Cell Press REVIEWS

Opinion

Navigating Novelty and Risk in Resilience Management

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Resilience theory is increasingly applied to the management of global change impacts. There is growing concern, however, that misapplications of resilience-based management (RBM) can sometimes lead to undesirable outcomes. We address here an inescapable conundrum in the application of resilience theory: systems will need to track environmental change, but management that aims to support adaptive capacity can introduce undesirable levels of change. We provide a framework that links concepts from novel ecosystems and resilience theory to inform management of ecosystem change. We highlight that resilience-based applications need to address risks associated with novel human impacts to improve management outcomes.

Highlights

Resilience-based management (RBM) has a complex relationship with ecosystem change and novelty.

When RBM is misapplied, undesirable novel ecosystems can emerge.

Some novelty, however, is crucial for long-term resilience.

RBM can be improved by clearly articulating goals and identifying how strategies use change and novelty.

Resilience in Natural Resource Management

Across the globe, ecosystems are experiencing unprecedented changes in environmental conditions [1]. Record-breaking beetle outbreaks in Western North America and widespread coral bleaching have dramatically transformed ecosystems [2]. Such events are often considered harbingers of global change, and many predict we will continue to see major alterations in environmental conditions [2,3]. Developing management approaches that support natural systems in an unpredictable future is therefore becoming an increasingly important challenge.

Resilience theory is gaining international attention in natural resource management as a conceptual foundation to mitigate or guide ecosystem shifts [4] (Figure S1 in the supplemental information online). Resilience thinking, in both the conceptualization and operationalization of ecosystem management, continues to diversify, comprising various informal and formal frameworks including adaptive management [5], ecosystem stewardship [6], resilience-based governance [7], and adaptive resilience-based management [8]. We use the term resilience-based management (RBM) to encompass the diversity of resilience applications in ecosystem management (Figure 1).

Although RBM plans are highly diverse, a unifying theme is a shift away from steady-state approaches to view management in the context of changing environmental and social conditions [6]. One frequently stated goal is to enhance the ability of a system to bounce back from disturbance towards a previously defined, historic state [8]. Manipulating herbivorous fish populations, for example, can facilitate coral reef recovery following bleaching events [9]. RBM approaches can also encourage a system to track environmental change, enabling a transformation into a more resilient state [3,6]. For instance, higher frequencies of megadisturbances in forests threaten many ecosystem services [3,10]. Some RBM approaches advocate facilitating forest transitions to more disturbance-tolerant and climate-adapted forests [3].

As RBM is increasingly applied, there is growing concern that the uncertainties of future global change impacts [11], as well as the ambiguities of resilience theory, can lead to misapplications

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Figure 1. A Conceptual Model of Resilience-Based Management. Depending on the goals, managers can choose to accept or manage change. If management actions are required, different approaches can be applied, including managing drivers of change, enhancing adaptive capacity and/or enabling transformation. The strategies associated with these approaches are overlapping and can be used to achieve multiple outcomes. Strategies focused on enabling transformations embrace higher levels of novelty and more actively shift systems towards novel ecosystems (the examples of strategies are derived from Table 1 and [3,6,9]). Abbreviation: HRV, historical range and variability.

(Table S1 in the supplemental information online). To improve RBM outcomes, we address an important conundrum in the operationalization of resilience theory: systems will need to track environmental change, but management that aims to support this ability to change can also inadvertently lead to undesirable outcomes [11–13]. We describe below the relationship between resilience, ecosystem change, and novelty. We then present a framework that highlights how resilience-based applications differently embrace change and novelty.

Resilience, Ecosystem Change, and Novelty

Ecosystem resilience describes the ability to resist and reorganize in response to a disturbance while retaining similar structure, function, and feedbacks, *sensu* Walker and colleagues [14]. Although resilience and adaptive capacity are closely related terms (some suggest they mean the same thing [15]), adaptive capacity tends to emphasize the flexibility of a system [16] or the ability to adjust to environmental conditions [17]. Thus, strategies that enhance adaptive capacity ultimately lead to long-term resilience. Depending on the interpretation of these terms, resilience and adaptive capacity are differentially applied in natural resource

Glossary

Historic state: an ecosystem state that retains similar structure, function, and composition to an ecosystem state that occurred at some predetermined point in the past (e.g., pre-Anthropocene, AD 1800 [40]).

