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# Resilience of aquatic systems: Review and management implications

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## Abstract

Our understanding of how ecosystems function has changed from an equilibria-based view to one that recognizes the dynamic, fluctuating, nonlinear nature of aquatic systems. This current understanding requires that we manage systems for resilience. In this review, we examine how resilience has been defined, measured and applied in aquatic systems, and more broadly, in the socioecological systems in which they are embedded. Our review reveals the importance of managing stressors adversely impacting aquatic system resilience, as well as understanding the environmental and climatic cycles and changes impacting aquatic resources. Aquatic resilience may be enhanced by maintaining and enhancing habitat connectivity as well as functional redundancy and physical and biological diversity. Resilience in aquatic socioecological system may be enhanced by understanding and fostering linkages between the social and ecological subsystems, promoting equity among stakeholders, and understanding how the system is impacted by factors within and outside the area of immediate interest. Management for resilience requires implementation of adaptive and preferably collaborative management. Implementation of adaptive management for resilience will require an effective monitoring framework to detect key changes in the coupled socioecological system. Research is needed to (1) develop sensitive indicators and

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monitoring designs, (2) disentangle complex multi-scalar interactions and feedbacks, and (3) generalize lessons learned across aquatic ecosystems and apply them in new contexts.

**Keywords**

Resilience adaptive management; Aquatic; Socioecological system

## Introduction

The United States' Clean Water Act (CWA) was implemented in 1972 to "restore and maintain the chemical, physical and biological integrity of the Nation's waters.' Although this law has been highly successful in protecting and restoring many of the Nation's waters, some areas are still impaired or threatened. For example, point source control efforts implemented under the CWA were very effective in reducing pollutant inputs to US waters, but non-point-source pollution was only indirectly addressed through state water quality standards and the Section 404 dredge and ill permits, which often impact wetlands (Glicksman and Batze: 2010). In addition, since the CWA was written, our understanding of how ecosystems function has evolved. It was once assumed that ecosystems were in equilibria and that degraded systems could be returned to their previous pristine state following the removal of stressors (Adler 2010; Glicksman and Batzel 2010). However, we now recognize that ecosystems are dynamic, fluctuating non-linear systems that may not revert to previous conditions even if stressors are removed. Realization of this inherent complexity has shown the need to understand and manage waterbodies for system resilience to achieve the ecological integrity goals envisioned in the CWA.

Resilience refers to the ability of systems to absorb changes and disturbance (Holling 1973). Disturbance in this context is defined broadly as anything that perturbs the system (e.g., nutrient enrichment and overharvesting). There are two major types of resilience—engineering and ecological (Table 1). Engineering resilience focuses on the stability of an ecosystem and the speed it reverts to a steady state condition following disturbance (Holling 1996). Ecological resilience focuses on the capacity of an ecosystem to absorb and adapt to disturbances while maintaining its essential structure and function (components and processes) and assumes the existence of multiple stable ecosystem states (Holling 1996). Distinguishing between ecological and engineering resilience, or whether a change in ecological condition is a regime change may seem inconsequential, but the application of these concepts may have consequences in how systems are managed. Within a given state, there may be environmental declines due to stressors, but if only one state is possible, then recovery is likely if the causative stressors are removed (Fig. 1). If there are multiple states, and the system has transitioned to a new state, then even with removal of stressors, there may not be full or immediate recovery due to hysteresis (Table 1, Fig. 2). Restoration and recovery studies suggest that hysteresis is a common pattern (Duarte et al. 2015) with ecosystems rarely recovering to their previous, undegraded condition (Borja et al. 2010; Lotze et al. 2011; Verdonschot et al. 2013) even when major stressors are reduced or removed. Although ecological resilience is often not recognized until after it is lost, some authors have suggested that engineering resilience may be predictive of ecological resilience

(Thrush et al. 2009; Scheffer et al. 2015). Also, because engineering resilience is concerned about recovery rates and management practices that enhance recovery, it is particularly relevant for restoration efforts.

A common way to visualize ecological resilience is the ‘cup and ball’ model (Beisner et al. 2003), with the ball representing ecosystem or socioecological state that can exist at any point along the surface of hills and valleys (Fig. 2a). Resilience is represented by the width of the cup, while resistance (Table 1) is represented by the height of the cup. With small perturbations, the ball may be nudged up the walls of the valley but remain in its current regime or state. With increasing perturbation (either internal or external), the ball may cross an ecological threshold (Table 1) into another valley, altering its state. Resistance is high if the ball remains in the valley in the face of these perturbations. Alternately, the landscape itself (environmental or social conditions) may also change (Beisner et al. 2003; Merrill et al. 2018), favoring a new state (Fig. 2b). Because they must overcome strong reinforcing feedback loops, these regime shifts (Table 1) can appear to be abrupt and are often characterized by hysteresis, where an ecological trajectory during ecosystem degradation does not match that of ecosystem recovery.

These multiple ecosystem states (alternate stable states, Table 1) have been demonstrated in a variety of aquatic systems. One classic example is the response of shallow lakes to eutrophication. There are at least two stable regimes: the clear water, oligotrophic state and the turbid water, eutrophic state (Carpenter and Cottingham 1997; Carpenter 2003; Scheffer and Carpenter 2003; Zhang et al. 2003; Bayley et al. 2007; Ibelings et al. 2007). Clear water lakes have high ecosystem and recreational value and are characterized by low nutrient inputs, low recycling of phosphorus, and extensive macrophyte beds. These macrophytes are key drivers reinforcing the clear water state (Scheffer et al. 2001; Carpenter 2003; Zhang et al. 2003). Macrophytes remove available nutrients for algal growth and stabilize sediment, providing a positive feedback loop that impedes planktonic algal growth and reduces turbidity (Scheffer et al. 1993; Ibelings et al. 2007). If nutrient loading into a lake exceeds a certain threshold, a different positive feedback loop can be initiated. This leads to a substantial decrease in macrophytes due to algal blooms and sediment resuspension that decreases light availability culminating in a lake tipping into a turbid state (Jeppesen et al. 1991; Scheffer et al. 1993). Grazing by duck and geese populations can also threaten the macrophyte dominated, clear water state (Bakker et al. 2016), and make the lake more sensitive to nutrient loading (van Altena et al. 2016). Eventually, without macrophytes, the lake can transition to the alternative turbid state, which is characterized by high phosphorus concentrations, increasing algal blooms and low dissolved oxygen concentrations, which have been considered to have lower ecological value (Carpenter et al. 1999).

There are two classic examples of regime shifts in marine systems: kelp forest/urchin barrens and coral dominated/macrophyte dominated reefs. The first involves shifts between kelp forests and urchin barrens (Estes and Palmisano 1974; Filbee-Dexter and Scheibling 2014). Kelp forest ecosystems in temperate coastal waters are dependent on otters. Otters prey on sea urchins, which in turn graze on kelp. When otters disappear from the system, due to overfishing, disease or predation, urchins graze down the kelp, which causes a regime shift to urchin barrens. The second example was documented on Jamaican coral reefs, where healthy reefs shifted from coral dominated to fleshy macrophyte dominated (Hughes 1994). The proximal cause of this shift was the die-off of the sea urchin, *Diadema antillarum.* However, other herbivorous fish had already been removed by overfishing so when the urchin disappeared, algae overgrew the coral reef. These are classic examples because the shift between states was fairly rapid and moved from a state that is more desirable (to humans) to a more degraded state. There are also well-known shifts in fisheries in the marine environment which are due to natural climatic cycles and are not necessarily anthropogenically induced. Examples include the shift between anchovy dominance and sardine dominance in the Pacific (Chavez et al. 2003) and between herring dominance and anchovy dominance in the Atlantic (Southward et al. 1988).

Alternate stable states have also been suggested in other aquatic habitats. In the southwestern United States, wide, slow-flowing, riverine wetlands (ciénegas) were common until the late nineteenth and early twentieth centuries when climatic variation and increased cattle grazing altered vegetation and disturbed soils, thereby increasing erosion and incision, which drained the wetland, resulting in further vegetation loss (Heffernan 2008). This resulted in a stable state of deeply incised channels (arroyos). In the Florida Everglades, increases in nutrients caused the historic state of sawgrass marshes and wet prairies to switch to a state dominated by cattails (Gunderson 2001). Recent data from the Prairie Pothole Region of North America suggests that changes in hydrologic or climatic variables may shift a nonfloodplain wetland into an alternate state (Mushet et al. 2018). Alberti and Marzluff (2004) suggested two potential alternative stable states in urban areas: an urban attractor with little natural capital (Table 1) and little ecological connectivity and a natural attractor which provides more ecosystem services (Table 1) but fewer human-engineered services. Streams in urban areas reflect these regimes, with urban streams being highly modified with a predictably degraded biotic state ("urban stream syndrome"; Walsh et al. 2005).

Regime shifts may also be functional, as was seen in anoxic mine drainage lakes impacted by increasing groundwater influx, where sediments shifted from iron-reduction to sulfate-reduction (Blodau and Knorr 2006). There may be also be regime shifts that are not necessarily rapid or abrupt. Estuaries respond to eutrophication similarly to lakes, shifting from a benthic dominated system, with rooted macrophytes and good water quality, to a pelagic dominated system characterized by high phytoplankton biomass, high turbidity and hypoxia (Viaroli et al. 2008; Krause-Jensen et al. 2012). However, response to eutrophication is often gradual, likely due in part to dilution of nutrient inputs due to estuary flushing from tidal action and riverine flow. Similar to other regime shifts, these systems rarely recover to their previous, historical undegraded condition (Duarte et al. 2009).

This paper explores how resilience concepts have been identified and interpreted in a variety of aquatic habitats as well as their associated socioecological systems to help address its application to restoration and management.

## Materials and methods

Using Google Scholar and Google, we assembled literature – primarily peer-reviewed articles but also some book chapters, using the following keywords: 'resilience', 'recovery', ‘resistance’, ‘stable states’, ‘alternative states’, ‘restoration’, ‘hysteresis’, ‘thresholds’, and ‘trophic cascades’, in combination with ‘lake’, ‘stream’, ‘river’, ‘coast’, ‘estuary’, ‘estuarine’, ‘wetland’, and ‘aquatic’. We also searched for ‘microbial community resilience’ and ‘restoration.’ We selected articles that focused on ecological processes and biological communities and excluded papers examining infrastructure resilience. We also focused on resilience concepts associated with aquatic systems and specifically excluded terrestrial systems. Concepts and phrases as well as cited papers from the selected articles were used to identify additional sources. We later searched for ‘socio-ecological resilience’, ‘ecosystem services’, and ‘management.’ These latter articles were screened to identify those that directly applied to the ecological systems identified in the first round of source assembly and assessment. We then included articles that were not focused specifically on resilience but helped to provide examples of the concepts highlighted in the resilience papers. The search was not temporally bounded initially, but later searches were constrained to between 2015 and 2019. Later searches focused on ‘early warning indicators’, ‘biodiversity and resilience’, and ‘metapopulations and resilience.’ We grouped sources by common themes, identified commonalities across aquatic systems, and summarized them from a resilience perspective. Methods for regime shift detection were highlighted. Socioecological resilience as an expansion of ecological resilience was described. We then compiled the factors affecting resilience of ecological and socioecological systems across aquatic systems and examined how resilience themes and concepts were applied to restoration and management.

## Results and discussion

### Detection of regime shifts

Regime shifts are generally not detected until an ecosystem has shifted into an undesirable state. Therefore, there is a need to understand how and why these shifts occur, and whether a system is approaching an ecological threshold or tipping point (Table 1) in order to anticipate and address impacts before a shift in state. Occurrence of shifts in ecological communities have been detected using a variety of statistical techniques (Anderson et al. 2009), including Principal Components Analysis (PCA), clustering and F-tests (Weijerman et al. 2005; Cloern et al. 2010; Spenser et al. 2010; Chaalali et al. 2013). Weijerman et al. (2005) used PCA and chronological cluster analysis with invertebrate, fish, bird, marine mammal and climate data to detect two regime shifts between 1970 and 2002 in the North and Wadden Sea. PCA has also been combined with a regime shift detection algorithm (Radionov 2004) to summarize ecological data and detect regime shifts (Cloern et al. 2010; Spenser et al. 2010). Cloern et al. (2010) summarized shrimp, crab and fish catches in San Francisco Bay, detecting a regime shift that was related to climate changes. Spenser et al. (2010) summarized six different biological communities in seven areas around the United Kingdom and Ireland that were interpreted as a temporal trend rather than a true regime shift. Other techniques have also been used that look for speciic changes in a single aspect of the ecosystem. Rebstock (2002) used locally weighted regression after removal of seasonal trends to look for shifts in California copepod populations. Anderson et al. (2009) used the maximum of F (Quandt 1958) to find a change point in bottom dissolved oxygen in the Danish straits.

There are a few issues with the use of statistical techniques to detect shifts. First, as the numbers of potential shifts increase, detection becomes progressively more difficult (Anderson et al. 2009). In addition, Petraitis and Hoffman (2010) demonstrated that alternative states may not be associated with non-linear dynamics or thresholds, so not all alternate regimes may be detected. Although these techniques may be useful to detect a shift after it has occurred, they do not allow prediction of a regime shift. They also do not identify the underlying cause of the shift, although some of the causes may be inferred by corresponding shifts in climate or stressors.

Early warning indicators (Table 1) have been developed to indicate if a system is close to a threshold, so that an ecological shift might be prevented. These early warning indicators are based on mathematical predictions of how a system responds when multiple alternative states are possible. As a system approaches a transition point (Fig. 3), it recovers more and more slowly to small perturbations (critical slowing down). Alternately, as the transition point gets very close, the system may ‘flicker’, briefly visiting each state (Scheffer et al. 2015). A variety of methods to measure autocorrelation and spectral properties and metrics to quantify variability and skewness have been developed and tested using simulated data (Dakos et al. 2012). Detection of potential shifts is more likely using a combination of approaches and metrics (Dakos et al. 2012; Burthe et al. 2016; Gsell et al. 2016). When these indicators were tested using real-world data from lakes and the North Sea, these indicators did not show good agreement with one another and were not particularly predictive (Burthe et al. 2016; Gsell et al. 2016). More recently, Butitta et al. (2017) suggested that spatial rather than temporal autocorrelation early warning indictors may be an effective approach to detect regime shifts. Similarly, Clements et al. (2017) suggested that using biological trait data such as body size along with abundance data to calculate early warning indicators will allow better prediction of regime shifts.

In order to detect or predict regime shifts, appropriate data are needed (Collie et al. 2004; Dakos et al. 2012, 2015; Clements et al. 2017, 2019) along with knowledge of the system and underlying mechanisms which may cause a regime shift (Hewitt and Thrush 2010; Gsell et al. 2010). Both Collie et al. (2004) and Clements et al. (2019) pointed out that biological data have a low signal to noise ratio, which may mask the underlying shift. Monitoring data may not have enough spatial or temporal resolution to allow use of early warning indicators. Clements et al. (2019) suggested that using early warning indicators may work better as early recovery indicators in collapsed systems that are being restored, as these may have more data collected to assess management effectiveness. However, even with good data the effectiveness of early warning indicators may be adversely impacted by extreme events, strong external drivers such as climate cycles, or high environmental stochasticity (Dakos et al. 2015). In addition, as ecosystems become more complex, early warning signals become less predictive (Boerlijst et al. 2013).

Anticipating and preventing unwanted regime shifts in a socioecological system (next section) may be even more difficult than in ecological systems alone as it requires an understanding of the complex processes that support or undermine the resilience and the socio-economic drivers and the governance systems that shape resources (Hughes et al. 2005). Additionally, the complex interactions in a socioecological system make it challenging to isolate a system property or principle (such as diversity) and establish its connection to the resilience of an ecosystem service (Biggs et al. 2012).

## Socioecological resilience

Although early theoretical work on resilience focused solely on ecological systems, it soon became apparent that human interactions with these systems must be considered as they both effect environmental change and suffer impacts from that change. As with ecological resilience generally, socioecological resilience (Table 1) refers to the coupled system's ability to retain similar structure, function and feedback mechanisms (Walker et al. 2004). Integrated socioecological systems can behave differently than their separate parts, therefore human and ecosystem functions need to be considered together to understand and manage for system resilience (Alberti and Marzluff 2004). An important aspect of socioecological resilience is panarchy (Holling 2001, Table 1), which considers the importance of multiple scales and the adaptive nature of social and ecological systems. Because of this it is important to define both the temporal and spatial scale being assessed or managed (Carpenter et al. 2001; Hughes et al. 2005).

