## Title
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# Resilience in ecology: abstraction, distraction, or where the action is?

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**Abstract**

Resilience is frequently encountered in policy as a desirable goal for ecosystem management, yet the demand for science-based frameworks for creating resilient systems is currently ahead of what ecologists can confidently provide. Here we consider which aspects of the multi-faceted concept of resilience can be usefully applied to ecosystem management. We highlight that resilience can maintain both desirable and undesirable states, and hence can be both helpful and unhelpful in a management context. A big hurdle in the application of the concept to management has been a lack of guidance on how to identify and measure resilience concepts, particularly ecological resilience. We explore species composition, functional diversity and landscape factors as potential measures. All three measures have a role in helping to define management goals (i.e., the desirable state), assessing ecosystem recovery after disturbance, distinguishing between 'unhelpful' and 'helpful' ecological resilience and monitoring the maintenance of helpful ecological resilience. In particular, trait-based approaches offer promise for their ability to link pattern to process across scales and so address a crucial element of resilience concepts. Identifying what drives changes in these measures and ultimately the switch between ecosystem states would enable managers to predict the likelihood of a state change and whether intervention would be useful in maintaining or creating a desired state. Lastly, clarifying which drivers (slow and fast) can and cannot be managed to influence these shifts between states could help translate abstract resilience concepts to real-world guidance in management decision-making.

## 1. Introduction

Resilience is a term used in a wide array of contexts, from human health and psychology through sociology to materials science and, of course, ecology and conservation biology. Resilience was introduced to the ecological literature with a clear and specific definition (Holling, 1973), but nowadays resilience is most often used in a vague and undefined manner, as a hook to attract an audience rather than being a truly meaningful concept driving research or conservation outcomes (Brand and Jax, 2007; Myers-Smith et al., 2012). Despite conceptual vagueness, its intuitive appeal is evident in its wide-spread adoption in policy and management documents (e.g., Benson and Garmestani, 2011). In particular, resilience is often mentioned in relation to predicting ecological thresholds and developing appropriate management for systems experiencing the effects of global change and catastrophic events (e.g., Elmqvist et al., 2003; Millar et al., 2007). In this context, resilience is seen as a property important for maintaining or restoring desired ecosystem states and the people connected to these states (Gunderson et al., 2010; Walker and Salt, 2012). Indeed, a real strength of the resilience concept is its acknowledgement of the complexity of ecosystems and potential application to the management of linked social-ecological systems (e.g., Venter et al., 2008). However, more clarity around the concept is needed before we can understand how we might measure resilience and thus operationalize it (Beisner, 2012).

Confusion about which definition to use and how to measure resilience has largely prevented the application of the concept to the practice of ecosystem management. The challenge of moving from concept to application in the real world has been recognized for some time, and various authors have called for steps to render resilience more operational (e.g., Carpenter et al., 2001; Cumming et al., 2005). Concrete examples of actual management of, or for, resilience remain rare and there is little evidence that operational approaches are actually emerging despite the increased use of the term in policy and ecology (Nyström et al., 2008). Although there are approaches available for predicting regime shifts associated with loss of resilience (Carpenter et al., 2011; Scheffer et al., 2001), these approaches have been developed in well-understood lake systems with a wealth of data; such understanding is lacking for many other systems. In addition, recent analyses have presented differing views of how resilience operates in systems such as coral reefs in response to anthropogenic disturbance and climate change, with opposing implications for management

(Côté and Darling, 2010). We often do not know enough about the processes involved in ecosystem change to effectively manage for resilience to individual let alone multiple disturbances.

Confusion has also stemmed from normative uses of the term (Brand and Jax, 2007). This confusion could potentially contribute to impaired connections between policy and on-the-ground actions. At worst, normative uses of terms that are compelling to policymakers can be used to impose partisan visions of how ecosystems 'should be' on societies that may not share that vision (Sundt, 2010). Indeed, the terms 'desirable' and 'undesirable', which are commonly applied to alternative ecosystem states for the purposes of defining goals for management, can be defined differently by different stakeholders. The different values of stakeholders are likely to be considered more explicitly in defining management goals as we come to terms with our human-dominated world (Shackelford et al., 2012). Equally, the benefit people derive from managed ecosystems is likely to be given more credence in the future (Suding, 2011). In the meantime, greater precision in the use of the resilience concept coupled with clear management goals will provide the necessary platform for its measurement, and eventually, the real-world application of resilience-related policy.