Hysteresis: two or more contrasting stable states that can exist for a specific environmental condition. Once a transition to a contrasting state occurs, a reversal back to the starting state is difficult and requires different environmental conditions [65].

Non-historical: an ecosystem or elements within an ecosystem that are new to the system; they are not conistent with the historic structure, function, and/or identity of the system.

Undesirable state: a state of an ecosystem that does not provide the target ecosystem services, biodiversity, or fails in other ways to meet management goals.

Vulnerable: susceptible to a state shift; can also be referred to as precariousness, the probability of the system tipping to an alternative state [66].

Table 1. Examples of Resilience-Based Natural Resource Management Recommendations, Plans, and Approaches Focused on Global Change[a]

Document	Date	Agency	Resilience-related goals	Example strategies that mitigate drivers of change	Example strategies that enhance adaptive capacity	Example strategies that can transform systems
Managing Mangroves for Resilience to Climate Change	2006	International Union for Conservation of Nature (IUCN)	'Goals of maintaining biodiversity, promoting ecosystem values, and enhancing resilience'	Manage human stresses on mangroves Protect climate adapted areas	Adaptive strategies that compensate for species range changes Establish greenbelts to allow for migrations	
England Biodiversity Strategy Climate Change Adaptation Principles	2008	United Kingdom Department for Environment, Food and Rural Affairs	'Increasing the resilience of ecosystems to the impacts of climate change, will help ... biodiversity to survive and adapt'	Maintain existing ecological networks Control spread of invasive species	Aid gene flow	Consider the role of species translocation and ex-situ conservation
Vulnerability of Canada's Tree Species to Climate Change and Management Options for Adaptation	2009	Canadian Council of Forest Ministers	'By modifying forest management policies and practices [adaptation] has the potential to reduce vulnerability'			Genetic outposts to hasten forest adaptation Establish forests less vulnerable to climate change
National Park Service Climate Change Response Strategy	2010	U.S. National Parks Service	'Implement adaptation strategies that promote ecosystem resilience and enhance restoration, conservation, and preservation'	Protect refugia	Increase redundancy Increase connectivity	
Australia's Biodiversity Conservation Strategy 2010–2030	2010	Department of Environment and Energy (Australia)	'Australia's biodiversity is healthy and resilient to threats, and valued . . . for its essential contribution'	Address threats to biodiversity	Restore habitat connectivity	*Ex situ* conservation strategies for species that may not be able to survive
Responding to Climate Change in National Forests: A Guidebook for Developing Adaptation Options	2011	United States Forest Service	'Sustainable resource management ... encompasses four management strategies–resistance, resilience, response, and realignment'	Minimize habitat fragmentation Remove roads	Enhance riparian habitats and dispersal corridors	Assisted migration Plant novel species mixes Transition towards more adapted genotypes
Taking Steps toward Marine and Coastal Ecosystem-Based Management – An Introductory Guide	2011	United Nations Environment Programme (UNEP)	'Resilience is the ability to return toward a previous state following a disturbance ... healthy and productive [ecosystems] ... maintain their resilience'	Ensure that forest systems remain healthy Shield against storm surges		
Adaptation to climate change in grassland management	2012	Saskatchewan Research Council	'Create resistance to change ... ; Promote resilience to change . . . ; Enable ecosystems to respond to change (long-term adaptation)'	Reduce stocking rates Increase protected areas Mitigate threats such as exotic invasion	Increase landscape connectivity	Assist northward migration of selected species
European Union Forest Strategy	2013	European Commission	'Maintain, enhance and restore forest ecosystems' resilience and multi-functionality ... providing key environmental services'	Fire prevention Climate change mitigation	Enhance genetic diversity	

Table 1. (continued)