A classic example of socioecological resilience was documented in Lake Mendota, Wisconsin (Carpenter et. al 2001). Development around the lake began at the turn of the century. After World War II, agriculture and urbanization growth led to increased lake enrichment, causing a discernable decrease in water quality. It took a decade for the social system to recognize the impacts of the degraded water quality and for the necessary stakeholders to divert sewage from the lake. This only resulted in marginal improvements in water quality due to intensification of nonpoint inputs (agriculture and urbanization). Attempts to decrease runoff from the more steeply sloped areas of the watershed resulted in little improvement due to the lack of farmer buy-in and participation. Stocking the lake with piscivorous fish to decrease zooplankton grazers initially increased water clarity, but increased fishing pressure diminished the effectiveness of biological control and heavy rains caused increased erosion from cleared construction sites, negating previous gains in water clarity. Finally, in the late 1990s managers and university scientists devised a plan to improve lake clarity by incorporating incentives for farmers to control erosion, enforcement of erosion control at construction sites, as well as purchase of riparian easements and wetlands. Only by incorporating social incentives were management actions able to promote continuous improvement. This case study highlights two points. First, degradation can occur over a long period (in this case 50 years) due to activity in the social system, but management actions were only taken when lake conditions become sufficiently degraded as to impact humans. Second, once degraded, the ecological system may require continuous management actions to maintain the resilience of the clear water state. In recent years, record rains and an invasive waterflea that preys on important plankton grazers (*Daphnia* spp.) that maintain water clarity, have threatened resiliency (Ness 2017). In contrast, another invasive, the zebra mussel, may increase water clarity. The story of this classic lake is one of continual change in both the social and ecological components of the system, suggesting the need for continual assessment of the ecological system and adaptation in the social system.

When ecosystems are altered by stressors, these changes can also increase the vulnerability of people and ecosystems to further change (Carpenter et al. 2006). These changes can be rapid or slow and can be either predictable or unpredictable. A slow loss in resilience can set the stage for even larger changes when an ecosystem crosses a threshold and experiences a regime shift, thereby causing substantial changes in ecosystem services and human well-being (Folke et al. 2004; Carpenter et al. 2006). These stressors are sometimes referred to as “slow-onset hazards” or chronic disturbances because of their longer-time scales for impact on the social and/or ecological systems (Cutter et al. 2008; Merrill et al. 2018). Although these slow-onset hazards can be difficult to identify and manage because of their longer time spans for impacts, this fact provides increased possibility to allow for social adaptation and possible mitigation of the hazards (Cutter et al. 2008). The response of these systems will depend upon the ecological and social context (Duh et al. 2008), and robust social networks will promote resiliency (Gunderson et al. 2006). These societal pressures challenge the resiliency of watersheds and their ability to provide benefits and ecosystem services to society (Merrill et al. 2018).

Socioecological resilience requires definition of the state being considered (Carpenter et al. 2001). In the example above, this was the clear water state. This desired state can be defined and quantified using the concept of ecosystem services (Millennium Ecosystem Assessment 2005). Ecosystem services are the benefits provided to humans from nature (Costanza et al. 1997). They provide a way to understand the relationships among the social and ecological systems (Lin et al. 2019). Because it is not possible to increase the resilience of all ecosystem services at one time, there are necessary trade-offs between services and across scales (Robards et al. 2011; Biggs et al. 2012; Birge et al. 2016). These trade-offs are necessary because ecosystem services rely on the natural capital (Guerry et al. 2015; Woodhead et al. 2018) provided by ecosystems. Researchers have worked to quantify this by linking biodiversity to ecosystem function (Durance et al. 2016; Oliver et al. 2016). Economic methods have also been used to quantify both use and non-use values of ecosystems. However, there are issues with using economic models. First, not all services can be easily measured or quantified (Guerry et al. 2015; Diaz et al. 2018; Woodhead et al. 2018). Second, natural resources are often inelastic to price (i.e., higher price will not reduce demand), which complicates economic valuation (Farley and Voinov 2016). Finally, the value of ecosystem services is context-specific (Cote and Nightingale 2012; Pearson et al. 2015; Diaz et al. 2018; Sattler et al. 2018; Woodhead et al. 2018). What is valued depends upon the cultural and social context of the system, as well as competing interests and the balance of power. Scale will also be important – what enhances ecosystem services at one scale or for one set of stakeholders may reduce overall system resilience. Recent work on ecosystem services recognizes that natural capital is the foundation of all ecosystem services, and that incorporation of cultural beliefs and concerns is needed to increase resilience of the overall system.

## Factors affecting the resilience of aquatic systems

Because we do not yet have methods to prevent ecological shifts, we need to be able to understand what increases or decreases system resilience (Table 2). In general, stressors that adversely impact communities also decrease resilience. Although the system may be initially resilient, eventually resilience may be degraded to the point where ecosystem condition is also diminished. Resilience is also reduced by lack of equity in the socioecological system. Power imbalances tend to promote use of the resource by certain actors without consideration of the needs of other stakeholders or the overall system. Resilience is maintained or enhanced by connectivity, habitat heterogeneity, functional redundancy (Table 1) and diversity. These factors allow the system to compensate for stress and/or promote recovery after adverse impacts. Strong linkages between the social and ecological system also enhance resilience. Disturbance and life history characteristics may increase or decrease resilience depending upon environmental conditions and scale. In addition, the resilience of a system depends upon its spatial or temporal scale. Understanding interactions at multiple scales will be necessary to promote resilience.

**Factors decreasing resilience—**Resilience can be reduced by increasing stressor loads. A common stressor in aquatic systems is nutrient overenrichment. Generally, high nutrient loading shifts ecosystems from benthic dominated to pelagic dominated production. Classically, nutrient (phosphorus) inputs to lakes can cause lakes to shift from a clear into a turbid state. These shifts can take place over the course of months or years and can oscillate between stable states frequently (Scheffer and Jeppesen 2007). During this period, excess phosphorus can be bound to insoluble iron compounds in the sediments (Carpenter 2003). Although the exact concentrations needed to cause this shift are unknown, thresholds for total phosphorus concentrations in the water column have been speculated (Jeppesen et al. 1991; Wang et al. 2014). Once in the turbid state, even with external phosphorus loading reduced, the lake may be resistant to shifting back to the clear state until the sequestered phosphorus is depleted from the sediment. Additional management techniques may need to be implemented (Carpenter et al. 1999; Søndergaard et al. 2003) because both resuspension and microbial processes are important for mediating the release of sequestered phosphorus into the water column (Søndergaard et al. 1992). Microbial communities may also mediate oxic and anoxic regimes in lakes, with cyanobacteria dominating in oxic conditions, and sulfur bacteria dominating in anoxic conditions (Bush et al. 2017). In estuaries, nitrogen loading is the main nutrient decreasing resilience, although phosphorus can also cause deleterious impacts, especially in lower salinity waters (Howarth and Marino 2006; Zedler 2017). As in lakes, nutrient inputs cause estuaries to shift from a state allowing for growth of seagrass and macrophytes to a turbid state dominated by phytoplankton and algal mats (Munkes 2005; Troell et al. 2005; Viaroli et al. 2008). Once in the turbid state, positive feedbacks act to maintain this state. Decreased circulation, sediment and organic matter accumulation, resuspension, release of nutrients from the sediments, and anoxic and sulfidic conditions act to keep lagoons and estuaries in their degraded state (Munkes 2005; Troell et al. 2005; Viaroli et al. 2008; Moore and Cuker 2018). Conditions that promote algal mat formation tend to decrease the probability of recovery (Moksnes et al. 2018; Watson et al. 2018). Beyond the impacts of nutrient pollution, other anthropogenic chemicals also decrease community diversity, which has been shown to decrease resilience (Peterson et al. 1998). Feio et al. (2015) found that mining effluent resulted in functionally homogeneous stream invertebrate communities that responded similarly to temperature and rainfall extremes, resulting in decreased resilience to other stressors. However, contaminant impacts seem to have fewer and less widespread impacts than nutrient overenrichment. For example, in marine systems, contaminant effects were often only seen at the individual level. When multiple functions or taxa were included, effects were often not seen, perhaps due to interactions among components of the larger system (Johnston et al. 2015). Similarly, while Zeglin (2015) found widespread and significant impacts of metals on microbial diversity, this response may be mediated by changes in environmental variables such as organic matter quality or quantity and hydrology.

A more generalized stressor is urbanization and associated land use changes. Increased human population growth and associated urbanization along with increased agricultural production and energy extraction have led to increased impervious cover, runoff, non-point source pollution and habitat fragmentation. With increasing impervious surface in the watershed, stream and river hydrology is altered, increasing sediment and contaminant loads, which causes adverse impacts on nearby aquatic systems. This is especially true in the coastal zone where over 50% of the world's cities and over 38% of the world's human population live (Small and Nicholls 2003). Urbanization has been shown to decrease the diversity of stream macroinvertebrates (Roy et al. 2003), and fish (Morgan and Cushman 2005). It can also cause aquatic populations to become more synchronized, and vulnerable to collapse. Pacific salmon populations along the US west coast showed decreasing behavioral and life history diversity as their watersheds became more developed with a greater number of dams (Griffiths et al. 2014). Urbanization can adversely impact wetlands through ditching, draining, or filling wetlands, which may ultimately lead to wetland loss. Similarly, deepening or consolidating wetlands reduces their suitability as habitat for amphibians and breeding birds (McCauley et al. 2015). Hydrological modifications may decrease spatial resilience by changing the distance between wetlands, which can negatively affect certain native amphibians with limited migration ability while favoring larger non-native predators that can migrate over much longer distances (Uden et al. 2014).

Overharvest of fish and apex predators has been well-documented as a cause of decreased resilience. Historically abundant marine mammals, bird and commercially exploited fish and invertebrate species have declined 75% to 95% from historic baselines (Lotze and Worm 2009), resulting in large ecosystem shifts (Lotze et al. 2011). Overfishing of piscivores caused an ecosystem shift to a community with fewer demersal fish and more forage fish (Savenkoff et al. 2007). Overfishing can also cause predatory fish to shift to smaller size classes. For example, larger predatory fish were needed to keep sea urchin numbers low enough to favor kelp forest persistence (Hamilton and Caselle 2015) Overhunting of otters for the fur trade eventually led to the destruction of kelp forests and their replacement by urchin barrens (Lotze et al. 2011). Coral reefs have also been negatively impacted due to overfishing. In the Caribbean this was due to overfishing of herbivorous fish, but in the Great Barrier Reef, overfishing may have resulted in a release of crown-of-thorns starfish, which eat corals (Jackson et al. 2001). Overfishing of parrotfish causes coral decline, but a reduction in fishing pressure may increase coral resilience (Bozec et al. 2016). In an upwelling area of Costa Rica, overfishing may also allow the overgrowth of colonial ascidians (Roth et al. 2015). The widespread decline in seagrass in tropical areas may have been due in part to overfishing of sea turtles (Jackson et al. 2001).

Climatic changes can cause a cascade of changes (Scavia et al. 2002) that adversely impact aquatic habitats by altering the landscape, decreasing ecosystem resilience. These changes may be self-reinforcing, resulting in systems being pushed well beyond expected ecological thresholds (Farley and Voinov 2016). Changes in wind and rainfall patterns can alter hydrology—leading to droughts or increased flashiness. More frequent floods may scour eggs from spawning substrates (Shanley and Albert 2014), which can decrease population viability. Changing precipitation patterns will alter water and sediment delivery to coastal waters making nutrient loading more extreme and variable (Scavia et al. 2002). Extreme events such as droughts and floods are expected to add additional stress to the socioecological system (Tompkins and Adger 2004). Predicted temperature increases will impact species metabolism and species distribution patterns. Freshwater zooplankton in temporary ponds may be particularly vulnerable, as climate change may decrease available habitat while also decreasing hatching success (Pinceel et al. 2018). In addition, climate change may alter the underlying physical forces driving existing climate cycles (Palumbi et al. 2008). Different ecosystems may be expected to respond differently. Marshes may drown due to sea level rise if they are unable to migrate into the upland, causing ecological shifts from marsh to open water. In estuaries, changes in freshwater inputs will change salinity and stratification as well as alter flushing and exchange rates. The interaction between anthropogenic stress and natural climate cycles can lead to unforeseen ecological impacts, especially in marine fisheries, as favorable climate conditions may lead to high natural stock levels which may temporarily mask underlying degradation in the underlying system. An example is the collapse of the sardine industry in Monterey Bay due to high fishing pressure followed by a switch in the Pacific Decadal Oscillation to a cool period, which did not favor sardine population growth (Palumbi et al. 2008). Another is the collapse of the coho salmon, where hatchery stocks and good offshore conditions masked issues in recruitment for an extended period (Bottom et al. 2009). Finally, climate change impacts the ecological baselines of these systems which will affect both restoration and preservation efforts (Duarte et al. 2015).

While a single stressor may be the dominant cause of adverse impacts, most systems are impacted by multiple stressors. For example, excess loading from agricultural and urban sources, may require phosphorus and nitrogen to be co-managed to control eutrophication in marine and freshwater systems (Conley et al. 2009). Similarly, overfishing and eutrophication can have interacting effects and would be best managed such that both stressors are considered (Breitberg et al. 2009; Zhang 2016), especially in the context of warming coastal waters (Ramírez et al. 2018). There is evidence that coral reefs that are stressed by eutrophication and sedimentation may be more vulnerable to climate change impacts (Maina et al. 2011). In addition to eutrophication and sedimentation, coral reefs can be affected by climate change related impacts such as storms, bleaching and acidification as well as overfishing, physical damage, and pollution (Anthony et al. 2015). Invasive species combined with other stressors may decrease resilience. The Pacific red lionfish, *Pterois volitans,* is a voracious predator on coral grazers (Albins and Hixon 2013), which in addition to overfishing and coastal development (Holdschlag and Ratter 2013) greatly reduces coral reef resilience. In the Mediterranean, it was predicted that climate change and invasive species impacts may overwhelm positive management actions designed to decrease fishing pressure and rebuild fishing stocks (Corrales et al. 2018). Seagrass can be adversely impacted by physical damage, invasive species, climate change, eutrophication and sedimentation (Waycott et al. 2009; Unsworth et al. 2015). Dredging of seagrass beds reduced shoot density (Oreska et al. 2017), which made seagrass less able to withstand storm events and moderate declines in water quality (Orth et al. 2017). Interacting stressors can alter expected response to a single stressor. In the classic example of kelp forests shifting into an alternative state, overfishing causes a trophic cascade that results in an alternative urchin barren state. However, in southern California, kelp forests survived even after the dominant grazers were removed due to environmental changes mediated by oceanographic cycles (Dayton et al. 1998). In Australia, urchin barrens developed due to climate shifts and associated warming waters rather than a trophic cascade after urchin removal (Wernberg et al. 2011). Another example of multiple stressor impact was seen in Alaska (Estes et al. 1998), where diminished forage fish availability, perhaps due to fishing and temperature changes, has led to declines in marine mammals. Killer whales then began preying on sea otters, which led to predictable declines in kelp forests. The impact of multiple stressors may affect the potential for restoration; once the major known stressor has been reduced or eliminated, other stressors may retard recovery (Duarte et al. 2015). While seagrass recovery has been achieved using nutrient reduction, other restoration efforts have combined nutrient reduction with altered fishing practices and physical interventions to alter hydrology (Waycott et al. 2009).

A final factor that may decrease resilience in the ecological system is a lack of equity in the socioecological system. Because ecological resources and their associated social systems are common-pool resources where everyone theoretically has equal access, individual users can impact the resource to the detriment of others (Ostrom 1999; Berkes 2017). Similarly, market forces may promote actions that reduce system resilience (Farley and Voinov 2016). For example, costs due to alternative energy patents may promote continued use of coal. One set of users may benefit from actions that eventually adversely impact the ecological system, (e.g., nutrient addition from agricultural lands to lakes) while the costs of those uses are borne by another group within the social system (Scheffer et al. 2000). The strength of the cultural or economic linkages to the ecological system and sense of ownership will affect the willingness of people to support management actions to promote resilience (Bottom et al. 2009; Campbell and Butler 2010). The Susquehanna River contributes most of the nitrogen loading to the mainstem of Chesapeake Bay (Hagy et al. 2004), much of which originates from the watersheds in Pennsylvania, where many of the residents have little or no connection to the bay. In addition, difference in values among stakeholders may result in decisions that do not enhance resilience of the entire system (Rhoads et al. 1999; Poff et al. 2016) and the monetary cost to avoid adverse impacts may be considered too high to deal with a hypothetical future issue (Levin and Möllman 2015). Actions to control pressures on the ecological systems may also have significant adverse impacts on the resilience of the social system. Attempts to reduce overfishing often result in the loss of fishing jobs (Worm et al. 2009), which provokes predictable political backlash against these management measures. Finally, the portions of the social system that benefit from exploiting the system are often more powerful than those trying to protect it (Scheffer et al. 2000; Holdschlag and

Ratter 2013). Business and agricultural interests may have more political clout, due to their economic contributions, than environmental interests.