Here, we make a first step towards a more operational concept of resilience for ecosystem management by considering three key aspects. First, we consider which aspects of the multi-faceted resilience concept can be most usefully applied to ecosystem management. Second, we consider how resilience might be measured and third, we consider how we might manage ecosystems for resilience. Specifically, we focus on:

1. Aspects of engineering and ecological resilience which are particularly relevant to ecosystem management. We also distinguish between resilience of desirable vs. undesirable ecosystem states. We consider a range of circumstances in which the resilience of a system can be used to achieve management goals, as well as situations where system resilience impedes the achievement of these goals.

2. How data on species composition, as well as recent advances in our understanding of the links between species traits and ecosystem function at the landscape scale, may provide measures of resilience, and ultimately suggest ways to predict and manage it.

3. Aspects of resilience are open to management intervention. In particular, examining which of the variables driving change can and cannot be managed.

## 2. Which resilience?

### *2.1 Ecological versus engineering resilience*

Two of the most highly cited papers in the ecological literature on resilience define the term differently. Holling (1973) describes resilience as the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes. Pimm (1984), however, defines it in terms of the time taken to return to the pre-disturbed state. These different forms of resilience are often referred to as ecological and engineering resilience, respectively (Gunderson et al., 2010), although usage is not consistent either in policy or the ecological literature.

In a management context, the most pressing questions are these—will ecosystems recover from disturbance without intervention? If so, how long will it take? If not, how can we intervene to promote ecosystem recovery after disturbance? Conversely, is disturbance needed to maintain a desired ecosystem state? Generally, managers have adopted concepts from both ecological and engineering resilience to help answer these questions, making each definition relevant to ecosystem management. For example, the concept of thresholds associated with ecological resilience has helped managers to identify systems that might need intervention to push them towards recovery versus those systems that will likely recover without intervention (Resilience Alliance and Santa Fe Institute, 2004; Suding and Hobbs, 2009). Ecological resilience has also informed attempts to incorporate system feedbacks into management practice particularly for the management of invasive species (e.g., plant-soil feedbacks; Eviner and Hawkes, 2008). Equally, management goals are often set on the basis of recovery times bringing the definition of engineering resilience to the forefront. Engineering resilience also emphasizes the idea of a single equilibrium (usually pre-disturbance) state. This idea is firmly entrenched in the practice of conservation and ecological restoration where it is often used to define or at least inform management goals (i.e., the desirable ecosystem state; SER, 2004), despite clear evidence of multiple stable states in many systems. Though not all systems have a single stable state, identifying the drivers of equilibrium and non-equilibrium states can help to inform management actions, and particularly the role of small-scale disturbances in maintaining desirable states (DeAngelis and Waterhouse, 1987). In summary, an assessment of the ecological resilience of an ecosystem state can aid in identifying the level of intervention required to maintain or create a desired state, and engineering resilience can inform predicted recovery times after disturbance and set a time-frame for the achievement of specific management goals. Both types of resilience thus might inform management actions that are necessary to reach desired goals.

*2.2 Helpful and unhelpful ecological resilience*

Given the current focus on ecological resilience as an essential property of ecosystems, it is important to emphasise that ecological resilience is not always desirable from a management perspective. Where a system is in a desirable state, in terms of species composition and/or function that are appealing to people, ecological resilience can be helpful in that it maintains the system in that desirable state (Fig. 1). In contrast, a degraded system may require complex, and often prolonged, intervention to rebuild the ecological interactions that are required for recovery of the system to a more desirable state (Fig. 1). In these latter cases ecological resilience is "unhelpful". Undesirable (degraded) states that have been modified by human activities can apparently have the same, or even greater, levels of ecological resilience to disturbance as those seen in desirable systems (e.g., Côté and Darling, 2010; Gunderson et al., 2010). Numerous examples of these types of "traps" have been described for social-ecological systems (Allison and Hobbs, 2004; Carpenter and Brock, 2008; Cinner, 2011; Enfors and Gordon, 2008), however, less emphasis has been placed on this idea in the ecological literature.

