. N., ATKINSON, R. J. A. & GORDON, J. D. M. (eds.) *Oceanography and Marine Biology: An Annual Review, Vol 48.*

MCGINNIS, M. D. & OSTROM, E. 2014. Social-ecological system framework: initial changes and continuing challenges. *Ecology and Society,* 19.

NELSON, D. R., ADGER, W. N. & BROWN, K. 2007. Adaptation to environmental change: Contributions of a resilience framework. *Annual Review of Environment and Resources.* Palo Alto: Annual Reviews.

QUINLAN, A. E., BERBÉS-BLÁZQUEZ, M., HAIDER, L. J. & PETERSON, G. D. 2016. Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology,* 53**,** 677-687.

REDMAN, C. L., GROVE, J. M. & KUBY, L. H. 2004. Integrating Social Science into the Long-Term Ecological Research (LTER) Network: Social Dimensions of Ecological Change and Ecological Dimensions of Social Change. *Ecosystems,* 7**,** 161-171.

REYNOLDS, C. S. 2006. *Ecology of Phytoplankton,* Cambridge, Cambridge Univ Press.

SCHEFFER, M., HOSPER, S. H., MEIJER, M. L., MOSS, B. & JEPPESEN, E. 1993. Alternative equilibria in shallow lakes. *Trends in ecology & evolution,* 8**,** 275-9.

WALKER, B., GUNDERSON, L., KINZIG, A., FOLKE, C., CARPENTER, S. & SCHULTZ, L. 2006. A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society,* 11.

WALKER, B., HOLLING, C. S., CARPENTER, S. R. & KINZIG, A. 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society,* 9.