**Factors increasing resilience—**Many studies emphasized the importance of connectivity to resilience of aquatic ecosystems (Carpenter et al. 2006; Elliott et al. 2007; Thrush et al. 2009; McCluney et al. 2014; Flotemersch et al. 2016). Connectivity can positively impact resiliency by increasing aquatic population dispersal and recruitment success (Carpenter et al. 2006) which can facilitate ecosystem recovery (Ray 2005; Elliott et al. 2007; Palumbi et al. 2008; Thrush et al. 2009; Lotze et al. 2011; de Juan et al. 2013; Duarte et al. 2015). Stream invertebrate communities were more likely to recover from extreme drought in well-connected streams, with short-lived dispersers replacing longer-lived, weaker dispersers (Bogan et al. 2015). In estuaries, connectivity with the regional species pool can help to support local benthic communities (de Juan et al. 2013), while more connected patches of kelp (via passively drifting spores) had higher probability of existence and lower probability of extinction (Castorani et al. 2015). Connectivity also allows access to multiple habitats and refugia. In streams, macroinvertebrate colonization was related to distance from upstream refugia (Fritz and Dodds 2004), while salmonid populations were able to expand into lakes when hydraulic conductivity was high (Campbell et al. 2019). In contrast Detenbeck et al. (1992) noted that the resilience of stream fish communities was reduced by migration barriers. Streams with good connections between ground water and surface water may allow maintenance of cooler thermal refugia for salmon, improving their resilience (Beechie et al. 2013). In wetlands, man-made ponds may help maintain wetland amphibian (Uden et al. 2014) and pond insect populations (Deacon et al. 2018) by improving connectivity across the landscape. In estuaries, connectivity between reefs and seagrasses can increase the diversity of organisms in the reef system (McCleod et al. 2019). Similarly, good connectivity between mangroves and protected areas enhanced the biomass of herbivorous fish on the reefs, enhancing resilience (Olds et al. 2012). However, variation in connectivity may also be important in maintaining resilience. For example, although watershed area is thought to be a surrogate for metapopulation stability, Terui et al. (2018) showed that amount of branching in river networks was more important than size, assuming that among branch heterogeneity was high. Similarly, varying connectivity in isolated wetlands may help to maintain unique biological communities (Cohen et al. 2016). Resilience of the watershed is enhanced by spatial and temporal connectivity among its individual components (Flotemersh et al. 2016) while stream resilience is determined by connectivity across scales (reach, sub-basin and basin) due to impacts and feedbacks between scales (McCluney et al. 2014).

Habitat heterogeneity (diversity) can help to maintain or improve resilience. This improvement can be due to a variety of mechanisms (Bisson et al. 2009), including the use of multiple habitats by taxa for different purposes, access to neighboring high-quality habitats, redundancy of habitats (i.e., insurance effect) as well as support for metapopulations. Habitat diversity may also act to promote response diversity (Table 1), directly via buffering and ‘insurance’ effect of environmental heterogeneity on physical disturbance, or indirectly via maintenance of an environmental template that fosters functional diversity (e.g., life history diversity, genetic diversity within species; Table 1). In streams, habitat complexity can provide refugia to both invertebrates and fish (Pearsons et al. 1992; Seabrook and Townsend 1993; Hershkovitz and Gasith 2013) as well as improve the resilience of native communities to invasive species (Chretien and Chapman 2016). Riparian habitat restoration has been shown to improve resilience in streams (Mantyka-Pringle et al. 2014) and large-scale habitat diversity was found to improve the resiliency of northern leopard frog populations in wetlands (Mushet et al. 2013). Wetlands often have within-system heterogeneity due to hydrological differences in flooding depth, duration, and timing (Penfound 1952; Euliss et al. 2004) which imparts resilience. Watershed habitat diversity affects habitat quality and species population which enhances watershed resilience (US EPA 2012). In estuaries, many different habitats, especially marshes, mangroves and seagrass provide needed nursery and juvenile habitat (Beck et al. 2001; Mumby et al. 2004) while Massicotte et al. (2015) determined that species richness of coastal fish populations was related to the spatial heterogeneity of water column characteristics. Habitat diversity is often needed to maintain valued faunal groups (Cicchetti and Greening 2011).

Functional redundancy also helps to maintain resilience (Peterson et al. 1998; Elmqvist et al. 2003; Nyström 2006; Walker et al. 2006; Levin and Lubchenco 2008; Biggs et al. 2012; Angeler et al. 2019). Functional redundancy is sometimes referred to as response diversity, but they may be more accurately viewed as related and interconnected concepts. Coral grazers encompass species that graze intensively and locally such as sea urchins as well as those that have wider ranges and graze intermittently like sea turtles (Elmqvist et al. 2003). Thus, if one of these taxa are eliminated, the other coral grazer will still be able to fill the grazer role (functional redundancy), with the different scales of response indicating response diversity. A lack of functional redundancy has been shown to make corals less resilient and more susceptible to collapse (McWilliam et al. 2018). Functional redundancy in subarctic phytoplankton communities appears to provide resilience to ocean acidification (Hoppe et al. 2017). West coast salmonid stocks have multiple distinct populations (functional redundancy), with different life histories and behaviors (Bottom et al. 2009; Schindler et al. 2010; Carlson and Satterthwaite 2011). This variation (response diversity) causes the individual stocks to respond asynchronously, reducing the variation in the overall stock, and spreading the risk of exposure to stressors across both space and time. A similar decrease in variance can also occur within individual taxa, and has been referred to as the portfolio effect, and has been seen in both relatively pristine habitats (Schindler et al. 2010) and heavily modified river systems (Carlson and Satterthwaite 2011). The portfolio effect is also seen in microbial communities (Doak et al. 1998; Allison and Martiny 2008). The overall service provided by the community stays the same because the positive responses of some taxa are balanced with negative responses of other taxa, resulting in no alteration in function. Response diversity in ecological systems can impact the resilience of socioecological systems; Carpenter et al. (2006) concluded that the resilience of ecosystem services depends on response diversity as indicated by the diversity of species and functional groups that exist in a system.

Diversity is assumed to enhance resilience because with more species, it is more likely that some of them would be able to functionally compensate for extirpated taxa (Gunderson 2000; Bell et al. 2005; Hughes et al. 2005; Palumbi et al. 2008; Oliver et al. 2015; Pires et al. 2018). Diversity in management and institutions can also enhance diversity by providing opportunities for learning and adaptations (Biggs et al. 2012). Highly diverse marine communities have been shown to be more resilient and resistant to invasion (Stachowicz et al. 2002) while low species diversity in some assemblages increase vulnerability (Elliott and Whitfield 2011). Higher diversity ecosystems are more likely to promote recovery of collapsed fisheries (Palumbi et al. 2008) while genetic diversity in kelp provides protection against marine heat waves, allowing kelp forest persistence (Wernberg et al. 2018). Biodiversity has been shown to be related to ecosystem function in both marine and freshwaters, although abiotic factors may drive much of this relationship (Strong et al. 2015; Thornhill et al. 2018). Many authors suggested the need to understand function. Thrush et al. (2009) suggested that protecting keystone species and ecological engineers might provide insurance against regime shifts while Lotze et al. (2011) indicated the importance of understanding life history strategy and food web interactions when predicting potential for recovery. Several authors suggest that functional diversity (Table 1) is more predictive of ecosystem resilience than species diversity (Elmqvist et al. 2003; Nyström 2006; Thrush et al. 2009). Functional diversity made stream invertebrate communities more resilient to floods and droughts (Woodward et al. 2015), enhanced coral recovery (McCleod et al. 2019), and buffered the impacts of temperature fluctuations to marine fish and fisheries (Dee et al. 2016; Duffy et al. 2016). Several authors suggested that biomass might be a better measure of ecosystem function that abundance (Davies et al. 2011; Magurran and Henderson 2012; Sundstrom et al. 2018). Peterson et al. (1998) first proposed that cross-scale resilience (Table 1) should be considered. Because ecosystems are hierarchical in both space and time, resilience is enhanced when there are species with similar functions at different scales that respond differently to environmental stressors (Angeler et al. 2016) with body size suggested as a proxy for spatial impact (Strong et al. 2015; Angeler and Allen 2016).

The resilience of the overall socioecological system can be enhanced through strong linkages between the social and ecological systems, which Carpenter et al. (2006) suggested could be enhanced via recognition of ecosystem services. Even aquatic systems with reduced resilience and condition may provide important supporting, regulating and cultural services (McPhearson et al. 2014; Wondie 2018) since in urban settings it may not be possible to significantly increase the resilience of the overall ecological system. The resilience of the connected social, economic, institutional and ecological subsystems may be increased through careful urban planning (Arnold et al. 2014) with improved linkages between science and society. In addition, communication needs to be fostered among stakeholders (Rhoads et al. 1999; Reyers et al. 2018) with several authors highlighting the importance of incorporating diverse values, beliefs and cultures (Rhoads et al. 1999; Restall and Conrad 2015; Folke et al. 2016; Reyers et al. 2018). Connectedness to nature is necessary for sustainability (Restall and Conrad 2015; Abson et al. 2017; Ives et al. 2018; van Putten et al. 2018). This connection to nature occurs at both the individual and societal levels (Abson et al. 2017). Connection to nature may involve a ‘sense of place,’ which can involve both physical access and emotional bonds that help to support conservation and management efforts. Ives et al. (2018) noted that while socioecological systems were more directly influenced by material and experiential connections, cognitive, emotional and philosophical connections are more likely to influence the underlying goals and values driving the system. Finally, Folke et al. (2016) suggested that stewardship is needed to foster sustainability given that social-ecological systems rely upon the biosphere. This stewardship will require not only management of ecosystem services, but also understanding of the social, economic, and cultural context.

**Factors that may increase or decrease resilience depending upon environmental conditions and scale—**Some factors that may either increase or decrease the resilience of aquatic systems have been identified (Table 2) including disturbance, life history characteristics and scalar issues. Carpenter et al. (2001) discussed the plasticity of resilience; resilience depends on which system and disturbance is being considered.

While disturbance can have negative effects on systems, it can also help to maintain diversity and allow reorganization of the system, which increases resilience. Floods, disease, pollution, and financial crises can wreak havoc on both ecological and social systems, decreasing resilience (Tompkins and Adger 2004). The timing, magnitude, and frequency of disturbance may be one measure of whether disturbance has positive or negative impacts on diversity. Stream invertebrates and fishes are better able to recover from disturbances occurring prior to spawning (Detenbeck et al. 1992; Milner et al. 2018), and stream biota are most strongly impacted by extreme climate events that are close in time or at unexpected time (Woodward et al. 2015). Similarly, Fu et al. (2015) showed impacts on wetland plant structural and functional diversity at lowest and highest levels of flood disturbance. Increasing salinity variation was strongly related to decreasing species richness, diversity and evenness in estuarine benthic invertebrate communities (Diggelen and Montagna 2016), while increasing drainage basin hydrologic variability decreased fish diversity (Rolls et al. 2018). More frequent disturbance was shown to adversely impact both stream and estuarine benthic communities (Ledger et al. 2012; Rehitha et al. 2017; Haghkerdar et al. 2018). However, disturbance can also positively impact diversity by diminishing specialization and increasing diversity and flexibility, allowing better responsiveness to varied future stresses (Peterson 2000; Timpane-Padgham et al. 2017). Disturbance can also act to connect ecological scales (Peterson et al. 1998). For example, storms can cause stream flooding that impacts portions of the stream network in different ways; stream macroinvertebrates diversity declines locally but creates a mosaic of habitats enhancing diversity at the landscape scale (Lepori and Hjerdt 2006). Plant diversity has been shown to increase in wetlands, floodplains and riparian areas as flood duration increases (Rolls et al. 2018). Similarly, Ellender and Weyl (2015) suggested that species in unpredictable habitats such as headwater streams may have evolved to be resilient to events. In these environments, the natural disturbance in the system helps increase variation and resilience. Estuaries and coasts are thought to be highly resilient (Elliott et al. 2007), at least in part due to the mosaic of ecological states resulting from the interaction among ecological gradients and stressor gradients (Duarte et al. 2015). Disturbance also allows ecological systems to reorganize (Gunderson et al. 2017). A drought in the Klamath River Basin in the western US caused conflicts over water allocation to farmers, ranchers, indigenous tribes and endangered species. Over time, litigation, and social conflict led to the development of cross–scale interactions among user groups that allowed new, adaptive governance arrangements in this system (Chaffin and Gunderson 2016).

Life history characteristics may influence whether a community is resilient and may depend upon environmental conditions. In wetlands, amphibians with large clutch sizes, and invertebrates with cold and drought-tolerant eggs or high dispersal ability (e.g., flying stages) are more likely to have persistent populations (Ryan et al. 2014). Life history strategy may also help to explain why species are sensitive to anthropogenic chemical exposure (Ibrahim et al. 2014). Sievert et al. (2016) suggested that knowing which aquatic taxa were intolerant and therefore vulnerable can inform conservation efforts. For example, slow growing seagrass may not be able to recover from boat moorings and anchoring damage, even if eco-friendly moorings are installed (Cullen-Unsworth and Unsworth 2016). Taxa adaptation to droughts or floods may explain taxa persistence or vulnerability. For example, wetlands with highly fluctuating drying regimes tend to be dominated by short-lived clonal plants rather than those sprouted from seeds (Clarke et al. 2015). Droughts promote invertebrates with small body size, aerial dispersion and respiration, generalist feeding, burrowing and desiccation resistance (Aspin et al. 2018). Similarly, invertebrates surviving in intermittent sites were more resistant to drying while those at perennial sites tended to have higher dispersal ability and a longer life span (Leigh et al. 2016). Taxa that prefer fast flow (i.e., EPT) are favored with increasing flow permanence (Rolls et al. 2018). Floods may negatively impact fish species that depend on the timing of the flood in relation to their spawning (Pearsons et al. 1992). Aquatic populations that were resilient under one set of environmental conditions, may become much less so under another set of conditions. Salmon’s connection to marine and freshwater habitats made them highly resilient in the past, but now may be a vulnerability as watersheds became more developed (Bisson et al. 2009). Climate change may enhance or decrease the successful expansion of invasive species based on their life history strategy (Kernan 2015). Under increasing temperatures, cold-water fish populations will be expected to decline, while warm-water fish populations will be expected to expand their range (Tisseuil et al. 2012). Dispersal traits and strategies used by invertebrates in intermittent streams may become less effective in a drying climate as effective connectivity decreases (Chester et al. 2015).

Scale mismatches may impact resilience as aquatic ecosystems are controlled and impacted by not only the internal components, but also by the larger systems that encompass them—and these processes may also vary temporally (Carpenter et al. 2006). Ecological shifts may be seen locally, or regionally. The shift from coral reefs to fleshy algae or kelp forests to urchin barrens is a local phenomenon that has been seen worldwide (de Yong et al. 2008; Ling et al. 2015). Expanding from the local scale may show a mosaic of kelp forests and urchin barrens (Estes et al. 1998). The impact of scale is seen for both stressors and biological response (Scheffer and Carpenter 2003; Elliott and Whitfield 2011). Understanding scale and metapopulation dynamics will be important for ecosystem recovery (Lotze et al. 2011). Lundquist et al. (2010) demonstrated that increased regional dispersal helped the shallow reef community resist disturbance while Casini et al. (2012) showed that trophic shifts in a smaller connected bay may be due to conditions in the Baltic Sea. Several authors noted the impact of spatial shifts in masking environmental impact. Powell et al. (2008) noted that oyster stocks were high but concentrated in lower salinity areas, which made them vulnerable to a later disease outbreak while locational shifts in cod populations caused temporary increases in catch per unit effort which marked an actual decline that lead to a stock collapse in the 1990s (deYong et al. 2008). Actions or impacts at one scale can result in cascading, unpredicted or unintended impacts at another scale for both the ecological and social systems. Estuaries are impacted by stressors and forcing factors outside of the immediate system (Elliott and Whitfield 2011) so system-wide constraints in the landscape and larger oceanic systems need to be considered in assessing system resilience (Simenstad et al. 2006). Freshwater requirements and urbanization impacts need be considered on the land side. On the ocean side, rising seas will alter hydrodynamics as well as nutrient and sediment transport (Scavia et al. 2002). Pacific salmon are affected by broad-scale oceanic and climatic cycles that have differing impacts on the oceans and freshwater streams which impacts population size and persistence. In addition, the salmon resource is managed by multiple jurisdictions at the national, regional, state and local scales, which can sometimes result in conflicting or interacting impacts (Bottom et al. 2009). The socioecological system may also be impacted by factors outside the immediate system; for example, the Chilean sea urchin industry is driven by the Asian sushi market (Berkes 2017).

## Restoration

We often do not recognize when a system is transitioning into a new state or realize that the system is losing resilience until there is significant degradation of the system. However, once this has occurred there is often a desire to restore the system back to or towards a desired state. These restoration efforts may provide some insights into system resilience.

Unfortunately, it can be difficult to determine recovery. There are often no accepted criteria used to define restoration success (Elliott et al. 2007, 2016; Duarte et al. 2015) so it is necessary to set clear restoration goals and indicators of success (Duarte et al. 2015; Zhao et al. 2016; White and Kaplan 2017). Although restoration aims to reestablish the structure and function of the naturally occuring ecosystem, existing anthropogenic alterations may make this goal impossible to achieve (Brown et al. 2018; Sinclair et al. 2018). Thus, it may be more tractable to focus on restoring functions and processes, desirable ecosystem services, or ecosystem integrity and resilience (Alexander et al. 2016; Krievins et al. 2018). Historical data including information on past disturbance regimes, historical trajectory and regional processes may give insights into what may be possible for a given restoration effort (Pearson et al. 2015; Brown et al. 2018; Knudson et al. 2018; Lin et al. 2019) as the interpretation of success can often be confounded by a lack of pre-disturbance information (Verdonschot et al. 2013). This can lead to shifting baselines (Pauly 1995), where the degraded conditions known to the current generation anchor what the environment ‘should’ look like even if conditions were far different a generation earlier. Selection of appropriate reference targets is also key to appropriate assessment of success. White and Kaplan (2017) suggested selecting sites that may not be ‘pristine’ but that reflect the broad-scale perturbations in the area (e.g., the dynamic reference concept; Hiers et al. 2012). In addition, because recovery trajectories can be complex and nonlinear, and recovery may be to a new alternative state, long-term monitoring and objective criteria are needed for assessment (Clements et al. 2010; Stanley et al. 2010; Duarte et al. 2015; Zhao et al. 2016).