Clearly the use of terms like "helpful" and "unhelpful" ecological resilience is itself, normative and, as we mentioned for "desirable" and "undesirable" ecosystem states, depends on the values placed by society on particular ecosystem states. The ways in which societies value different ecosystem states are likely to be both complex and dynamic, and may shift with social and ecological change (Schlaepfer et al., 2011). Although dichotomies between "helpful" and "unhelpful" or "desirable" and "undesirable" may be overly simplistic, these distinctions allow for a much more explicit understanding of ecological resilience in the management context (e.g., Hughes et al., 2010; Vetter, 2009). Furthermore, defining management goals based on the maintenance or creation of desirable ecosystem states rather than that of ecological resilience *per se* may prove beneficial in the application of resilience concepts to management.

The pursuit of societal goals (i.e., desirable ecosystem states) requires that we specify the mechanisms of both helpful and unhelpful ecological resilience. Practically speaking, society may be missing opportunities for restoration by over-emphasizing the loss of helpful ecological resilience and down-playing the importance of unhelpful ecological resilience in preventing restoration outcomes. For instance, if we are ignorant of the drivers that are maintaining a novel undesirable state (i.e., the unhelpful ecological resilience) then we risk compromising restoration efforts by focusing on replanting a desired species assemblage without addressing the environmental conditions that are helping to maintain the undesirable state. In summary, clearly defining management goals will help to distinguish between situations where ecological resilience is helpful from those situations where it is potentially unhelpful. Distinguishing between these types of resilience may also aid in a more accurate estimation of the financial cost of restoring particular desirable ecosystem states, leading to a better understanding of the likely returns on investment or perhaps a re-valuation of undesirable ecosystem states.

## 3. Measuring engineering and ecological resilience: a way forward?

### *3.1 Engineering resilience*

Engineering resilience is measured in units of time; it is the time taken for an ecosystem to recover after disturbance (Pimm, 1984). Estimates of recovery times require a concomitant assessment of whether an ecosystem has recovered. Data describing species composition are commonly used to assess the extent and speed of recovery towards the species composition of the pre-disturbed or reference state (e.g., Allison, 2004; Conway-Cranos, 2012; Rydgren et al., 1998). A recent review of recovery rates across a range of ecosystems highlighted the importance of disturbance intensity and ecosystem type for determining recovery rates (Jones and Schmitz 2009). Specifically, the authors found that recovery from ‘press’ disturbances such as agriculture and grazing tended to occur over longer time scales than recovery from ‘pulse’ disturbances such as hurricanes and cyclones, and that aquatic ecosystems apparently recover from disturbance more rapidly than terrestrial ecosystems. The faster recovery times for aquatic ecosystems are explained by the faster turnover times of their constituent species (Connell and Sousa, 1983). These data contribute to a predictive framework for engineering resilience, and could be used to make decisions about whether intervention might be necessary to accelerate an ecosystem’s recovery.

*3.2 Ecological resilience*

Measures of ecological resilience are not well defined but could include an integrated measure of ecosystem composition and/ or function paired with contextual information such as disturbance regimes and human influences (Folke et al., 2004; Ives and Carpenter, 2007; Gordon et al., 2008; Chapin et al., 2009). As we have discussed, clearly defining the desirable ecosystem state must precede the measurement of ecological resilience. Once again, data on species composition is often used to determine whether a system is in a desirable or undesirable state and thus whether their ecological resilience is helpful or unhelpful (Hallett et al., 2013; Jaunatre et al. 2013). However, these data are rarely sufficient in their own right to measure ecological resilience and could not be used in a predictive manner.

Despite these drawbacks, matching species-composition data to ecosystem attributes such as climate, landscape features or disturbance history may allow us to assess if there are attributes that confer ecological resilience or signify the distance to a threshold. For example, a long-term study of vegetation dynamics in a subalpine system identified fuel loads, climate and, landscape connectivity as factors contributing to the ecological resilience of the ecosystem to fire (Blarquez and Carcaillet, 2010). Switches between ecosystems states dominated by fire-sensitive species and fire-tolerant species were predicted by these factors (Blarquez and Carcaillet, 2010). In this case, the dominant vegetation types produced strong density dependence and stabilizing dynamics that were important in conferring ecological resilience. Also, van der Heide et al. (2007) described the case of a sea-grass ecosystem where a highly resilient degraded state persisted due to positive feedbacks between loss of sea-grass and turbidity. In these examples, ecological resilience is predicted when there are stabilizing negative feedbacks or density-dependent responses to resources and predation, and a lack of ecological resilience when there are positive feedbacks, positive frequency dependence or a disturbance that changes processes sufficiently that a new set of negative feedbacks develop (Holling, 1973).