Document	Date	Agency	Resilience-related goals	Example strategies that mitigate drivers of change	Example strategies that enhance adaptive capacity	Example strategies that can transform systems
Adapting to climate change in the Pacific: the PACC programme	2013	The Secretariat of the Pacific Regional Environment Programme and UNDP	'A resilient community [can] quickly respond to and recover ... resulting in a similar or improved state ... strong linkages between resilience and adaptive capacity'	Strengthen early warning systems	Develop crop germplasm banks Risk insurance schemes for risk transfer and risk sharing	
Priority Agenda: Enhancing the Climate Resilience of America's Natural Resources	2014	U.S. Council on Climate Preparedness and Resilience	'Foster climate-resilient lands and waters ... enable species and ecosystems to rebound in the face of great stresses without transforming'	Assess climate impacts on landscapes and habitats Build landscape-scale resilience	Protect habitat areas with redundant linkages Minimize barriers that restrict adaptive movement	
Adapting to a changing climate: A proposed framework for the conservation ... in New Zealand	2014	New Zealand Department of Conservation	'Manage and restore ecosystem function ... maintain and enhance ecosystem resilience'	Increase protected areas Reduce pressures on species from sources other than climate change	Improve replication within protected areas Protect movement corridors, stepping stones and refugia	Translocate species at risk Establish captive populations that would otherwise go extinct
South Australian Murray–Darling Basin Natural Resources Management Plan	2015	Government of South Australia, South Australian Murray–Darling Basin ... Management Board	'Improved condition and resilience of natural systems'	Manage nutrient and salinity levels Minimize impacts of pollutants	Barriers to migration overcome River system connectivity significantly improved	

[a]The table shows resilience-related goals and the associated approaches used to achieve these goals. The approaches reflect the interpretation of resilience and adaptive capacity, as well as the variability in the operationalization of resilience. The suggested strategies are equally diverse, and range from those only focused on managing drivers of change to those embracing more transformative approaches.

management. For instance, some applications focus primarily on building resilience in response to global change [United Nations Environment Programme (UNEP), Table S1], others on adaptation strategies (Canadian Council of Forest Ministers, Table S1), while or both (US Forest Service, Table S1).

Theory advocates that a certain amount of ecosystem change is crucial for tracking environmental shifts because it ultimately enhances the resilience of a species or ecosystem [4,18]. The key to achieving success is to ensure that the elements needed for change are available, such as diversity in nearby patches, redundant hierarchies that support function, dormant elements such as seed-banks, or rare genes in a population [18–20]. If these elements (e.g., genes, species, or functions) were not historically present within the system they are considered to be novel [21]. Some argue that the ability to generate and use novelty is central to the resilience of species and ecosystems [18,19]. In water fleas (*Daphnia*), for example, an increase in genetically derived thermal tolerance, a novel genetic adaptation, enables them to adjust to higher temperatures [22]. Novel species can also assist ecosystem recovery following unprecedented disturbances. For instance, the non-native gorse shrub (*Ulex* spp.) in New Zealand facilitates succession of native species in deforested pastureland by providing more shade and nutrients compared to the denuded landscape [23].

Although ecosystem change and novelty can enhance resilience, they can also be counter-productive by facilitating shifts towards **undesirable states** [11,18,19]. Invasive species in particular are widely recognized for enabling transformations [24,19]. Non-native grasses, for instance, can establish dominance over native species through positive feedbacks that shift nutrient cycling and light availability [25]. Once past a threshold, stabilizing feedbacks can create novel ecosystems, a class of alternative states comprising **non-historical** abiotic and biotic conditions that did not previously exist [25,26]. Depending on the type of transformation, novelty and change can compromise management goals by reducing function or biodiversity [27]. We present a conceptual model of RBM (Figure 1) and suggest there are two fundamental ways to improve the effectiveness of RBM: (i) clearly articulate management goals, and (ii) identify how different management approaches embrace novelty and change. Ultimately, conversations about when and how RBM strategies should build resilience and introduce novelty are crucial for mitigating an undesirable state emergence.