A consistent theme in restoration is that there is seldom full recovery after degradation (Simenstad et al. 2006; Elliott et al. 2007, 2016; Palumbi et al. 2008; Lotze et al. 2011; Shade et al. 2012; Verdonschot et al. 2013; Duarte et al. 2015), suggesting that hysteresis and multiple ecological states may be common. Simenstad et al. (2006) indicated that wetland restoration efforts yielded only partial function. In coastal areas, recovery of faunal groups and habitats was often incomplete and took decades (Lotze et al. 2011; Duarte et al. 2015). Shade et al. (2012) found that very few disturbed microbial communities recovered to their original state. Similarly, lake recovery after phosphorus removal can take decades (Scheffer et al. 1993; Carpenter et al. 1999; Jeppesen et al. 2005). For most systems, lags in recovery after implementation of restoration activities should be expected (Simenstad et al. 2006; Duarte et al. 2015; Lin et al. 2019), suggesting that expectations of management effectiveness should incorporate these lags.

Restoration appears to be most effective when there is an understanding of the stressors impacting the system and how the natural system behaved in the absence of those stressors. Recovery will depend on the type and intensity of the stress as well as correspondence with natural events and causative stressors may need to be reduced to levels much lower than those that caused degradation due to hysteresis (Duarte et al. 2015). Physical and chemical variables may interact to enhance, or retard impacts of stress. Low salinity was shown to buffer the impacts of increasing nutrients in lagoonal systems, while at higher salinities, the system shifted to a turbid water state (Jeppesen et al. 2007). Removing eutrophication stress may allow ecosystems to be resistant to higher temperatures, salinity variability, disease, storms and invasive species (Wainger et al. 2017). Understanding the underlying physical and chemical factors influencing the ecological system will be critical when determining appropriate management action. Recovery from acute stressors may be quicker than from chronic stressors (Elliott et al. 2007). Distinguishing stressors that can be directly controlled from those over which managers have no direct control, such as climate change will also be critical (Verdonschot et al. 2013), especially since climate change is changing ecological baselines (Duarte et al. 2015).

Many authors highlighted the importance of protecting, enhancing or preserving natural features, processes and functions (Simenstad et al. 2006; Elliott et al. 2007, 2016; Waples et al. 2009; Verdonschot et al. 2013; Duarte et al. 2015; Timpane-Padgham et al. 2017). Accounting for current or matching historical variability of abiotic drivers and ecological processes will increase resilience of the restoration (Waples et al. 2009; Truchy et al. 2015; Zhao et al. 2016). Hydromorphology is a major structuring variable in aquatic systems (Elliott and Whitfield 2011; Elliott et al. 2016; Zhao et al. 2016; Zedler 2017; Amelie and Creed 2018; Arthington et al. 2018). Restoration of parts of the natural flow regime will help restore biodiversity and ecological processes (Arthington et al. 2018). Freshwater flow to estuaries is a major structuring factor; those with less freshwater inflow tend to be more sensitive than those with large flow (Zedler 2017). Similarly, hydrologic resilience of watersheds may be enhanced by restoring freshwater wetlands; any wetland can help with drought, but only riparian wetlands help with floods (Ameli and Creed 2018). In addition to hydrology, restoration efforts should focus on other factors known to increase resilience. Life history diversity rather than overall stock abundance should be prioritized along with habitat heterogeneity (Waldman et al. 2016), and floodplain connectivity (Timpane-Padgham et al. 2017). Success of restoration should consider local and regional context in addition to the particular site to ensure that natural disturbance regimes are restored so that a mosaic of communities is more likely to develop (Sinclair et al. 2018; Janssen et al. 2019). Site-specific factors may be important as well. Elliott et al. (2007) suggested that restoration may be enhanced through the use and protection of keystone species and ecological engineers. Site characteristics may act as an environmental filter; invasive species may be present in large numbers in seedbanks, while nearby intact wetlands may be a source of native propagules (Hazelton et al. 2018).

Many authors indicated that stakeholder involvement was critical for restoration success (Elliott et al. 2016; Waldman et al. 2016; Christie et al. 2018; Kibler et al. 2018; Krievins et al. 2018). While several authors suggested that including stakeholder involvement can improve restoration effectiveness (Christie et al. 2018; Krievins et al. 2018), they may also limit restoration either through necessary tradeoffs (Elliott et al. 2016; Alexander et al. 2016) or because of a desire to maintain the current, unrestored state (e.g., reservoirs behind dams Kibler et al. 2018;). It is also important to remember that stakeholders may value and experience a place differently depending upon class, gender or race (Kibler et al. 2018) and that it takes time and money to develop relationships and trust needed for successful restoration (Christie et al. 2018).

## Management

There is tremendous uncertainty when managing aquatic systems. We seldom know the precise mechanisms that maintain desired conditions, regulatory mechanisms may target different aspects of the systems in conflicting ways, and cultural and economic pressures may not support desired aquatic conditions. Uncertainty and ‘hedging’ should be incorporated into management by managing for heterogeneity (e.g., multiple habitats, functional redundancy and response diversity) or implementing a portfolio of management interventions (Hughes et al. 2005; Schindler and Hilborn 2015; Truchy et al. 2015; Penaluna et al. 2018). Because restoring natural disturbance regimes may not be possible due to social system constraints, it may be necessary to manage for processes that emulate natural disturbance to produce habitat heterogeneity (Penaluna et al. 2018). Considering the socioecological system on a landscape scale while incorporating uncertainty will help ensure that management can be responsive in the face of an uncertain future (Beller et al. 2019). Incorporation of variability into management frameworks will increase resilience. Reeves and Duncan (2009) suggested management goals not be based on a mean of historical variability but rather the variability of the system (high and low thresholds) given current environmental conditions.

Ecosystems are affected by and respond to disturbances on multiple scales. Additionally, the system may be managed at multiple scales, through multiple organizations with different management goals. Although adding complexity, this may allow for more effective management (Gunderson 2000). Even if management actions focus on a local area, assessment of the larger landscape will be required (Poiani et al. 2000; Hughes et al. 2005; Beller et al. 2019). For example, while local management efforts may improve coral health, the global pressures of climate change and ocean acidification will place an upper limit on coral reef resilience (Anthony 2016). Management of inland freshwater waters should incorporate the watershed. Management of estuary condition or salmon stocks should include measures to enhance resilience in the estuary as well as the watershed and oceanic system (Bottom et al. 2009; White and Kaplan 2017; McCleod et al. 2019). Temporal scales for management need to be expansive enough to track the resilience of key ecosystem services and need to be paired with monitoring that encompasses natural seasonal cycles and is long enough (decades) to see ecological trends. Effective monitoring encompassing spatial and temporal scales allows determination of the effectiveness of management interactions on the system (Arnold et al. 2014; Schindler and Hilborn 2015). A mismatch between the temporal or spatial scale of ecological area and the institutional level responsible for management may adversely impact resilience (Maciejewski et al. 2015).

Management for specific goals or optimal conditions can decrease or minimize other ecological functions, decreasing resilience and increasing system vulnerability to stressors that might otherwise have been absorbed (Peterson et al. 1998). However, managing for ecosystems services may support resilience (Folke et al. 2004; Bottom et al. 2009). For example, improved lake water quality is related to resilience and improved ecosystem services (Carpenter and Cottingham 1997). Similarly, increased biodiversity is positively related to ecosystem services (Birge et al. 2016). However, optimizing the social system to maximize ecosystem services may lead to overexploitation of the ecological system unless the ecology is well understood (Hughes et al. 2005). Reducing the fishing fleet did not increase salmon stocks but did adversely impact the livelihood of coastal fishers; managing to maximize community and cultural resilience may lead to better outcomes (Healey 2009). Because there is no optimum level of ecosystem services, trade-offs need to be made at multiple scales which balance the desires of diverse, competing groups (Robards et al. 2011; Birge et al. 2016; Berkes 2017) although ecological models may assist in examining some of these trade-offs (Weijerman et al. 2018).

Adaptive management may help with these issues detailed above (Gunderson 2000; Schindler and Hilborn 2015) as it is multidisciplinary, so more than one perspective is incorporated, and iterative, so that decisions can be made even in the face of uncertainty and unpredictability. Carpenter and Gunderson (2001) showed that adaptive management increased resilience and stabilized system behavior. Two facets of adaptive management are inclusion of stakeholders, and management by multiple entities at multiple scales (Hughes et al. 2005; Camp et al. 2015; Thom et al. 2016; Peat et al. 2017; Zedler 2017). Although this inclusion is desirable, the time and money costs of involving multiple stakeholders and governance bodies must be considered (Biggs et al. 2015; Thom et al. 2016; Peat et al. 2017). Because management agencies are constrained by their laws and policies, adaptive management can be implemented in limited areas, with the support and flexibility of agency managers (Thom et al. 2016; Peat et al. 2017). Employing stakeholders to implement multiple potential restoration experiments is one way to encourage buy-in and increase resilience of the system (Camp et al. 2015). Adaptive management also requires monitoring encompassing spatial and temporal scales to allow determination of the effectiveness of management actions (Arnold et al. 2014; Schindler and Hilborn 2015; Thom et al. 2016; Peat et al. 2017; Zedler 2017).

## Conclusions

Meeting societal expectations for aquatic systems and the ecosystem services they provide is a growing challenge. Understanding socioecological resilience and managing systems to enhance resilience will be critical to meet this challenge but will not be easy. As outlined in this review, many factors interact across scales and in complex ways to influence the ability of aquatic systems to absorb and respond to stressors and disturbance. Furthermore, managing for aquatic socioecological resilience will be fraught with social conflict given the inevitability of tradeoffs among valued ecosystem services and the reality that different segments of society are dependent to varying degrees on these services.

Our review revealed evidence for the importance of managing stressors adversely impacting aquatic system resilience, as well as understanding the environmental and climatic cycles and changes impacting aquatic resources. Resilience may be strengthened by maintaining and enhancing habitat connectivity as well as functional redundancy and physical and biological diversity. These factors interact with each other to maintain metapopulations and provide ‘insurance’ against environmental changes. Resilience in aquatic socioecological system may be enhanced by understanding and fostering linkages between the social and ecological subsystems and understanding how the system is impacted by factors within and outside the area of immediate interest. Within the social system, collaborative and adaptive management can result in a system that works to optimize and equitably distribute ecosystem services, especially if stakeholders have a good understanding of the underlying ecological systems. Restoration may help to recover ecosystem services but is likely to be incomplete and characterized by lags in response. Management of the ecological system requires understanding of how the system functions, including incorporation of uncertainty and scalar issues, as well as understanding the social pressures upon the system.

In order to effectively implement adaptive management of aquatic systems for resilience, monitoring to detect changes in the socioecological system will be needed. In addition, research will continue to be needed to: (1) inform development of sensitive indicators and monitoring designs (2) disentangle complex multi-scalar interactions and feedbacks that currently limit our ability to foresee outcomes of managements decisions and stressors, and (3) help generalize lessons learned across aquatic ecosystems as adaptive management progresses and apply them in new contexts.

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## References

Abson DJ, Fischer J, Leventon J, Jens Newig J, Schomerus T, Vilsmaier U, von Wehrden H, Abernethy P, Ives CD, Jager NW, Lang DJ (2017) Leverage points for sustainability transformation. Ambio 46:30–39 [PubMed: 27344324]

Adler RW (2010) Resilience, restoration, and sustainability: Revising the fundamental principles of the Clean Water Act. Wash Univ J Law Pol 32:139–173

Alberti M, Marzluff JM (2004) Ecological resilience in urban ecosystems: linking urban patterns to human and ecological functions. Urban Ecosyst 7:241–265

Albins MA, Hixon MA (2013) Worst case scenario: potential long-term effects of invasive predatory lionfish (*Pterois volitans*) on Atlantic and Caribbean coral-reef communities. Environ Biol Fishes 96:1151–1157

Alexander S, Aronson J, Whaley O, Lamb D (2016) The relationship between ecological restoration and the ecosystem services concept. Ecol Soc 21:34

Allison SD, Martiny JBH (2008) Resistance, resilience, and redundancy in microbial communities. Proc Natl Acad Sci U S 105:11512–11519

Ameli AA, Creed IF (2018) Does wetland location matter when managing wetlands for watershed-scale flood and drought resilience? J Am Water Resour Assoc 55:529–542

Anderson T, Cartensen J, Hernandez-Garcia E, Duarte CM (2009) Ecological thresholds and regime shifts: approaches to identification. Trends Ecol Evol 24:49–57 [PubMed: 18952317]

Angeler DG, Allen CR (2016) Quantifying resilience. J Appl Ecol 53:617–624

Angeler DG, Allen CR, Barichievy C, Eason T, Garmestani AS, Graham NAJ, Granholm D, Gunderson LH, Knutson M, Nash KL, Nelson RJ, Nyström M, Spanbauer TL, Stow CA, Sundstrom SM (2016) Management applications of discontinuity theory. J Appl Ecol 53:688–698

Angeler DG, Fried-Petersen HB, Allen CR, Garmestani A, Twidwell D, Chuang W-C, Donovan VM, Eason T, Roberts CP, Sundrum SM, Wonkka CL (2019) Adaptive capacity in ecosystems In: Bohan DA, Dumbrill AJ (eds) Advances in Ecological Research. Academic Press, London, pp 1–24

Anthony KRN, Marshall PA, Abdulla A, Beeden R, Bergh C, Black R, Eakin CM, Game ET, Gooch M, Graham NAJ, Green A, Heron SF, van Hooidonk R, Knowland C, Mangubhai S, Marshall N, Maynard JA, McGinnity P, McLeod E, Mumby PJ, Nyström M, Obura D, Oliver J, Possingham HP, Pressey RL, Rowlands GP, Tamelander J, Wachenfeld D, Wear S (2015) Operationalizing resilience for adaptive coral reef management under global environmental change. Glob Change Biol 21:48–61

Anthony KRN (2016) Coral reefs under climate change and ocean acidification: challenges and opportunities for management and policy. Annu Rev Environ Resour 41:59–81

Arnold CA, Green OO, DeCaro DA, Chase A, Ewa JG (2014) The social-ecological resilience of an eastern urban-suburban watershed: the Anacostia River Basin. Idaho Law Rev 51:29–90

Arthington AH, Kennen JG, Stein ED, Webb JA (2018) Recent advances in environmental flows science and water management—innovation in the Anthropocene. Freshw Biol 63:1022–1034

Aspin TWH, Khamis K, Matthews TJ, Milner AM, O'Callaghan MJ, Trimmer M, Woodward G, Ledger ME (2018) Extreme drought pushes stream invertebrate communities over functional thresholds. Glob Change Biol 25:230–244

Bakker ES, Wood KA, Pagès JF, Veen GF, Christianen MJA, Santamaría L, Nolet BA, Hilt S (2016) Herbivory on freshwater and marine macrophytes: a review and perspective. Aquat Bot 135:18–36

Bayley SE, Creed IF, Sass GZ, Wong AS (2007) Frequent regime shifts in trophic states in shallow lakes on Boreal Plain: Alternative "unstable" states? Limnol Oceanogr 52:2002–2012

Beck MW, Heck KL, Able KW, Childers DL, Eggleston DB, Gillanders BM, Halpern B, Hays CG, Hoshino K, Minello TJ, Orth RJ, Sheridan PF, Weinstein MP (2001) The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates: a better understanding of the habitats that serve as nurseries for marine species and the factors that create site-specific variability in nursery quality will improve conservation and management of these areas. Bioscience 51:633–641

Beechie T, Imaki H, Greene J, Wade A, Wu H, Pess G, Roni P, Kimball J, Stanford J, Kiffney P, Mantua N (2013) Restoring salmon habitat for a changing climate. River Res Appl 29:939–960

Beisner BE, Haydon DT, Cuddington K (2003) Alternative stable states in ecology. Front Ecol Environ 1:376–382

Bell T, Newman JA, Silverman BW, Turner SL, Lilley AK (2005) The contribution of species richness and composition to bacterial services. Nature 436:1157–1160 [PubMed: 16121181]

Beller EE, Spotswood EN, Robinson AH, Anderson MG, Higgs ES, Hobbs RJ, Suding KN, Zavaleta ES, Grenier JL, Grossinger RM (2019) Building ecological resilience in highly modified landscapes. Bioscience 69:80–92

Berkes F (2017) Environmental governance for the Anthropocene? Social-ecological systems, resilience, and collaborative learning. Sustainability 9:1232

Biggs R, Schlüter M, Biggs D, Bohensky EL, BurnSilver S, Cundill G, Dakos V, Daw TM, Evans LS, Kotschy K, Leitch AM, Meek C, Quinlan A, Raudsepp-Hearne C, Robards MD, Schoon ML, Schultz L, West PC (2012) Toward principles for enhancing the resilience of ecosystem services. Annu Rev Environ Resour 37:421–448

Biggs R, Schlüter M, Schoon ML (2015) Principles for Building. Resilience sustaining ecosystem services in social-ecological systems. Cambridge University Press, Cambridge