Trait-based approaches offer a promising way forward in the search for measures of ecological resilience. Increasingly, trait-based approaches are recognised for their ability to link species composition to ecosystem function and to enable predictions about ecosystem responses to disturbance (Lavorel and Garnier, 2002; Suding et al., 2008). In particular, trait-based measures of functional diversity have recently become central to the discussion of ecological resilience of ecosystems (e.g., Peterson et al., 1998; Van Ruijven and Berendse, 2010; Laliberté et al. 2010). Here, we examine the potential for functional diversity to measure (helpful) ecological resilience. Then we consider landscape factors (i.e., connectivity, spatial heterogeneity) and cross-scale (patch-landscape) interactions for their likely importance to both engineering and ecological resilience (Gunderson et al., 2010; Kerkhoff and Enquist, 2007). Finally, we discuss the value of incorporating measures of functional diversity and landscape factors for a holistic understanding of engineering and ecological resilience.

*3.3 Functional diversity*

Ecological resilience could be made operational through a focus on functional diversity, and more specifically, functional redundancy and response diversity in ecosystems (Brand and Jax, 2007). Functional redundancy is measured as the number of species contributing similarly to an ecosystem function (Walker, 1992). Field studies reveal clear evidence for functional redundancy in some ecosystems (Balvanera et al., 2006). However, most species contribute to more than one function and therefore a level of redundancy is probably required for ecosystem multi-functionality (Hector and Bagchi, 2007). From a practical perspective, trait selection for ecological resilience to one disturbance could alter the types of traits that respond to another disturbance such as grazing (Diaz et al., 2007). This perspective is consistent with emerging empirical evidence that suggests the importance of combinations of complementary functional groups, such as $N_2$-fixing legumes with grass species, for determining ecosystem productivity in grasslands (Lambers et al., 2004; Marquard et al., 2009) and thus may also contribute to ecological resilience. Taken together, the available data imply that maximising functional redundancy across a range of disturbance types increases the ecological resilience of ecosystems.

Response diversity is a measure of how functionally similar species respond differently to disturbance (Elmqvist et al., 2003). It is likely to be a particularly relevant measure in the restoration of degraded systems as it may predict species responses to drivers of change and hence trajectories of community assembly, which is basically what we are attempting to direct in restoration projects (Funk et al., 2008). Yet, response diversity has not received much attention, perhaps in part because it is difficult to measure (Mori et al., 2013). Multivariate analyses offer one approach to estimating response diversity. Using a global dataset of plant communities, Laliberté et al. (2010) use multivariate analysis to first define functional groups on the basis of effect traits, and then estimate response diversity to increasing land-use intensity as the multivariate within-group dispersion in response trait space. Using this approach to measure ecosystem states before and after disturbance will improve our mechanistic understanding of the link between response diversity and ecological resilience.

Integrating trait-based approaches with scaling approaches may offer another way forward for predicting ecological resilience (Allen et al., 2005; Kerkhoff and Enquist, 2007). For example, response diversity is predicted to increase when a given function is fulfilled by species operating at different scales because species perceive and respond to their environment according to these scales (Elmqvist et al. 2003). Thus, response diversity can be estimated by the mean number of scales at which functional groups are represented (averaged across all functional groups; Allen et al., 2005). Fischer et al. (2007) used this measure to estimate response diversity of bird communities in agricultural regions and concluded that their 'relative ecological resilience' was reduced due to the selective extinction of particular body mass and functional groups. Once more, experimental tests of the response of ecosystems to disturbance would improve our understanding of the contribution of response diversity to ecological resilience.

### *3.4 Landscape factors*

Spatial heterogeneity and connectivity can affect both engineering and ecological resilience (Van Nes and Scheffer, 2005). For example, the degree of connectivity among patches may affect ecological and engineering resilience by influencing dispersal and, hence, diversity and species turnover; positive or negative impacts could occur, depending on how local communities respond to disturbance and track environmental change (e.g., Starzomski and Srivastava, 2007; Thrush et al., 2008). Connectivity can also affect the scale of disturbances such as fire and erosion by affecting their spread (Allen, 2007; Okin et al., 2009) which in turn will affect both ecological and engineering resilience (Beisner et al., 2003). The degree to which the flux of diversity across space affects both types of resilience will depend on the rates of dispersal and the traits of colonizing species (e.g., Cramer et al. 2008). On a landscape scale, the loss of native diversity may be one reason why diversity predictions relating to ecological resilience do not seem to apply to degraded systems: i.e., degraded systems may be more strongly resilient in terms of numerical (landscape propagule input, native species loss) rather than functional (response diversity) processes. Thus landscape factors could be important in the maintenance of both helpful and unhelpful ecological resilience.