Clearly Articulate Management Goals

Goals define desired outcomes and give direction to management [28]. Goals also reflect human values such as esthetics, spiritual contentment, protection from other organisms, and adequate provisioning of resources [28]. Although effective natural resource management depends upon the clear articulation of goals and values [28], some RBM plans sidestep this stage by embracing generic calls to 'build resilience' or 'support adaptive capacity'. For instance, article 7 of the *Paris Agreement* described the global goal on adaptation as 'enhancing adaptive capacity and resilience' (https://unfccc.int/topics/adaptation-and-resilience/the-big-picture/new-elements-and-dimensions-of-adaptation-under-the-paris-agreement-article-7). Ecosystem resilience and adaptive capacity, however, are characteristics that best accompany other management goals. Some types of resilience help to sustain ecosystem services and biodiversity, while in other circumstances resilience can impede management [29]. Many historically intact, biodiverse reefs, for instance, are very susceptible to global change impacts [30]. By contrast, degraded, weed-dominated reefs can be very resilient owing to their adaptations to multiple stressors [31]. By focusing on generic resilience as the ultimate goal, managers can favor a system that might be in conflict with other values and goals, such as biodiversity conservation [12].

Clearly identifying which system attributes should be resilient can also help managers to address a common concern that resilience is too ambiguous for effective policy application [12,32,33]. As the concept of resilience has evolved, the definition has become increasingly vague and flexible, leading to greater risks to biodiversity [12]. Resilience has been invoked in Europe, for example, to advocate assisted migration, genetic modifications, and introductions of non-native species, actions which can threaten old growth forests and reduce the evolutionary fitness of locally adapted species [34]. Placing greater emphasis on which characteristics of a system should be resilient to different stressors [31,33] can help to guide the selection of strategies, particularly those that enable transformations. Some elements in a system, for instance, might need to change (e.g., species turnover as climate shifts) for target processes to be resilient (e.g., ecosystem productivity). Thus, identifying aspects of the system that enhance resilience and selecting strategies to support these processes can reduce ambiguity and improve RBM outcomes [35].

It is also important to consider all aspects of a system that contribute to resilience [20], and move away from single causation approaches. For instance, identifying the possible tradeoffs that can emerge in the operationalization of resilience can help to mitigate unintended outcomes [36]. Particularly when facing unprecedented mortality events, catastrophic fires, or flooding threats, factors that do not directly build resilience to such events might be overlooked or deprioritized, at times facilitating greater levels of undesirable novelty. Agencies in California, for example, are applying resilience strategies to manage the increasing threats from droughts and megafires. A recent report highlighted 'the need for decisive action to restore California's forests to resiliency' (http://www.lhc.ca.gov/report/fire-mountain-rethinking-forest-management-sierra-nevada). The treatments recommended included forest thinning and prescribed burning, which are known to reduce resistance to invasion of non-native species, including the grass, *Bromus tectorum* [37]. *B. tectorum* can shift the fire regime, reducing fire severity but increasing fire frequency [38]. In chaparral environments, this positive feedback between fire and invasive grasses has enabled a complete type conversion to grass-dominated systems [39]. Thus, long-term ecosystem resilience can be compromised if RBM goals and strategies do not consider the complex causal networks within an ecosystem.

Finally, global change is driving systems away from historical conditions, forcing some level of change in most ecosystems [11,40]. RBM is often motivated by the hope of preventing an undesirable state-shift, while at the same time encouraging ecosystem adaptations that can cope with global change. Conversations around ideal states, as well as acceptable versus inevitable levels of ecosystem change, can help to direct management interventions. RBM management plans for systems **vulnerable** to a state-change, for instance, might be more willing to frame approaches using the language of adaptation and implement strategies that add greater novelty (Box 1). In these circumstances, identifying how these interventions can fail and developing strategies to mitigate such failures can minimize associated dangers.

Identify How Different Management Approaches Embrace Novelty and Change

Managers can select from a variety of approaches when applying RBM (Figure 1). At one end, managers might decide that current or predicted ecosystem changes are acceptable and no intervention is necessary. Even when facing unprecedented shifts in temperatures and disturbance regimes, some systems might be relatively well equipped to cope [41]. The Chihuahuan Desert grasslands, for instance, are surprisingly resilient to pulse perturbations [42], as are one of the largest nesting rookeries of loggerhead sea turtles (*Caretta caretta*) in West Africa [43]. Thus, in more resilient systems, letting nature respond to drivers of change can result in desired outcomes [44]. Managers can also decide to accept the emerging shifts in ecosystems.