Birge HE, Allen CR, Garmestani AS, Pope KL (2016) Adaptive management for ecosystem services. J Environ Manag 183:343–352

Bisson PA, Dunha JB, Reeves GH (2009) Freshwater ecosystems and resilience of Pacific salmon: habitat management based on natural variation. Ecol Soc 14:45

Blodau C, Knorr KH (2006) Experimental inflow of groundwater induces a “biogeochemical regime shift” in iron-rich and acidic sediments. J Geophys Res 111:G02026

Bogan MT, Boersma KS, Lytle DA (2015) Resistance and resilience of invertebrate communities to seasonal and supraseasonal drought in arid-land headwater streams. Freshw Biol 60:2547–2558

Boerlijst MC, Oudman T, de Roos AM (2013) Catastrophic collapse can occur without early warning: examples of silent catastrophes in structured ecological models. PLoS ONE 8:e62033 [PubMed: 23593506]

Borja A, Dauer DM, Elliott M, Simenstad CA (2010) Medium- and long-term recovery of estuarine and coastal ecosystems: patterns, rates and restoration effectiveness. Estuaries Coasts 33:1249–1260

Bottom DL, Jones KK, Simenstad CA, Smith CL (2009) Reconnecting social and ecological resilience in salmon ecosystems. Ecol Soc 14:5

Bozec Y-S, O’Farrell S, Bruggemann JH, Luckhurst BE, Mumby PJ (2016) Tradeoffs between fisheries harvest and the resilience of coral reefs. Proc Natl Acad Sci U S A 113:4536–4541 [PubMed: 27044106]

Breitberg DL, Craig JK, Fulford RS, Rose KA, Boyton WR, Brady DC, Ciotti BJ, Diaz RJ, Friedland KD, Hagy JD III, Hart DR, Hines AH, Houde ED, Kolesar SE, Nixon SW, Rice JA, Secor DH, Targett TE (2009) Nutrient enrichment and fisheries exploitation: interactive effects on estuarine living resources and their management. Hydrobiologia 629:31–47

Brown AG, Lespez L, Sear DA, Macaire J-J, Houben P, Klimek K, Brazier RE, Van Oost K, Pears B (2018) Natural vs anthropogenic streams in Europe: history, ecology and implications for restoration, river-rewilding and riverine ecosystem services. Earth Sci Rev 180:185–205

Burthe SJ, Henrys PA, Mackay EB, Spears BM, Campbell R, Carvalho L, Dudley B, Gunn IDM, Johns DG, Maberly SC, May L, Newell MA, Wanless S, Winfield IJ, Thackeray SJ, Daunt F (2016) Do early warning indicators consistently predict nonlinear change in long-term ecological data? J Appl Ecol 53:666–676

Bush T, Diao M, Allen RJ, Sinnige R, Muyzer G, Huisman J (2017) Oxic-anoxic regime shifts mediated by feedbacks between biogeochemical processes and microbial community dynamics. Nat Commun 8:789 [PubMed: 28986518]

Butitta VL, Carpenter SR, Loken LC, Pace ML, Stanley EH (2017) Spatial early warning signals in a lake manipulation. Ecosphere 8:e01941

Camp EV, Pine WE III, Havens K, Kane AS, Walters CJ, Irani T, Lindsey AB, Morris JG Jr (2015) Collapse of a historic oyster fishery: diagnosing causes and identifying paths toward increased resilience. Ecol Soc 20:45

Campbell SK, Butler VL (2010) Archaeological evidence for resilience of Pacific Northwest salmon populations and the socioecological system over the last ~ 7500 years. Ecol Soc 15:17

Campbell T, Simmons J, Saenz J, Jerde CL, Cowan W, Chanda S, Hogan Z (2019) Population connectivity of adfluvial and stream-resident Lahontan cutthroat trout: implications for resilience, management and restoration. Can J Fish Aquat Sci 76:426–437

Carlson SM, Satterthwaite WH (2011) Weakened portfolio effects in a collapsed salmon population complex. Can J Fish Aquat Sci 68:1579–1589

Carpenter SR, Cottingham KL (1997) Resilience and restoration of lakes. Ecol Soc 1:2

Carpenter SR, Ludwig D, Brock WA (1999) Management of eutrophication for lakes subject to potentially irreversible change. Ecol Appl 9:751–771

Carpenter SR, Gunderson LH (2001) Coping with collapse: ecological and social dynamics in ecosystem management. Bioscience 51:451–457

Carpenter S, Walker B, Anderies JM, Abel N (2001) From metaphor to measurement: resilience of what to what? Ecosystems 4:765–781

Carpenter SR (2003) Regime shifts in lake ecosystems: pattern and variation. Ecology Institute, Oldendorf/Luhe

Carpenter SR, Bennet EM, Peterson GD (2006) Scenarios for ecosystem services: an overview. Ecol Soc 11:29

Casini M, Blenckner T, Möllmann C, Gårdmark A, Lindegren M, Llope M, Kornilovs G, Plikshs M, Stenseth NC (2012) Predator transitory spillover induces trophic cascades in ecological sinks. Proc Natl Acad Sci U S A 109:8185–8189 [PubMed: 22505739]

Castorani MCN, Reed DC, Alberto F, Bell TW, Simons RD, Cavanaugh KC, Siegel DA, Raimondi PT (2015) Connectivity structures local population dynamics: a long-term empirical test in a large metapopulation system. Ecology 96:3141–3152 [PubMed: 26909421]

Chaalali A, Beaugrand G, Boet P (2013) Climate-caused abrupt shifts in a European macrotidal estuary. Estuaries Coasts 36:1193–1205

Chaffin BC, Gunderson LH (2016) Emergence, institutionalization and renewal: rhythms of adaptive governance in complex social-ecological systems. J Environ Manag 165:81–87

Chavez FP, Ryan J, Lluch-Cota SE, Niquen CM (2003) From anchovies to sardines and back: Multidecadal change in the Pacific. Ocean Sci 299:217–221

Chretien E, Chapman LJ (2016) Habitat heterogeneity facility coexistence of native fishes with an introduced predator: the resilience of a fish community 5 decades after the introduction of Nile perch. Biol Invasions 18:3449–3464

Christie P, Fluharty D, Kennard H, Pollnac R, Warren B (2018) Policy pivot in Puget Sound: lessons learned from marine protected areas and tribally-led estuarine restoration. Ocean Coast Manag 163:72–81

Cicchetti G, Greening H (2011) Estuarine biotope mosaics and habitat management goals: an application in Tampa Bay, FL, USA. Estuaries Coasts 34:1278–1292

Clarke PJ, Bell DM, Lawes MJ (2015) Testing the shifting persistence niche concept: plant resprouting along gradients of disturbance. Am Nat 185:747–755 [PubMed: 25996860]

Clements CF, Blanchard JL, Nash KL, Hindell MA, Ozgul A (2017) Body shifts and early warning signals precede the historic collapse of whale stocks. Nat Ecol Evol 1:0188

Clements CF, McCarthy MA, Blanchard JL (2019) Early warning signals of recovery in complex systems. Nat Commun 10:1681 [PubMed: 30975997]

Clements WH, Vleiea NKM, Church SE (2010) Quantifying restoration success and recovery in a metal-polluted stream: a 17-year assessment of physicochemical and biological responses. J Appl Ecol 47:899–910

Cloern JE, Hieb KA, Jacobson T, Sanso B, Di Lorenzo E, Stacy MT, Largier JL, Meiring W, Peterson WT, Powell TM, Winder M, Jassby AD (2010) Biological communities in San Francisco Bay track large-scale climate forcing over the North Pacific. Geophys Res Lett 37:L21602

Cohen MJ, Creed IF, Alexander L, Basu NB, Calhoun AJK, Craft C, D'Amico E, DeKeyser E, Fowler L, Golden HE, Jawitz JW, Kalla P, Kirkman LK, Lane CR, Lang M, Leibowitz SG, Lewis DB, Marton J, McLaughlin DL, Mushet DM, Raanan-Kiperwas H, Rains MC, Smith L, Walls SC (2016) Do geographically isolated wetlands influence landscape functions? Proc Natl Acad Sci U S A 113:978–1986 [PubMed: 26755601]

Collie JS, Richardson K, Steele JH (2004) Regime shifts: can ecological theory illuminate the mechanisms? Prog Oceanogr 60:281–302

Conley DJ, Paerl HW, Howarth RW, Boesch DF, Seitzinger SP, Havens KE, Lancelot C, Likens GE (2009) Controlling eutrophication: nitrogen and phosphorus. Science 323:1014–1015 [PubMed: 19229022]

Corrales X, Coll M, Ofr E, Heymans JJ, Steenbeek J, Goren M, Edelist D, Gal G (2018) Future scenarios of marine resources and ecosystem conditions in the Eastern Mediterranean under the impacts of fishing, alien species and sea warming. Sci Rep 8:14284 [PubMed: 30250047]

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260

Cote M, Nightingale AJ (2012) Resilience thinking meets social theory: situating social change in socio–ecological systems (SES) research. Prog Hum Geogr 36:475–489

Cullen-Unsworth LC, Unsworth RKF (2016) Strategies to enhance the resilience of the world's seagrass meadows. J Appl Ecol 53:967–972

Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J (2008) A place-based model for understanding community resilience to natural disasters. Glob Environ Change 18:598–606

Dakos V, Carpenter SR, Brock WA, Ellison AM, Guttal V, Ives AR, Kéfi S, Livina V, Seekell DA, van Nes EH, Scheffer M (2012) Methods for detecting early warnings of critical transitions in time series illustrated using simulated ecological data. PLoS ONE 7:e41010 [PubMed: 22815897]

Dakos V, Carpenter SR, van Nes EH, Scheffer M (2015) Resilience indicators: prospects and limitations for early warnings of regime shifts. Philos Trans R Soc B 370:20130263

Davies TW, Jenkins SR, Kingham R, Kenworthy J, Hawkins SJ, Hiddink JG (2011) Dominance, biomass and extinction resistance determine the consequences of biodiversity loss for multiple coastal ecosystem processes. PLoS ONE 6:e28362 [PubMed: 22163297]

Dayton PK, Tegner MJ, Edwards PB, Riser KL (1998) Sliding baselines, ghosts and reduced expectations in kelp forest communities. Ecol Appl 8:309–322

de Juan S, Thrush SF, Hewitt JE (2013) Counting on β-Diversity to safeguard the resilience of Estuaries. PLoS ONE 8:e65575 [PubMed: 23755252]

Deacon C, Samways MJ, Pryke JS (2018) Artificial reservoirs complement natural ponds to improve pondscape resilience in conservation corridors in a biodiversity hotspot. PLoS ONE 13:e0204148 [PubMed: 30235267]

Dee LE, Miller SJ, Peavey LE, Bradley D, Gentry RR, Startz R, Gaines SD, Lester SE (2016) Functional diversity of catch mitigates negative effects of temperature variability on fishery yields. Proc R Soc B 283:20161435

Detenbeck NE, Devore PW, Nieme GJ, Lima A (1992) Recovery of temperate-stream fish communities from disturbance: a review of case studies and synthesis of theory. Environ Manag 16:33–53

deYong B, Barange M, Beaugrand G, Harris R, Perry RI, Scheffer M, Werner F (2008) Regime shifts in marine ecosystems: detection, prediction and management. Trends Ecol Evol 23:402–409 [PubMed: 18501990]

Diaz S, Pascual U, Stenseke M, Martin-Lopez B, Watson RT, Molnar Z, Hill R, Chan KMA, Baste IA, Brauman KA, Polaski S, Church A, Lonsdale M, Lariganderie A, Leadley PW, van Oudenhoven APF, van der Paat F, Schroter M, Lavorel S, Anmeeruddy-Thomas Y, Bukvareva E, Davies K, Demissew S, Erpul G, Failler P, Guerra CA, Hewitt CL, Keune H, Lindley S, Shirayama Y (2018) Assessing natures contribution to people. Science 359:270–272 [PubMed: 29348221]

Diggelen AD, Montagna PA (2016) Is salinity variability a benthic disturbance in estuaries? Estuaries Coasts 39:967–980

Doak DF, Bigger D, Harding EK, Marvier MA, O'Malley RE, Thomson D (1998) The statistical inevitability of stability-diversity relationships in community ecology. Am Nat 151:264–276 [PubMed: 18811357]

Duarte CM, Conley DJ, Carstensen J, Sanchez-Camacho M (2009) Return to Neverland: shifting baselines affect eutrophication restoration targets. Estuaries Coasts 32:29–36

Duarte CM, Borja A, Cartensen J, Elliott M, Krause-Jensen D, Marbà N (2015) Paradigms in the recovery of estuarine and coastal ecosystems. Estuaries Coasts 38:1202–1212

Duffy JE, Lefcheck JS, Stuart-Smith RD, Navarrete SA, Edgar GJ (2016) Biodiversity enhances reed fish biomass and resistance to climate change. Proc Natl Acad Sci U S A 113:6230–6235 [PubMed: 27185921]

Duh J-D, Shandas V, Chang H, George LA (2008) Rates of urbanizations and the resiliency of air and water quality. Sci Total Environ 440:238–256

Durance I, Bruford MW, Chalmers R, Chappell NA, Christie M, Cosby BJ, Noble D, Ormerod SJ, Prosser H, Weightman A, Woodward G (2016) The challenges of linking ecosystem services to diversity: lessons from a large-scale freshwater study In: Woodward G, Bohan DA (eds) Advances in ecological research, vol 54 Academic Press, London, pp 87–134

Ellender BR, Weyl OLF (2015) Resilience of imperiled headwater stream fish to an unpredictable high-magnitude flood. Koedoe 57:1258

Elliott M, Burdon D, Hemingway KL, Apitz SE (2007) Estuarine, coastal and marine ecosystem restoration: confusing management and science—a revision of concepts. Estuar Coast Shelf Sci 4:349–366

Elliott M, Whitfield AK (2011) Challenging paradigms in estuarine ecology and management. Estuar Coast Shelf Sci 94:306–314

Elliott M, Mander L, Mazik K, Simenstad C, Valesini F, Whitfield Wolanski E (2016) Ecoengineering with ecohydrology: success and failures in estuarine restoration. Estuar Coast Shelf Sci 176:12–35

Elmqvist T, Folke C, Nyström M, Peterson G, Bengtsson J, Walker Norberg J (2003) Response diversity, ecosystem change, and resilience. Front Ecol Environ 1:488–494

Estes JA, Palmisano JF (1974) Sea Otters: their role in structuring nearshore communities. Science 185:1058–1060 [PubMed: 17738247]

Estes JA, Tinker MT, Williams TM, Doak DF (1998) Killer whale predation on sea otters linking oceanic and nearshore ecosystems. Science 282:473–476 [PubMed: 9774274]

Euliss NH Jr, LaBaugh JW, Fredrickson LH, Mushet DM, Laubhan MK, Swanson GA, Winter TC, Rosenberry DO, Nelson RD (2004) The wetland continuum: a conceptual framework for interpreting biological studies. Wetlands 24:448–458

Feio MJ, Doledec S, Graca MAS (2015) Human disturbance affects the long-term spatial synchrony of freshwater invertebrate communities. Environ Pollut 196:300–308 [PubMed: 25463726]

Filbee-Dexter K, Scheibling RE (2014) Sea urchin barrens as alternative stable states of collapsed kelp ecosystems. Mar Ecol Prog Ser 495:1–25

Farley J, Voinov A (2016) Economics, socio-ecological resilience and ecosystem services. J Environ Manag 183:389–398

Flotemersch JE, Leibowitz SG, Hill RA, Stoddard JL, Thoms MC, Tharme RE (2016) A watershed integrity definition and assessment approach to support strategic management of watersheds. River Res Appl 32:1654–1671

Folke C, Carpenter S, Walker B, Scheffer M, Elmqvist T, Gunderson L, Holling CS (2004) Regime shifts, resilience, and biodiversity in ecosystem management. Annu Rev Ecol Evol Syst 35:557–581

Folke C, Biggs R, Norstrom AV, Reyers B, Rockstrom J (2016) Social-ecological resilience and biosphere-based sustainability science. Ecol Soc 21:41

Fritz KM, Dodds WK (2004) Resistance and resilience of macroinvertebrate assemblages to drying and flood in a tallgrass prairie stream system. Hydrobiologia 527(1):99–112

Fu H, Zhong J, Yuan G, Guo C, Ding H, Feng Q, Fu Q (2015) A functional-trait approach reveals community diversity and assembly processes response to flood disturbance in a subtropical wetland. Ecol Res 30:57–66

Glicksman RL, Batzel MR (2010) Science, politics, law and the arc of the Clean Water Act: the role of assumptions in the adoption of a pollution control landmark. Wash Univ J Law Pol 32:99–138

Griffiths JR, Schindler DE, Armstrong JB, Scheuerell MD, Whited DC, Clark RA, Hilborn R, Holt CA, Lindley ST, Stanford JA, Volk EC (2014) Performance of salmon fishery portfolios across western North America. J Appl Ecol 51:1554–1563 [PubMed: 25552746]

Gsell AS, Scharfenberger U, Özkundakci D, Walters A, Hansson L, Janssen ABG, Nöges P, Reid PC, Schindler DE, Van Donk E, Dakos V, Adrian R (2016) Evaluating early-warning indicators of critical transitions in natural aquatic systems. Proc Natl Acad Sci U S A 113:E8089–E8095 [PubMed: 27911776]