The balance of degraded and intact patches across the landscape may also affect its ecological resilience through abiotic controls or abiotic fluxes among patches (e.g., Massol et al., 2011). Degradation of key factors that supported the unmodified system in the context of the surrounding landscape (e.g., structure, heterogeneity, and connectivity), or particular local features that were influenced by the landscape matrix (e.g., nutrient and energy fluxes, microclimate) may mean that even high levels of propagule dispersal will not facilitate recovery. Increasing the scale of landscape degradation should increase the probability that a patch embedded in that matrix will remain in a degraded state, through reduced abiotic and biotic connectivity among patches. For example, animals preferring matrices of spatially heterogeneous vegetation may not move through degraded, homogenous landscapes (Fuhlendorf et al., 2012). Conversely, spatial continuity of an unmodified state in the landscape is likely to positively impact ecological and engineering resilience of individual patches (e.g., microclimate mitigation by intact areas could lead to recovery of degraded patches at their edges). Thus, the extent to which recovery occurs in either of these situations will be context specific: for instance recovery may not occur after very large scale ephemeral pulse disturbance if the landscape context has been modified (e.g., Lindenmayer et al., 2010).

The spatial extent, type, duration and intensity of degradation will affect the interaction of fast and slow variables. Fast variables are ecosystem processes that occur over short time scales, such as fire or drought, and slow variables are ecosystem processes with slow rates of turnover such as soil development. Slow variables are often emphasized in the ecological resilience literature for their role in determining system dynamics, and particularly how they can interact with fast variables to drive a switch between alternative stable states (Rinaldi and Scheffer, 2000; Carpenter and Turner, 2001). Developing a clear framework for these interactions is still a work in progress. Slow, broad features of landscapes such as climate, regional species pools, and topography constrain and control smaller-scale variables, while fast features such as patch diversity and patterning in a landscape, affect regional processes (Chapin et al., 2009). The challenge is to understand interactions and feedbacks within and across these scales (Peters et al., 2004; Suding et al., 2008).

*3.5 The value of combining functional diversity and landscape factors*

Determining how stabilizing biotic interactions shift across landscapes in response to the changes in biotic and abiotic conditions would help improve our understanding of the complex interplay of slow and fast variables and small- and large-scale variables determining ecological and engineering resilience. However, measuring these interactions at landscape scales is unrealistically costly and time consuming. One approach would be to assess the importance of species' effect traits to ecosystem function. This might involve measuring effect traits in representative communities across landscapes and identifying relations between these traits, large-scale functions (such as productivity) and changes across gradients of environmental conditions and species combinations. Recent efforts to co-ordinate ecological experiments at a global-level could potentially help to achieve this goal (e.g., Fraser et al. 2013).

At the patch scale, changes in species composition caused by management activities or environmental change may lead to the loss and/or replacement of both response and effect traits (Laliberté et al., 2010). At the landscape scale, there is potential for patch reorganisation, where the loss of species with particular response and effects traits from some patches is coupled with their gain in other patches. This could be due to changes in resource availability or changes in climate (e.g., shift in temperature across altitude due to warming). In order to capture these cross-scale nuances, ecological resilience could be considered in terms of the dynamics of particular traits at the patch and landscape levels, perhaps by defining transitions explicitly in these terms and how changing response and effect traits are bundled in patches and organized in landscapes. This landscape scale trait-based approach could then further be incorporated into state and transition models to guide management.

## 4. Managing resilience

Clearly, management decisions will depend on the state of a focal system—whether it is desirable or not—which determines if the goal is to maintain it or to intervene in order to push it towards an alternative more desirable state. In practice, there are numerous different possible states for every biological system, depending on a wide range of factors including causes of decline, acceptability of alternative states, and the prospects for recovery/ conversion (Fig. 2). The incorporation of ecological and engineering resilience into management would be aided by systematic consideration of each of these elements. We have outlined some key measures that might be used for this process:

1. Species compositional data for defining goals (i.e., the desirable state), assessing recovery (for engineering resilience) and for distinguishing between unhelpful and helpful ecological resilience.