Box 1. Enabling Change and Planning for Failure

The *National Fish, Wildlife, and Plants Climate Adaptation Strategy* (USFWS) featured an adaptation strategy in Alaska where local agencies are replanting beetle killed areas with white spruce and non-native lodgepole pines (*Pinus contorta*) [67]. The RBM intervention ideally restores the forest and encourages adaptive capacity. However, by adding novel species into the system, they could be introducing elements that have known risks of being transformative. Lodgepole pines are considered to be an aggressive invasive species in New Zealand (Figure I) that alters native landscapes, negatively impacting farming and tourism industries and reducing water availability [New Zealand Department of Conservation (http://www.doc.govt.nz/nature/pests-and-threats/common-weeds/wilding-conifers/)]. Although lodgepole pines are native to areas in North America, in the absence of transparent discussions of risk tolerance it remains unclear whether migrating lodgepole pine as an adaptation strategy will result in desired outcomes.

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Figure I. Red Trees in the Foreground Are Wilding Pines, Including Invasive Lodgepole Pines (*P. contorta*), Killed by Herbicide in an Attempt To Control Spread Around Lake Pukaki, New Zealand. Photo taken January 2018 by Joan Dudney.

Treeline advance in the arctic, for instance, can alter species diversity and ecosystem function in the tundra, but it might also increase the rate of carbon sequestration in particular areas depending on the level of warming [45]. Acceptance might also be a default, given limited resources and uncertainty surrounding the likely success of interventions.

When managers choose to intervene, RBM often details three approaches to enhance resilience: (i) manage drivers of change, (ii) increase adaptive capacity, or (iii) enable transformation (Figure 1) [4,6]. On-the-ground strategies associated with these approaches are highly diverse and are not necessarily exclusive to RBM because; many were developed under different paradigms, including conservation, restoration, and even steady-state approaches [11]. The focus on ecosystem change demands not only that new strategies are developed [41,46] but also that they balance the need for adaptation with the possible emergence of undesirable outcomes. Introducing climate-adapted, novel ecosystem engineers into a system, for instance, can be more risky than adding novel, subordinate species because engineers are more likely to facilitate ecosystem transformations [19]. We highlight below how three commonly used RBM approaches represent dramatically different relationships towards risk tolerance and the need for bold measures in the face of unprecedented change (please refer to Figure 2). Few agencies using RBM are explicitly drawing links between their strategies,