Guerry AD, Polasky S, Lubchenco J, Chaplin-Kramer R, Daily GC, Griffin R, Ruckelshaus M, Bateman IJ, Duraiappah A, Elmqvist T, Feldman MW, Folke C, Hoekstra J, Kareiva PM, Keeler BL, Li S, McKenzie E, Ouyang Z, Reyers B, Ricketts TH, Rockstrom J, Tallis H, Vira B (2015) Natural capital and ecosystem services informing decisions: from promise to practice. Proc Natl Acad Sci U S A 112:7348–7355 [PubMed: 26082539]

Gunderson LH (2000) Ecological resilience—in theory and application. Annu Rev Ecol Syst 31:425–439

Gunderson LH (2001) Managing surprising ecosystems in southern Florida. Ecol Econ 37:371–378

Gunderson LH, Carpenter SR, Folke C, Olsson P, Peterson G (2006) Water RATs (resilience, adaptability, and transformability) in lake and wetland social–ecological systems. Ecol Soc 11:16

Gunderson L, Cosens BA, Chaffin BC, Arnold CA, Fremier AK, Garmestani AS, Kundis Craig RK, Gosnell H, Birge HE, Allen CR, Benson MH, Morrison RR, Stone MC, Hamm JA, Nemec K, Schlager E, Llewellyn D (2017) Regime shifts and panarchies in regional scale social–ecological water systems. Ecol Soc 22:31

Haghkerdar JM, McLachlan JR, Ireland A (2018) Repeat disturbances have cumulative impacts on stream communities. Ecol Evol 9:2898–2906

Hagy JD, Boynton WR, Keefe CW, Wood KV (2004) Hypoxia in Chesapeake Bay, 1950–2001: Long-term change in relation to nutrient loading and river flow. Estuaries Coasts 27:634–658

Hamilton SL, Caselle JE (2015) Exploitation and recovery of a sea urchin predator has implications for the resilience of southern California kelp forests. Proc R Soc B 282:20141817

Hazelton ELG, Downard R, Kettenring KM, McCormick MK, Whigham DF (2018) Spatial and temporal variation in brackish wetland setbacks: implications for wetland restoration following Phragmites control. Estuaries Coasts 41:S68–S84

Healey MC (2009) Resilient salmon, resilient fisheries for British Columbia Canada. Ecol Soc 14:2

Heffernan JB (2008) Wetlands as an alternative stable state in desert streams. Ecology 89:1261–1271 [PubMed: 18543620]

Hershkovitz Y, Gasith A (2013) Resistance, resilience, and community dynamics on Mediterranean-climate streams. Hydrobiologia 719:59–75

Hewitt JE, Thrush SF (2010) Empirical evidence of an approaching alternate state produced by intrinsic community dynamics, climate variability and management actions. Mar Ecol Prog Ser 413:267–276

Hiers JK, Mitchell RJ, Barnett A, Walters JR, Mack M, Williams B, Sutter R (2012) The dynamic reference concept: measuring restoration success in a rapidly changing no-analogue future. Ecol Restor 30:27–36

Holdschlag A, Ratter BMW (2013) Multiscale system dynamics of humans and nature in the Bahamas: perturbation, knowledge, panarchy and resilience. Sustain Sci 8:407–442

Holling CS (1973) Resilience and stability of ecological systems. Annu Rev Ecol Syst 1:1–23

Holling CS (1996) Engineering resilience versus ecological resilience In: Shulze P (ed) Engineering within ecological constraints. National Academy Press, Washington, pp 31–44

Holling CS (2001) Understanding the complexity of economic, ecological, and social systems. Ecosystems 4:390–405

Hoppe CJM, Schuback N, Semeniuk DM, Maldonado MT, Rost B (2017) Functional redundancy facilitates resilience of subarctic phytoplankton assemblages toward ocean acidification and high irradiance. Front Mar Sci 4:229

Howarth RW, Marino R (2006) Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: evolving views over three decades. Limnol Oceanogr 51:364–376

Hughes TP (1994) Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. Science 265:1547–1551 [PubMed: 17801530]

Hughes TP, Bellwood DR, Folke C, Steneck RS, Wilson J (2005) New paradigm for supporting the resilience of marine ecosystems. Trends Ecol Evol 20:380–386 [PubMed: 16701400]

Ibelings BA, Portielje R, Lammens EHRR, Noorduis R, van den Berg MS, Joose W, Meijer ML (2007) Resilience of alternative stable states during the recovery of shallow lakes from eutrophication: Lake Veluwe as a case study. Ecosystems 10:4–16

Ibrahim L, Preuss TH, Schaeffer A, Hommen U (2014) A contribution to the identification of representative vulnerable fish species for pesticide risk assessment in Europe—a comparison of population resilience using matrix models. Ecol Model 280:65–75

Ives CD, Abson DJ, von Wehrden H, Dorninger C, Klaniecki K, Fischer J (2018) Reconnecting with nature for sustainability. Sustain Sci 13:1389–1397 [PubMed: 30220917]

Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ, Warner RR (2001) Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629–637 [PubMed: 11474098]

Janssen ABG, Teurlincx S, An S, Janse JH, Paerl HW, Mooij WM (2014) Alternative stable states in large shallow lakes? J Great Lakes Res 40:813–826

Janssen P, Piegay H, Evette A (2019) How maintenance and restoration measures mediate the response of riparian plant functional composition to environmental gradients on channel margins: insights from a highly degraded large river. Sci Total Environ 656:1312–1325 [PubMed: 30625660]

Jeppesen E, Kristensen P, Jensen JP, Sondergaard M, Mortensen E, Lauridsen T (1991) Recovery resilience following a reduction in external phosphorus loading of shallow eutrophic Danish lakes: duration, regulating factors and methods for overcoming resilience. Int J Limnol 48:127–148

Jeppesen E, Sondergaard M, Jensen JP, Havens KE, Anneville O, Carvalho L, Coveney MF, Deneke R, Dokulil MT, Foy B, Gerdeaux D, Hampton SE, Hilt S, Kangur K, Kohler J, Lammens EHHR, Lauridsen TL, Manca M, Miracle MR, Moss B, Noges P, Persson G, Phillips G, Portielje R, Schelske CL, Straile D, Tatrai I, Willen E, Winder M (2005) Lake responses to reduced nutrient loading—an analysis of contemporary long-term data from 35 case studies. Freshw Biol 50:1747–1771

Jeppesen E, Søndergaard M, Pedersen AR, Jürgens K, Strzelczak A, Lauridsen TL, Johansson LS (2007) Salinity induced regime shift in shallow brackish lagoons. Ecosystems 10:47–57

Johnston EL, Mayer-Pinto M, Crowe TP (2015) Chemical contaminant effects on marine ecosystem functioning. J Appl Ecol 52:140–149

Kernan M (2015) Climate change and the impact of invasive species on aquatic ecosystems. Aquat Ecosyst Health Manag 18:321–333

Kibler KM, Cook GS, Chambers LG, Donnelly M, Hawthorne TL, Rivera FI, Walters L (2018) Integrating sense of place into ecosystem restoration: a novel approach to achieve synergistic social-ecological impact. Ecol Soc 23:25

Knudson C, Kay K, Fisher S (2018) Appraising geodiversity and cultural diversity approaches to building resilience through conservation. Nat Clim Change 8:678–685

Krause-Jensen D, Markager S, Dalsgaard T (2012) Benthic and pelagic primary production in different nutrient regimes. Estuaries Coasts 35:527–545

Krievins K, Plummer R, Baird J (2018) Building resilience in ecological restoration processed: a social-ecological perspective. Ecol Restor 36:195–207

Ledger ME, Harris RML, Armitage PD, Milner AM (2012) Climate change impacts on community resilience: evidence from a drought disturbance experiment. Adv Ecol Res 46:211–258

Leigh C, Bonada N, Boulton AJ, Hugueny B, Larned ST, Vander Vorste R, Datry T (2016) Invertebrate assemblage responses and the dual roles of resistance and resilience to drying in intermittent rivers. Aquat Sci 78:291–301

Lepori F, Hjerdt N (2006) Disturbance and aquatic biodiversity: reconciling contrasting views. Bioscience 56:809–818

Levin SA, Lubchenco J (2008) Resilience, robustness, and marine ecosystem-based management. Bioscience 58:27–32

Levin PS, Möllmann C (2015) Marine ecosystem regime shifts: challenges and opportunities for ecosystem-based management. Philos Trans R Soc B 370:20130275

Lin Q, Zhang K, Shen J, Liu E (2019) Integrating long-term dynamics of ecosystem services into restoration and management of large shallow lakes. Sci Total Environ 671:66–75 [PubMed: 30927729]

Ling SD, Scheibling RE, Rassweiler A, Johnson CR, Shears N, Connell SD, Salomon AK, Norderhaug KM, Pérez-Matus A, Hernández JC, Clemente S, Blamey LK, Hereu B, Ballesteros E, Sala E, Garrabou J, Cebrian E, Zabala M, Fujita D, Johnson LE (2015) Global regime shift dynamics of catastrophic sea urchin overgrazing. Philos Trans R Soc B 370:20130269

Lotze HK, Worm B (2009) Historical baselines for large marine animals. Trends Ecol Evol 24:254–262 [PubMed: 19251340]

Lotze HK, Coll M, Magera AM, Ward-Paige C, Airoldi L (2011) Recovery of animal populations and ecosystems. Trends Ecol Evol 26:595–605 [PubMed: 21852017]

Lundquist CJ, Thrush SF, Coco G, Hewitt JE (2010) Interactions between disturbance and dispersal reduce persistence thresholds in a benthic community. Mar Ecol Prog Ser 413:217–228

Maciejewski K, De Vos A, Cumming GS, Moore C, Biggs D (2015) Cross-scale feedbacks and scale mismatches as influences on cultural services and the resilience of protected areas. Ecol Appl 25:11–23 [PubMed: 26255354]

Magurran SE, Hendersen PA (2012) How selection structures species abundance distributions. Proc R Soc B 279:3722–3726

Maina J, McClanahan TR, Venus V, Ateweberhan M, Madin J (2011) Global gradients of coral exposure to environmental stresses and implications for local management. PLoS ONE 6:e23064 [PubMed: 21860667]

Mantyka-Pringle CS, Martin TG, Moffatt DB, Linke S, Rhodes JR (2014) Understanding and predicting the combined effects of climate change and land-use change on freshwater macroinvertebrates and fish. J Appl Ecol 51:572–581

Massicotte P, Proulx R, Cabana G, Rodríguez MA (2015) Testing the influence of environmental heterogeneity on fish species richness in two biogeographic provinces. PeerJ 3:e760 [PubMed: 25699209]

McCauley LA, Anteau MJ, van der Burg MP, Wiltermuth MT (2015) Land use and wetland drainage affect water levels and dynamics of remaining wetlands. Ecosphere 6:92

McCleod E, Anthony KRN, Mumby PJ, Maynard J, Beeden R, Graham NAJ, Heron SF, Hoegh-Guldberg O, Jupiter S, MacGowan P, Mangubhai MN, Marshall PA, McClanahan HP, McCleod K, Nystrom M, Obura D, Parker B, Posingham HP, Salm RV, Tamelander J (2019) The future of resilience-based management in coral reef ecosystems. J Environ Manag 233:291–391

McCluney KE, Poff NL, Palmer MA, Thorp JH, Poole GC, Williams BS, Williams MR, Baron JS (2014) Riverine macrosystems ecology: sensitivity, resistance, and resilience of whole river basins with human alterations. Front Ecol Environ 12:48–58

McPhearson T, Hamstead ZA, Kremer P (2014) Urban ecosystem services for resilience planning and management in New York City. Ambio 43:502–515 [PubMed: 24740621]

McWilliam M, Hoogenboom MO, Baird AH, Kuo C-Y, Madin JS, Hughes TP (2018) Biogeographical disparity in the functional diversity and redundancy of corals. Proc Natl Acad Sci U S A 115:3084–3089 [PubMed: 29507193]

Merrill NH, Mulvaney KK, Martin DM, Chintala MM, Berry W, Gleason T, Balogh S, Humphries A (2018) A resilience framework for chronic exposures: water quality and ecosystem services in coastal social-ecological systems. Coast Manag 46:242–258

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: synthesis. Island Press, DC

Milner AM, Picken JL, Klaar MJ, Robertson AL, Clitherow LR, Eagle L, Brown LE (2018) River ecosystem resilience to extreme flood events. Ecol Evol 8:8354–8363 [PubMed: 30250708]

Moksnes PO, Eriander L, Infantes E, Holmer M (2018) Local regime shifts prevent natural recovery and restoration of lost eelgrass beds along the Swedish west coast. Estuaries Coasts 41:1712–1731

Moore TN, Cuker BE (2018) Sedimentary oxygen demand and orthophosphate release: sustaining eutrophication in a tributary of the Chesapeake Bay. J Water Resour Ocean Sci 7:42–48

Morgan RP, Cushman SF (2005) Urbanization effects on stream fish assemblages in Maryland, USA. J N Am Benthol Soc 24:643–655

Mumby PJ, Edwards AJ, Arias-González JE, Lindeman KC, Blackwell PG, Gall A, Gorczynska MI, Harborne AR, Pescod CL, Renken H, Wabnitz CCC, Llewellyn G (2004) Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature 427:533–536 [PubMed: 14765193]

Munkes B (2005) Eutrophication, phase shift, the delay and potential return in the Greifswalder Bodden, Baltic Sea. Aquat Sci 67:372–381

Mushet DM, Euliss NH Jr, Stockwell CA (2013) Complex spatial dynamics maintain northern leopard frog genetic diversity in a temporally varying landscape. Herpetol Conserv Biol 8:163–175

Mushet DM, McKenna OP, LaBaugh JW, Euliss NH Jr, Rosenberry DO (2018) Accommodating state shifts within the conceptual framework of the wetland continuum. Wetlands 38:647–651

Ness E (2017) The Model Lake. Isthmus, Madison, WI, 24 8 2017 https://www.isthmuscom/news/cover-story/steve-carpenter-sounds-a-warning-for-lake-mendota. Accessed 15 May 2018

Nyström M (2006) Redundancy and response diversity of functional groups: implications for the resilience of coral reefs. Ambio 35:30–35 [PubMed: 16615697]

Olds AD, Pitt KA, Maxwell PS, Connolly RM (2012) Synergistic effects of reserves and connectivity on ecological resilience. J Appl Ecol 49:1195–1203

Oliver TH, Heard MS, Isaac NJB, Roy DB, Procter D, Eigenbrod F, Freckleton R, Hector A, Orme CDL, Petchey OL, Proença V, Raffaelli D, Suttle KB, Mace GM, Martín-López B, Woodcock BA, Bullock JM (2015) Biodiversity and resilience of ecosystem functions. Trends Ecol Evol 30:673–684 [PubMed: 26437633]

Oliver TH, Heard MS, Isaac NJB, Roy DB, Proctor D, Eigenbrod F, Freckleton R, Hector A, Orme CDL, Petchey OL, Proenca V, Raffaelli D, Suttle KB, Mace GM, Martin-Lopez B, Woodcock BA, Bullock JM (2016) A synthesis is emerging between biodiversity-ecosystem function and ecological resilience research: reply to Mori. Trends Ecol Evol 31:89–92 [PubMed: 26774554]

Oreska MPJ, Truitt B, Orth RJ, Luckenbach MW (2017) The bay scallop (*Argopecten irradians*) industry collapse in Virginia and its implications for the successful management of scallop-seagrass habitats. Mar Pol 75:116–124

Orth RJ, Dennison WC, Lefcheck JS, Gurbisz C, Hannam M, Keisman J, Landry JB, Moore KA, Murphy RR, Patrick CJ, Testa J, Weller DE, Wilcox DJ (2017) Submersed aquatic vegetation in Chesapeake Bay: sentinel species in a changing world. Bioscience 67:698–712

Ostrom E, Burger J, Field CB, Norgaard RB, Policansky D (1999) Revisiting the commons: local lessons, global challenges. Science 284:278–282 [PubMed: 10195886]

Palumbi SR, McLeod KL, Grunbaum D (2008) Ecosystems in action: lessons from marine ecology about recovery, resistance, and reversibility. Bioscience 58:33–42

Pauly D (1995) Anecdotes and the shifting baseline syndrome of fisheries. Trends Ecol Evol 10:430 [PubMed: 21237093]

Pearson S, Jasmyn A, Lynch J, Plant R, Cork S, Taffs K, Dodson J, Maynard S, Gergis J, Gell P, Thackway R, Sealie L, Donaldson J (2015) Increasing understanding and use of natural archives of ecosystem services, resilience and thresholds to improve policy, science and practice. The Holocene 25:366–378

Pearsons TN, Li HW, Lamberti GA (1992) Influence of habitat complexity on resistance to flooding and resilience of stream fish assemblages. Trans Am Fish Soc 121:427–436

Peat M, Moon K, Dyer F, Johnson W, Nichols SJ (2017) Creating institutional flexibility for adaptive water management: insights from two management agencies. J Environ Manag 202:188–197