2. Functional redundancy and response diversity for their likely contributions to ecological resilience. The available data suggest that maximizing these properties via management, for example, by maintaining or restoring the structural complexity of vegetation and size distribution of fauna in ecosystems, will give ecosystems the potential to recover from future disturbances.

3. Landscape factors such as connectivity, scale and context (e.g., land-use history, ecosystem type, and climate). These measure are perhaps the most challenging to apply to management and yet essential to both engineering and ecological resilience. Trait-based approaches offer promise in this regard for their ability to combine aspects of all three groups of measurements.

Ultimately, a comprehensive understanding of ecological and engineering resilience and their management will likely depend on our ability to identify the drivers of change (identifying system specific thresholds) and which of these drivers are key in forcing a switch from an undesirable to a desirable state and vice-versa. State changes may be the result of gradual changes in slow variables combined with particular triggering events or changes in fast variables. In some cases the drivers will be easy for local managers to manipulate (e.g., grazing/stocking rates), while in others they will be beyond the scope of local management alone and involve landscape-scale approaches (e.g., patch configuration, connectivity), while yet others are global in scale and cannot be manipulated directly (e.g., climate change). With ongoing press disturbances like climate change, ecological resilience may not be the most relevant concept to operationalize for management goals. Nonetheless, local actions may help to facilitate desired responses and may include managing for species not historically present on a particular site (e.g., creating habitat corridors for migration). Resilience concepts will become operational if the limits of their application are recognised (i.e., if it is a relevant framework to use and the management goals are well defined) and if the appropriate scales of intervention are clarified and integrated into management plans.

Approaches that combine 'top-down' (i.e., understanding the key drivers of state change) and 'bottom-up' (i.e., understanding the ecosystem attributes that confer ecological resilience) drivers of ecological and engineering resilience are necessary to fully operationalize these concepts. For example, drought coupled with heavy grazing are probably key drivers in the switch from a grassland state to a shrubland state in Chihuahuan semiarid grasslands and the attributes that affect whether or not the transitions occur are probably soil clay content and associated water holding capacity (Bestelmeyer et al., 2011). Similarly, in coastal wetlands on the Gulf of Mexico, sea level rise and hurricane storm surges can trigger transitions from diverse native floodplain forest to exotic-dominated salt marsh communities (Shirley and Battaglia, 2006) and hurricane storm surges can drive compositional shifts toward assemblages more tolerant of salinity (Tate and Battaglia, 2013). Recovery from these disturbances appears related to the interaction between the topographic gradient, eustatic sea level rise, precipitation, as well as the condition of the coastal vegetation (Morris et al., 2009). Thus, while the triggers co-occur regularly, the question is what combination of variables determines whether or not the triggers result in a state change.

The interaction of processes and structures at different spatial and temporal scales is central to considering how to manage both helpful and unhelpful resilience. The interaction of patch- and landscape-scale pattern and process will determine the efficacy of focusing ecosystem management on the patch-scale only. As the modification and simplification of landscapes increase, patch-scale management approaches used in isolation are less likely to succeed unless coupled with broader landscape approaches. For example, restoration projects that aim to restore small patches of vegetation embedded within highly-modified and simplified landscapes are unlikely to be successful, as the slow, large-scale processes that constrain smaller scale processes are unlikely to be effectively modified.

## 5. Conclusion

The idea that ecosystems can recover from human-mediated disturbances, either with or without our help, is a compelling one. Thus, resilience concepts are likely to continue to be featured in environmental policy documents. The primary task ahead for ecologists is to continue to work towards the measurement and application of these concepts to ecosystem management. We have made a step towards this goal by clarifying the relevance of the concepts to management and suggesting some ways in which they could be measured for application in the management context. We think that understanding the ecosystem attributes that confer resilience coupled with knowledge about the key drivers of state changes is an approach that could be used to inform management interventions.

Resilience concepts are about embracing change as opposed to resisting it. Yet the current conservation and restoration norms aim to maintain or restore desirable states. How desirable states are defined is likely to change over the coming decades as people respond to our changing world. In the broader context of meshing ecosystems with social systems, social adaptation will undoubtedly play a major role in determining how successfully humanity can manage ecosystems for their own sake and for ongoing human survival and well-being. Although we have focused primarily on ecosystems here, we recognise the importance of the broader social-ecological systems approach. However, embedded in this broader scheme must be a clear understanding of ecosystem dynamics and what resilience concepts mean in this context. Moving from abstraction to action requires that, in each ecosystem, societies clearly identify the possible referents of the resilience concepts and determine what it will take to achieve particular ecological states before intervening.

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## Figure headings

**Figure 1.** Lake Toolibin (a) is a wetland in the wheatbelt of Western Australia which is threatened by salinization (Wallace 2003). Lake Taarblen (b) is an adjacent lake affected by salinization in the 1950s, which resulted in the death of all the canopy trees and the development of a low, relatively uniform cover of halophytes. The process of salinization arises in these landscapes from a hydrological imbalance caused by extensive vegetation clearing and subsequent rise of saline water tables (Cramer and Hobbs, 2002). Panel (c) shows the theoretical expectations for how two possible ecosystem states (depicted as balls) may shift under environmental change. One state is desirable (black-filled ball) and one is undesirable (white-filled ball). The ecological resilience of the states (balls) to disturbance is proportional to the width and depth of the cups. Lake Toolibin represents the black-filled ball, apparently ecologically resilient, but threatened by saline inundation. Lake Taarblen, represents the white-filled ball, unhelpfully resilient. Taarblen has undergone a state change caused by slow landscape-scale processes, and cannot be returned to its former state without unrealistically extensive and expensive intervention. Conversely, management of Toolibin to maintain its condition despite ongoing broad-scale drivers pushing it towards the undesirable state includes electric pumps to divert saline water around the lake (local action) and the planting of perennial vegetation to lower groundwater levels (landscape-scale actions; George et al., 2005; Wallace, 2003).

**Figure 2.** An expanded version of Fig 1 illustrating the general pathways of decline and recovery of ecosystems in relation to how desirable they are (state) and our suggested approach to managing their ecological resilience. Note that pathways of decline and recovery can differ (Suding et al., 2004); this figure presents representative pathways only. Ecosystem attributes can indicate whether the state is desirable or undesirable and may also be used to assess ecological (and engineering) resilience to disturbance. This assessment may be coupled with an understanding of the key drivers of ecosystem change to inform specific management interventions. Management to maintain helpful ecological resilience may focus on local-scale manipulation of fast variables (e.g., seed addition, predator removal) whereas management to overcome unhelpful ecological resilience needs to focus on large-scale long-term interventions to successfully push the system towards a desirable state.

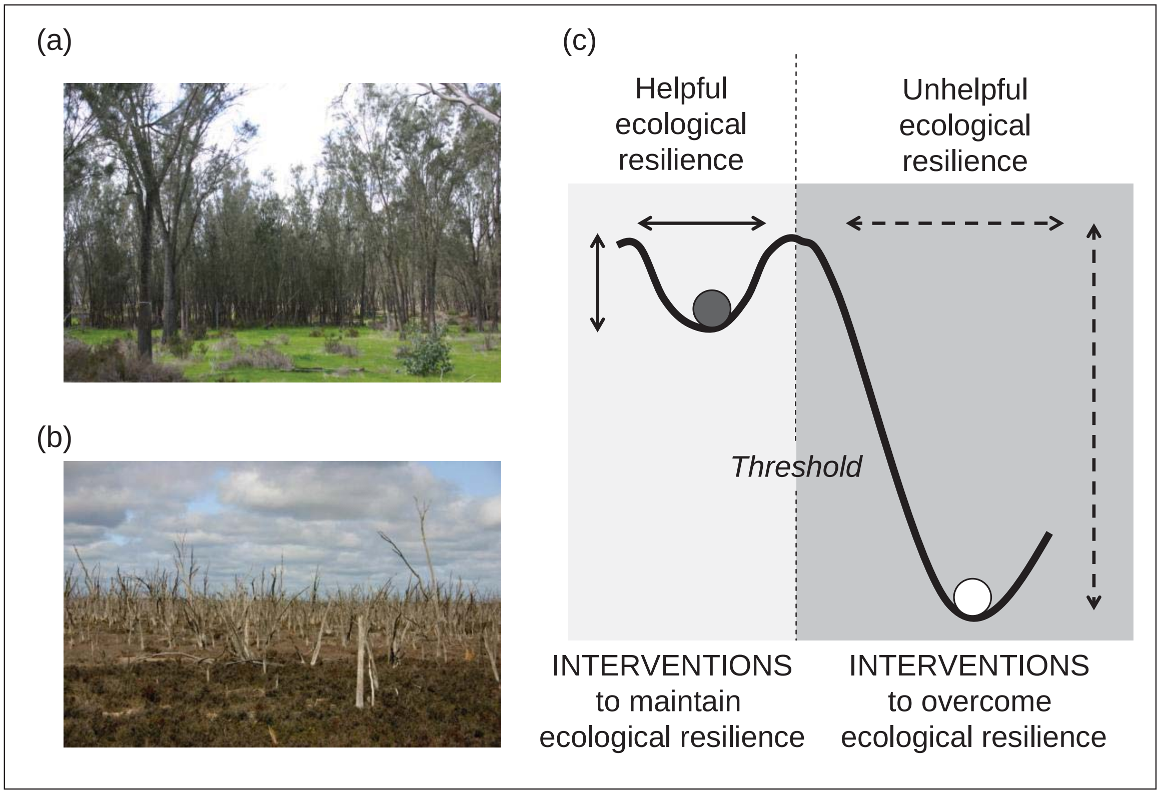
(a)
(b)
(c)
Helpful ecological resilience
Unhelpful ecological resilience
Threshold
INTERVENTIONS to maintain ecological resilience
INTERVENTIONS to overcome ecological resilience