Penaluna BE, Reeves GH, Barnett ZC, Bisson PA, Buffington JM, Dolloff CA, Flitcroft RL, Luce CH, Nislow KH, Rothlisberger JD, Warren ML Jr (2018) Using natural disturbance and portfolio concepts to guide aquatic-riparian ecosystem management. Fisheries 43:406–422

Penfound WT (1952) An outline for ecological life histories of herbaceous vascular hydrophytes. Ecology 33:123–128

Petchey OL, Gaston KL (2006) Functional diversity: back to basics and looking forward. Ecol Lett 9:741–758 [PubMed: 16706917]

Peterson G, Allen GR, Holling CS (1998) Ecological resilience, biodiversity and scale. Ecosystems 1:6–18

Peterson G (2000) Political ecology and ecological resilience: an integration of human and ecological dynamics. Ecol Econ 35:323–336

Petraitis PS, Hoffman C (2010) Multiple stable states and relationship between thresholds in processes and states. Mar Ecol Prog Ser 413:189–200

Pinceel T, Buschke F, Weckx M, Brendonck L, Vanschoenwinkel B (2018) Climate change jeopardizes the persistence of freshwater zooplankton by reducing both habitat suitability and demographic resilience. BMC Ecol 18:2 [PubMed: 29361977]

Pires APF, Srivastava DS, Farjalla VF (2018) Is biodiversity able to buffer ecosystems from climate change? What we know and what we don't. Bioscience 68:273–280

Poff NL, Brown CM, Grantham TE, Matthews JH, Palmer MA, Spence CM, Wilby RL, Haasnoot M, Mendoza GF, Dominique KC, Baeza A (2016) Sustainable water management under future uncertainty with eco-engineering decision scaling. Nat Clim Change 6:25–34

Poiani KA, Richter BD, Anderson MG, Richter HE (2000) Biodiversity conservation at multiple scales: functional sites, landscapes, and networks. Bioscience 50:133–145

Powell EN, Ashton-Alcox KA, Kraeuter JN, Fors SE, Bushek D (2008) Long-term trends in oyster population dynamics in Delaware Bay: regime shifts and response to disease. J Shellfish Res 27:729–755

Quandt RE (1958) The estimation of the parameters of a linear regression system obeying two separate regimes. J Am Stat Assoc 53:873–880

Radionov SN (2004) A sequential algorithm for testing climate regime shifts. Geophys Res Lett 31:L09204

Ramírez F, Coll M, Navarro J, Bustamante J, Green AJ (2018) Spatial congruence between multiple stressors in the Mediterranean Sea may reduce its resilience to climate impacts. Sci Rep 8:14871 [PubMed: 30291298]

Ray CG (2005) Connectivity of estuarine fishes to the coastal realm. Estuar Coast Shelf Sci 64:18–32

Rebstock GA (2002) Climatic regime shifts and decadal-scale variability in calanoid copepod populations off southern California. Glob Change Biol 8:71–89

Reeves GH, Duncan SL (2009) Ecological history vs. social expectations: managing aquatic ecosystems. Ecol Soc 14:8

Rehitha TV, Ullas N, Vineetha G, Benny PY, Madhu NV, Revichandran C (2017) Impact of maintenance dredging on macrobenthic community structure of a tropical estuary. Ocean Coast Manag 144:71–82

Restall B, Conrad E (2015) A literature review of connectedness to nature and its potential for environmental management. J Environ Manag 159:264–278

Reyers B, Folke C, Moore M-L, Biggs R, Galaz V (2018) Socio-ecological systems insights for navigating the dynamics of the Anthropocene. Annu Rev Environ Resour 43:267–289

Rhoads BL, Wilson D, Urban M, Herricks EE (1999) Interaction between scientists and nonscientists in community-based watershed management: emergence of the concept of stream naturalization. Environ Manag 24:297–308

Robards MD, Schoon ML, Meek CL, Engle NL (2011) The importance of social drivers in the resilient provision of ecosystem services. Glob Environ Change 21:522–529

Rolls RJ, Heino J, Ryder DS, Chessman BC, Growns IO, Thompson RM, Gido KB (2018) Scaling biodiversity responses to hydrological regimes. Biol Rev 93:971–995 [PubMed: 29115026]

Roth F, Stuhldreier I, Sánchez-Noguera C, Morales-Ramírez A, Wild C (2015) Effects of simulated overfishing on the succession of benthic algae and invertebrates in an upwelling-influenced coral reef of Pacific Costa Rica. J Exp Mar Biol Ecol 468:55–66

Roy AH, Rosemond AD, Paul MJ, Leigh DS, Wallace JB (2003) Stream macroinvertebrate response to catchment urbanization (Georgia, U.S.A.). Freshw Biol 48:329–346

Ryan ME, Palen WJ, Adams MJ, Rochefort RM (2014) Amphibians in the climate vice: loss and restoration of resilience of montane wetland ecosystems in the western US. Front Ecol Environ 12:232–240

Sattler C, Loft L, Mann C, Meyer (2018) Methods in ecosystem services governance analysis. Ecosyst Serv 34:155–168

Savenkoff C, Castonguay M, Chabot D, Hammill MO, Bourdages H, Morissette L (2007) Changes in the northern Gulf of St. Lawrence ecosystem estimated by inverse modeling: evidence of a fishery-indices regime shift? Estuar Coast Shelf Sci 73:711–724

Scavia D, Field JC, Boesch DF, Buddemeier RW, Burkett V, Cayan DR, Fogerty M, Harwell MA, Howarth RW, Mason C, Reed DJ, Royer TC, Sallenger AH, Titus JG (2002) Climate change impacts on U.S. coastal and marine ecosystems. Estuaries 25:149–164

Scheffer M, Hosper SH, Meijer ML, Moss B, Jeppesen E (1993) Alternative equilibria in shallow lakes. Trends Ecol Evol 8:275–279 [PubMed: 21236168]

Scheffer M, Brock W, Westley F (2000) Socioeconomic mechanisms preventing optimum use of ecosystem services: an interdisciplinary theoretical analysis. Ecosystems 3:451–471

Scheffer M, Carpenter SR, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in ecosystems. Nature 413:591–596 [PubMed: 11595939]

Scheffer M, Carpenter SR (2003) Catastrophic regime shifts in ecosystems: linking theory to observation. Trends Ecol Evol 18:648–656

Scheffer M, Jeppesen E (2007) Regime shifts in shallow lakes. Ecosystems 10:1–3

Scheffer M, Carpenter SR, Dakos V, van Ness EH (2015) Generic indicators of ecological resilience. Inferring the chance of a critical transition. Annu Rev Ecol Syst 46:145–167

Schindler DE, Hilborn R, Chasco B, Boatright CP, Quinn TP, Rogers LA, Webster MS (2010) Population diversity and the portfolio effect in an exploited species. Nature 465:609–612 [PubMed: 20520713]

Schindler DE, Hilborn R (2015) Prediction, precaution, and policy under global change. Science 347:953–954 [PubMed: 25722401]

Seabrook MR, Townsend CR (1993) Stream community structure in relation to spatial and temporal variation: a habitats template study of two contrasting New Zealand streams. Freshw Biol 29:395–410

Shade A, Peter H, Allison SD, Baho DL, Berga M, Bürgmann H, Huber DH, Langenheder S, Lennon JT, Martiny JBH, Matulich KL, Schmidt TM, Handelsman J (2012) Fundamentals of microbial community resistance and resilience. Front Microbiol 3:417 [PubMed: 23267351]

Shanley CS, Albert DM (2014) Climate change sensitivity index for Pacific salmon habitat in southeast Alaska. PLoS ONE 9:e104799 [PubMed: 25127398]

Sievert NA, Paukert CP, Tsang Y-P, Infante D (2016) Development and assessment of indices to determine stream fish vulnerability to climate change and habitat alteration. Ecol Ind 67:401–416

Simenstad C, Reed D, Ford M (2006) When is restoration not? Incorporating landscape scale processed to restore self-sustaining ecosystems in coastal wetland restoration. Ecol Eng 26:27–39

Sinclair ARE, Pech RP, Fryxell JM, McCann K, Byrom AE, Savory CJ, Brashares J, Arthur AD, Catling PC, Triska MD, Craig MD, Sinclair TJE, McLaren JR, Turkington R, Beyers RL, Harrower WL (2018) Predicting and assessing progress in the restoration of ecosystems. Conserv Lett 11:1–10

Small C, Nicholls RJ (2003) A global analysis of human settlement in Coastal Zones. J Coastal Res 19:584–599

Søndergaard M, Kristensen P, Jeppesen E (1992) Phosphorus release from resuspended sediment in the shallow and wind exposed Lake Arresø, Denmark. Hydrobiologia 228:91–99

Søndergaard M, Jensen JP, Jeppesen E (2003) Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia 506:135–145

Southward AJ, Boalch GT, Maddock L (1988) Fluctuations in the herring and pilchard fisheries of Devon and Cornwall linked to change in climate since the 16th century. J Mar Biol Assoc UK 68:423–445

Spenser M, Birchenough SNR, Mieszkowska N, Robinson LA, Simpson SD, Burrows MT, Capasso E, Cleall-Harding P, Crummy J, Duck C, Eloire D, Frost M, Hall AJ, Hawkins SJ, Johns DG, Sims DW, Smyth TJ, Frid CLJ (2010) Temporal change in UK marine communities: trends or regime shifts? Mar Ecol 32:10–24

Stachowicz JJ, Fried H, Osman RW, Whitlach RB (2002) Biodiversity, invasion resistance, and marine ecosystem function: reconciling pattern and process. Ecology 83:2575–2590

Stanley EH, Powers SM, Lottig NR (2010) The evolving legacy of disturbance in stream ecology: concepts, contributions, and coming challenges. J N Am Benthol Soc 29:67–83

Strong JA, Angonegi E, Bizsel KC, Danovaro R, Elliott M, Franco A, Garces E, Little S, Mazik K, Moncheva S, Papadopoulou N, Patricio J, Queiros AM, Smith C, Stefanova K, Solaum O (2015) Marine biodiversity and ecosystem function relationships: the potential for practical monitoring applications. Estuar Coast Shelf Sci 161:46–64

Sundstrom SM, Angeler DG, Barichievy C, Eason T, Garmestani A, Gunderson L, Knudson M, Nash KL, Spanbauer T, Stow C, Allen CR (2018) The distribution and role of functional abundance in cross-scale resilience. Ecology 99:2421–2432 [PubMed: 30175443]

Terui A, Ishiyama N, Urabe H, Ono S, Finlay JC, Nakamura F (2018) Metapopulation stability in branching river networks. Proc Natl Acad Sci U S A 115:e5965

Thom R, St Clair T, Burns R, Anderson M (2016) Adaptive management of large aquatic ecosystem recovery programs in the United States. J Environ Manag 183:424–430

Thornhill IA, Biggs J, Hill MJ, Briers R, Gledhill D, Wood PJ, Gee JHR, Ledger M, Hassall C (2018) The functional response and resilience in small waterbodies along land-use and environmental gradients. Glob Change Biol 24:3079–3092

Thrush SF, Hewitt JE, Dayton PK, Coco G, Lohrer AM, Norkko A, Norkko J, Chiantore M (2009) Forecasting the limits of resilience: integrating empirical research with theory. Proc R Soc B 276:3209–3217

Timpane-Padgham BL, Beechie T, Klinger T (2017) A systematic review of ecological attributes that confer resilience to climate change in ecological restoration. PLoS ONE 12:e0173812 [PubMed: 28301560]

Tisseuil C, Vrac M, Grennouillet G, Wade AJ, Gevrey M, Oberforff T, Grodwohl J-B, Lek S (2012) Strengthening the link between climate, hydrological and species distribution modeling to assess the impacts of climate change on freshwater biodiversity. Sci Total Environ 424:193–201 [PubMed: 22425276]

Tompkins E, Adger N (2004) Does adaptive management of natural resources enhance resilience to climate change? Ecol Soc 9:10

Troell M, Rönnbäck P, Wennhage H, Söderqvist T, Kautsky (2005) Regime shifts and ecosystem services in Swedish coastal soft bottom habitats: when resilience is undesirable. Ecol Soc 10:30

Truchy A, Angeler DG, Sponseller RA, Johnson RK, McKie BG (2015) Linking biodiversity, ecosystem functioning and services, and ecological resilience: towards an integrated framework for improved management. Adv Ecol Res 53:55–96

Uden DR, Hellman ML, Angeler DG, Allen CR (2014) The role of reserves and anthropogenic habitats for functional connectivity and resilience of ephemeral wetlands. Ecol Appl 24:1569–1582 [PubMed: 29210223]

Unsworth RKF, Collier CJ, Waycott M, Mckenzie LJ, Cullen-Unsworth LC (2015) A framework for the resilience of seagrass ecosystems. Mar Pollut Bull 100:34–46 [PubMed: 26342389]

US EPA (2012) Identifying and Protecting Healthy Watersheds: Concepts, Assessments, and Management Approaches. EPA/841/B-11/002. U.S. Environmental Protection Agency, Washington, DC

van Altena C, Bakker ES, Kuiper JJ, Mooij WM (2016) The impact of bird herbivory on macrophytes and the resilience of the clearwater state in shallow lakes: a model study. Hydrobiologia 777:197–207

van Putten IE, Plaganyi EE, Cvitanovic C, Kelly R, Punt AE, Richards SA (2018) A framework for incorporating sense of place into the management of marine systems. Ecol Soc 23:4

Verdonschot PM, Spears BM, Feld CK, Brucet S, Keizer-Vlek BA, Elliott M, Kernan M, Johnson RK (2013) A comparative review of recovery processes in rivers, lakes, estuarine and coastal waters. Hydrobiologia 704:453–474

Viaroli P, Bartoli M, Giordani G, Naldi M, Orfanidis S, Zaldivar JM (2008) Community shifts, alternative stable states, biogeochemical controls and feedbacks in eutrophic coastal lagoons: a brief overview. Aquat Conserv Mar Freshw Ecosyst 18:S105–S117

Wainger LA, Secor DH, Gurbisz C, Kemp WM, Gilbert PM, Houde ED, RichkusJ BMC (2017) Resilience indicators in support of estuarine ecosystem restoration under climate change. Ecosyst Health Sustain 3:e01268

Waldman J, Wilson KA, Mather M, Snyder NP (2016) A resilience approach can improve anadromous fish restoration. Fisheries 41:116–126

Walker B, Holling CS, Carpenter SR, Kinzig A (2004) Resilience, adaptability and transformability in social–ecological systems. Ecol Soc 9:5

Walker B, Gunderson L, Kinzig A, Folke C, Carpenter S, Schultz L (2006) A handful of heuristics and some propositions for understanding resilience in socio–ecological systems. Ecol Soc 11:13

Walsh CJ, Roy AH, Feminella JW, Cottingham PD, Groffman PM, Morgan RP II (2005) The urban stream syndrome: current knowledge and the search for a cure. J N Am Benthol Soc 24:706–723

Wang HJ, Wang HZ, Liang XM, Wu SK (2014) Total phosphorus thresholds for regime shifts are nearly equal in subtropical and temperate shallow lakes with moderate depths and areas. Freshw Biol 59:1659–1671

Waples RS, Beechie T, Pess GR (2009) Evolutionary history, habitat disturbance regimes, and anthropogenic changes: what do these mean for resilience of Pacific salmon populations? Ecol Soc 14:3

Watson SCL, Grandfield FGC, Herbert RJH, Newton AC (2018) Detecting ecological thresholds and tipping points in the natural capital assets of a protected coastal ecosystem. Estuar Coast Shelf Sci 215:112–123

Waycott M, Duarte CM, Carruthers TJB, Orth RJ, Dennison WC, Olyarnik S, Calladine A, Fourqurean JW, Heck KH Jr, Hughes AR, Kendrick GA, Kenworthy WJ, Short FT, Williams SL (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc Natl Acad Sci U S A 106:12377–12381 [PubMed: 19587236]

Weijerman M, Lindeboom H, Zuur AF (2005) Regime shifts in marine ecosystems of the North Sea and Wadden Sea. Mar Ecol Prog Ser 298:21–39

Weijerman M, Gove JM, Williams ID, Walsh WJ, Minton D, Polovina JJ (2018) Evaluating management strategies to optimise coral reef ecosystem services. J Appl Ecol 55:1823–1833

Wernberg T, Russell BD, Moore PJ, Ling SD, Smale DA, Campbell A, Coleman MA, Steinberg PD, Kendrick GA, Connell SD (2011) Impacts of climate change in a global hotspot for temperate marine biodiversity and ocean warming. J Exp Mar Biol Ecol 400:7–16

Wernberg T, Coleman MA, Bennett S, Thomsen MS, Tuya F, Kelaher BP (2018) Genetic diversity and kelp forest vulnerability to climatic stress. Sci Rep 8:1851 [PubMed: 29382916]

White E, Kaplan D (2017) Restore or retreat? Saltwater intrusion and water management in coastal wetlands. Ecosyst Health Sustain 3:e01258

Wondie A (2018) Ecological conditions and ecosystem services of wetlands in the Lake Tana Area, Ethiopia. Ecohydrol Hydrobiol 18:231–244

Woodhead AJ, Hicks CC, Norström AV, Williams GJ, Graham NAJ (2018) Coral reef ecosystem services in the Anthropocene. Funct Ecol 33:1023–1034

Woodward G, Bonada N, Feeley HB, Giller PS (2015) Resilience of a stream community to extreme climatic events and long-term recovery from a catastrophic flood. Freshw Biol 60:2497–2510

Worm B, Hilborn R, Baum JK, Branch TA, Collie JS, Costello C, Fogarty MJ, Fulton EA, Hutchings JA, Jennings S, Jensen OP, Lotze HK, Mace PM, McClanahan TR, Minto C, Palumbi SR, Parma AM, Ricard D, Rosenberg AA, Watson R, Zeller D (2009) Rebuilding global fisheries. Science 325:578–585 [PubMed: 19644114]

Zedler JB (2017) What's new in adaptive management and restoration of coats and estuaries? Estuaries Coasts 40:1–21

Zeglin LH (2015) Stream microbial diversity in response to environmental changes: review and synthesis of existing research. Front Microbiol 6:454 [PubMed: 26042102]

Zhang J, Jorgensen SE, Beklioglu M, Ince O (2003) Hysteresis in vegetation shift—Lake Morgan prognoses. Ecol Model 164:227–238

Zhang K (2016) Regime shifts and resilience in China's coastal ecosystems. Ambio 45:89–98 [PubMed: 26286204]

Zhao Q, Bai J, Huang L, Gu B, Lu Q (2016) A review of methodologies and success indicators for coastal wetland restoration. Ecol Ind 60:442–452

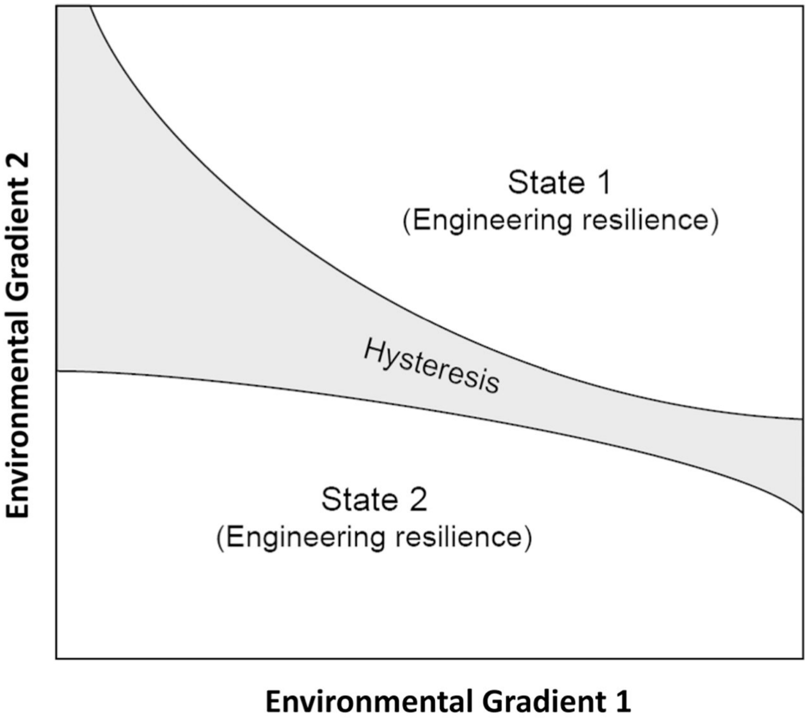

**Fig. 1.**
Model of resilience adapted from Jannsen et al. (2014). Ecological resilience assumes the possibility of multiple ecological states. It is possible to move between these states (regime shifts). Regime shifts can appear to be abrupt and are often characterized by hysteresis, where an ecological trajectory during ecosystem degradation does not match that of ecosystem recovery. This is represented by the grayed area between the two states. Within either state, there may also be disturbance. Engineering resilience focuses on the stability of an ecosystem and the speed it reverts to a steady state condition following disturbance (i.e., within that state). It has been suggested that engineering resilience may provide some insight into its ecological resilience

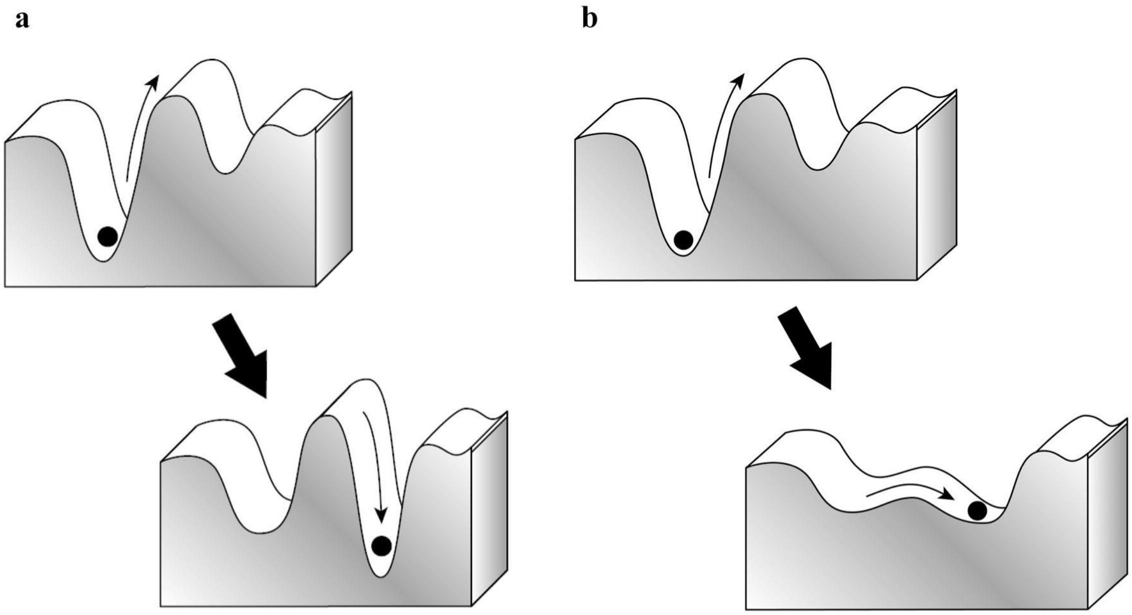

**Fig. 2.**

Schematic of ‘ball and cup’ model of resilience. The ball represents the ecosystem or socioecological state that can exist at any point along the surface of hills and valleys. The valleys indicate different regimes, while the arrows indicate variables impacting the population or community directly (e.g., predator removal, overharvesting or completion). The ball may be nudged up the walls of the valley but remain in its current regime or state with small perturbations. **a** With increasing perturbation (either internal or external; e.g., predator removal, or competition), the ball may be pushed into another valley, altering its state. **b** The landscape itself (environmental conditions) may also change, favoring a new state

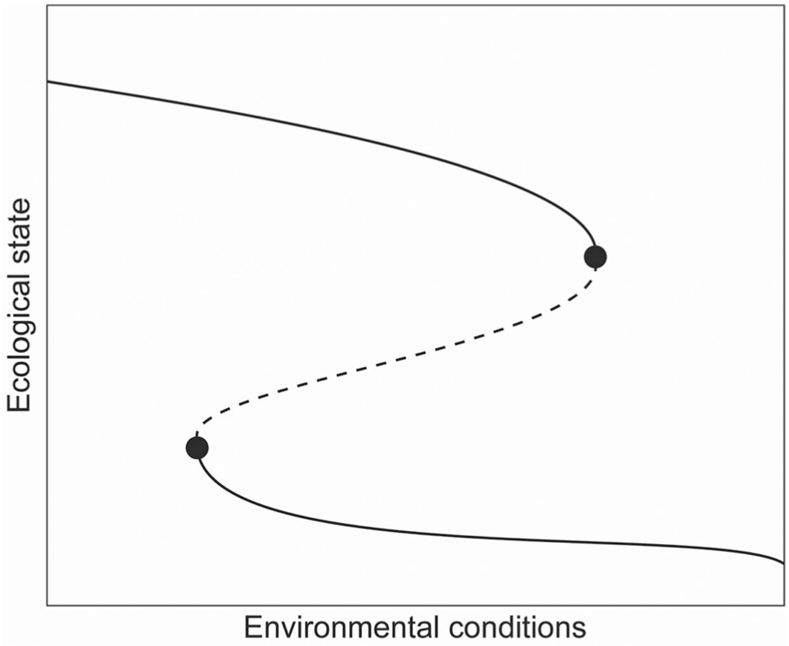

**Fig. 3.**

Conceptual model showing the transition between two states. The solid line indicates a stable state, while the dotted line shows an unstable transition area. The solid dots show thresholds where there can be a sudden transition to a new ecological state

## Table 1

Definition of resilience-related concepts

| Concept | Definition | References |
|---|---|---|
| Alternate stable states | More than one ecosystem condition (state) possible for a particular set of environmental variables. Associated with abrupt shifts in ecosystems, tipping points, and hysteresis | Oliver et al. (2015) |
| Cross-scale resilience | Diverse and overlapping function within scales and redundancy of function across scales | Petersen et al. (1998) |
| Early warning (leading) indicators | Statistical characteristics that allow prediction of a regime shift | Dakos et al. (2012) |
| Ecological threshold ("tipping point") | Point at which there is an abrupt change in ecological state; may be due to a small change or distubance | Groffman et al. (2006) |
| Ecological resilience | Capacity of an ecosystem to absorb and adapt to disturbances while maintaining its essential structure and function and assumes the existence of multiple stable ecosystem states | Holling (1973) |
| Ecosystem services | Direct and indirect benefits provided to humans from ecosystems | Costanza et al. (1997) |
| Engineering resilience | Stability of an ecosystem and the speed it reverts to a steady state condition following disturbance. Only one stable state or regime is assumed | Holling (1996) |
| Functional diversity | Diversity based on species ecological traits (feeding guild, trophic position, etc.) rather than taxonomy | Petchey and Gaston (2006) |
| Functional redundancy | Species or aspects of the socioecological system perform similar roles | Biggs et al. (2012) |
| Hysteresis | Forward trajectory not equivalent to the return trajectory between alternate states | Beisner et al. (2003) |
| Natural capital | Living and non-living components of ecosystems that contribute to people | Guerry et al. (2015) |
| Panarchy | Hierarchical structure of socioecological systems at multiple spatial and temporal scales characterized by adaptive cycles of growth, accumulation, restructuring, and renewal | Holling (2001) |
| Regime shift | Ecosystem threshold is crossed due to due to a sudden change in feedbacks; system trajectory moves towards a different attractor (change to an alternative stable state, e.g., shift from clear to turbid water in shallow lakes) | Folke et al. (2004) |
| Resistance | Capacity of a populations and communities to remain unchanged in the face of disturbance | Angeler and Allen (2016) |
| Response diversity | Within a given functional group, individual species respond differently to environmental stress, which acts to stabilize the ecological system. Diversity in the spatial distribution of species within a functional group may also contribute | Elmqvist et al. (2003) |
| Socioecological resilience | Ability of the coupled social and ecological system to retain similar structure, function and feedback mechanisms; considers the importance of multiple scales (panarchy) | Alberti and Marzluff (2004),<br>Walker et al. (2004) |

## Table 2

Factors affecting resilience

| Direction of Influence | Factor | References |
|---|---|---|
| Decreasing | Increasing stressor loads (e.g., nutrients and contaminants) | Jeppesen et al. (1991), Søndergaard et al. (1992), Peterson et al. (1998), Carpenter et al. (1999), Carpenter (2003), Søndergaard et al. (2003), Munkes (2005), Troell et al. (2005), Howarth and Marino (2006), Scheffer and Jeppesen (2007), Viaroli et al. (2008), Wang et al. (2014), Feio et al. (2015), Johnston et al. 2015, Zeglin (2015), Bush et al. (2017), Moksnes et al. (2018), Moore and Cuker (2018), Watson et al. (2018) |
| | Urbanization | Roy et al. (2003), Small and Nicholls (2003), Morgan and Cushman (2005), Griffiths et al. (2014), Uden et al. (2014), McCauley et al. (2015) |
| | Overharvesting | Jackson et al. (2001), Savenkoff et al. (2007), Lotze and Worm (2009), Lotze et al. (2011), Hamilton and Caselle (2015), Roth et al. (2015), Bozek et al. (2016) |
| | Climatic changes | Scavia et al. (2002), Tompkins and Adger (2004), Palumbi et al. (2008), Bottom et al. (2009), Shanley and Albert (2014), Duarte et al. (2015), Farley and Voinov (2016), Pinceel et al. (2018) |
| | Multiple stressors | Dayton et al. (1998), Estes et al. (1998), Breitberg et al. (2009), Conley et al. (2009), Waycott et al. (2009), Maina et al. (2011), Wernberg et al. (2011), Albins and Hixon (2013), Holdschlag and Ratter (2013), Anthony et al. (2015), Duarte et al. (2015), Kernan (2015), Unsworth et al. (2015), Zhang (2016), Oreska et al. (2017), Orth et al. (2017), Corrales et al. (2018), Ramirez et al. (2018) |
| | Lack of equity (in the socioecological system) | Ostrom (1999), Rhoads et al. (1999), Scheffer et al. (2000), Hagy et al. (2004), Bottom et al. (2009), Worm et al. (2009), Campbell and Butler (2010), Levin and Mollman (2015), Farley and Voinov (2016), Holdschlag and Ratter (2013), Poff et al. (2016), Berkes (2017) |
| Increasing | Connectivity | Detenbeck et al. (1992), Fritz and Dodds (2004), Ray (2005), Carpenter et al. (2006), Elliot et al. (2007), Palumbi et al. (2008), Thrush et al. (2009), Lotze et al. (2011), Olds et al. (2012), Beechie et al. (2013), de Juan et al. (2013), McCluney et al. (2014), Uden et al. (2014), Bogan et al. (2015), Castorani et al. (2015), Duarte et al. (2015), Flotemersh et al. (2016), Cohen et al (2016), Deacon et al. (2018), Terui et al. (2018), Campbell et al. (2019) |
| | Habitat heterogeneity | Penfound (1952), Pearsons et al. (1992), Seabrook and Townsend (1993), Beck et al. (2001), Mumby et al. (2004), Bisson et al. (2009), Euliss et al. (2004), Cicchetti and Greening (2011), US EPA (2012), Hershkovitz and Gasith (2013), Mushet et al. (2013), Mantyka-Pringle et al. (2014), Massicotte et al. (2015), Chretien and Chapman (2016) |
| | Functional redundancy | Doak et al (1998), Peterson et al. (1998), Elmqvist et al. (2003), Carpenter et al. (2006), Nyström (2006), Walker et al. (2006), Allison and Martiny (2008), Levin and Lubchenco (2008), Bottom et al. (2009), Schindler et al. (2010), Carlson and Satterthwaite (2011), Biggs et al. (2012), Hoppe et al. (2017), McWilliam et al. (2018), Angeler et al. (2019) |
| | Diversity | Petersen et al. (1998), Gunderson (2000), Stachowicz et al. (2002), Elmqvist et al. (2003), Bell et al. (2005), Hughes et al. (2005), Nyström (2006), Palumbi et al. (2008), Thrush et al. (2009), Davies et al. (2011), Elliott and Whitfield (2011), Lotze et al. (2011), Magurran and Henderson (2012), Oliver et al. (2015), Strong et al. (2015), Woodward et al. (2015), Angler and Allen (2016), Angeler et al. (2016), Dee et al. (2016), Duffy et al. (2016), Pires et al. (2018), Sundstrom et al. (2018), Thornhill et al. (2018), Wernberg et al. (2018) |
| | Strong linkages between the social and ecological systems | Rhoads et al. (1999), Carpenter et al. (2006), Arnold et al. (2014), McPhearson et al. (2014), Restall and Conrad (2015), Folke et al. (2016), Abson et al. (2017), Reyers et al. (2018), Ives et al. (2018), von Putten et al. (2018), Wondie (2018) |
| Depends upon context | Disturbance | Detenbeck et al. (1992), Peterson et al. (1998), Peterson (2000), Tompkins and Adger (2004), Lepori and Hjerdt (2006), Elliott et al. 2007, Matono et al. (2012), Ledger et al. (2012), Duarte et al. (2015), Ellender and Weyl (2015), Fu et al. (2015), Woodward et al. (2015), Chaffin and Gunderson (2016), Diggelen and Montagna (2016), Gunderson et al. (2017), Rehitha et al. (2017), Timpane-Padgham et al. (2017), Haghkerdar et al. (2018), Milner et al. (2018), Rolls et al. (2018) |
| | Life history characteristics | Pearsons et al. (1992), Bisson et al. (2009), Tisseuil et al. (2012), Ibrahim et al. (2014), Ryan et al. (2014), Chester et al. (2015), Clarke et al. (2015), Kernan (2015), Cullen-Unsworth and Unsworth (2016), Leigh et al. (2016), Sievert et al. (2016), Aspin et al. (2018), Rolls et al. (2018) |
| | Scalar issues | Estes et al. (1998), Scavia et al. (2002), Scheffer and Carpenter (2003), Carpenter et al. (2006), Simenstad et al. (2006), de Yong et al. (2008), Powell et al. (2008), Bottom et al. (2009), Lundquist et al. (2010), Elliott and Whitfield (2011), Lotze et al. (2011), Casini et al. (2012), Ling et al. (2015), Berkes (2017) |