Figure 1.

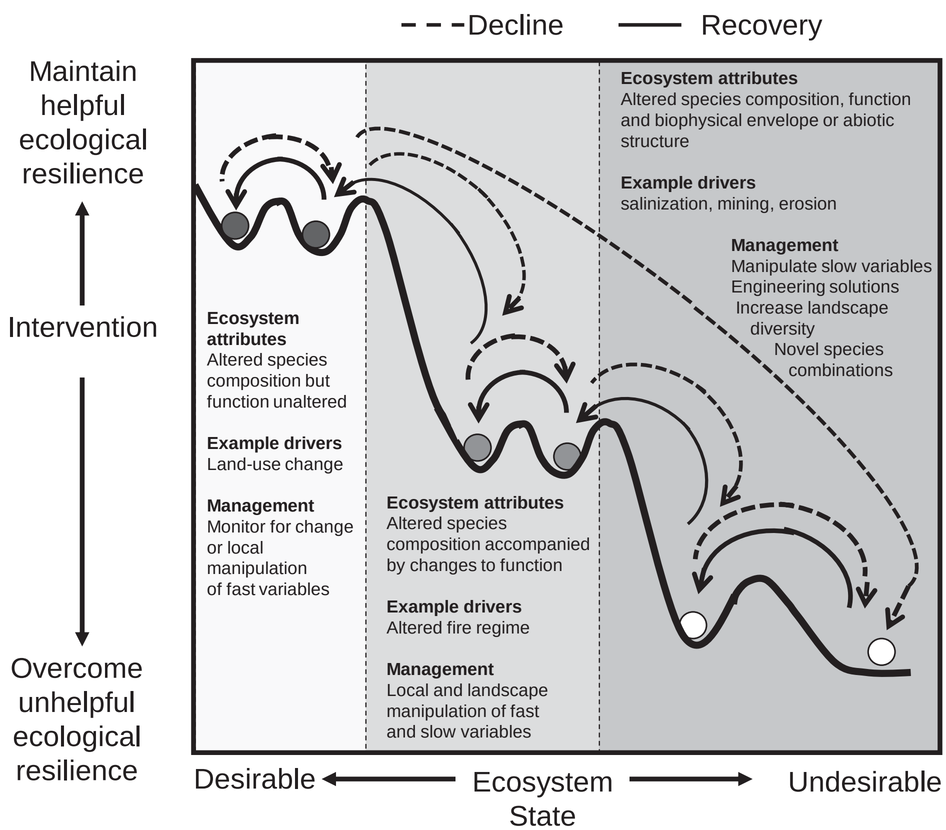
Decline
Recovery
Maintain helpful ecological resilience
Intervention
Overcome unhelpful ecological resilience
Ecosystem attributes
Altered species composition but function unaltered
Example drivers
Land-use change
Management
Monitor for change or local manipulation of fast variables
Ecosystem attributes
Altered species composition accompanied by changes to function
Example drivers
Altered fire regime
Management
Local and landscape manipulation of fast and slow variables
Ecosystem attributes
Altered species composition, function and biophysical envelope or abiotic structure
Example drivers
salinization, mining, erosion
Management
Manipulate slow variables
Engineering solutions
Increase landscape diversity
Novel species combinations
Desirable
Ecosystem State
Undesirable

Figure 2.