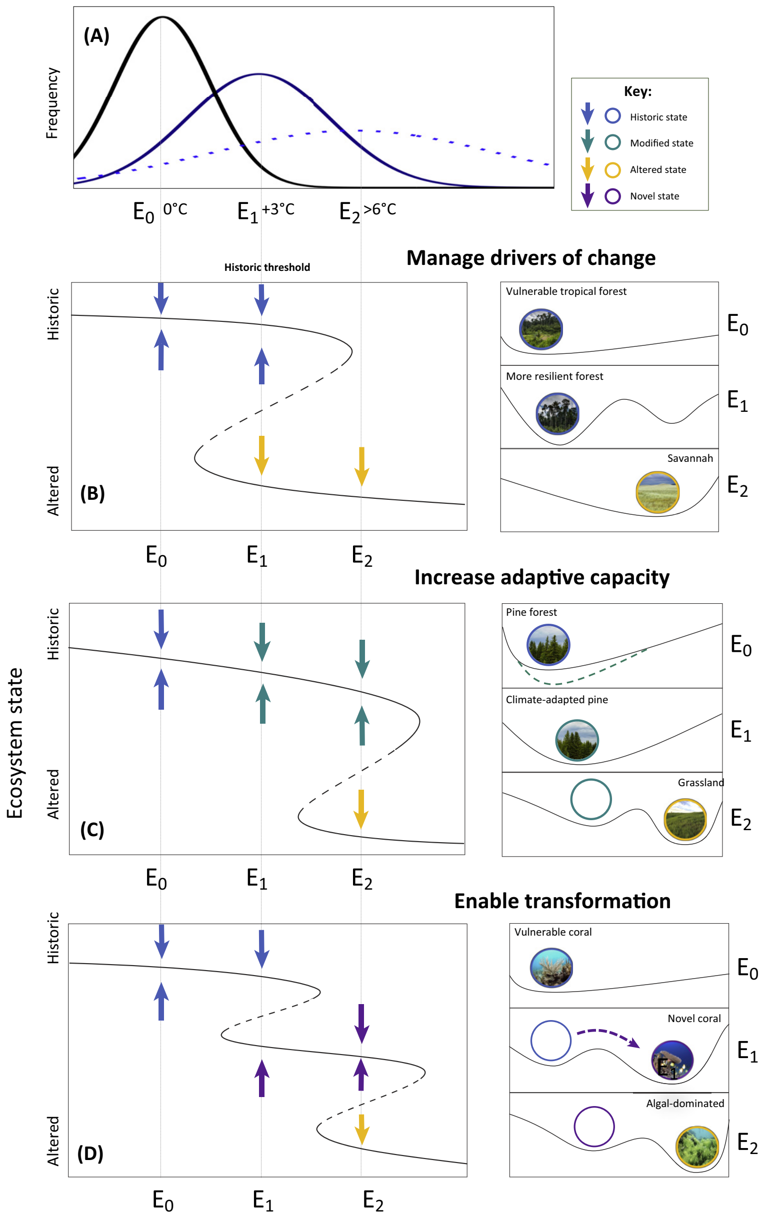

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Figure 2. Options and Outcomes of Resilience-Based Management (RBM). Against the backdrop of directional change in an environmental condition, such as temperature (panel A: E_0, E_1, E_2), we present three scenarios with different management approaches: (B) manage drivers of change, (C) increase adaptive capacity, and (D) enable transformation. While we use hystereis diagrams to illustrate the three scenarios B–D, we acknowledge that there are other types of ecosystem dynamics. To the right of the main panels B–D, ball and cup diagrams illustrate the ecosystem states corresponding to the bisection of the **hysteresis** diagram associated with environmental conditions E_0–E_2. Broken lines show the direction of management. Broken lines show direction of RBM. Specifically, if drivers of change can be mitigated, then the system can persist beyond the historic threshold (B:E_1). By contrast, if the rate of environmental change overwhelms existing resilience, then increases in adaptive capacity are necessary to sustain the historic state (C). Particularly if novelty is added or naturally generated within the system, the historic identity and functions are altered. The novelty widens the basin of attraction and shifts the system towards a modified state (C:E_1) that does not, however, constitute a state-change (C:E_2). In more extreme cases -where a shift is inevitable (D), managers might consider actions to guide a beneficial shift to a novel ecosystem (D:E_1) that is able to maintain more functions or services than the highly altered state (D:E_2).

expected outcomes, and associated risks. By drawing these connections, surprise outcomes can be reduced.

Manage Drivers of Change

In some cases, multiple drivers of change reduce the resilience of a system. Focusing on the drivers that are manageable, typically those occurring at local or regional scales, can increase resilience to drivers of change at broader scales (Figure 2B). For example, interactions between land use, fire, and climate change raise the possibility of a state-change in large regions of the Amazon, shifting the forested state to a savannah-like grassland [47]. The imminent state-shift is supported by theory [48], model experiments [49], and field-based evidence [50]. To reduce the likelihood of a state-shift, managers can mitigate local anthropogenic impacts, in this case deforestation and fire frequency, to increase the resilience of the Amazon system to climate change [47,49,51]. Managing local threats can therefore help to constrain ecosystem shifts of a system. Relying upon the ability of a system to naturally adapt to global threats also avoids active manipulation of the system and reduces the likelihood of undesirable novelty emerging in response to management interventions.

Increase Adaptive Capacity

Common strategies to increase adaptive capacity include: (i) encouraging characteristics that organically give rise to adaptation, or (ii) actively introducing adaptive elements into the system (Figure 2C). The US Government *Priority Agenda for Enhancing Climate Resilience of America's Natural Resources* (https://obamawhitehouse.archives.gov/sites/default/files/docs/enhancing_climate_resilience_of_americas_natural_resources.pdf), for example, suggests protecting system properties that foster resilience by increasing species diversity, pathways for movement and migration, and topographic and climate gradients. Because these strategies facilitate processes that increase natural adaptive capacity (e.g., species turnover, dispersal, local adaptation), success can be achieved without directly introducing novelty into the system.

By contrast, when the natural processes that enable adaptive capacity cannot keep pace with shifting environmental conditions, interventions can encourage the ability of a system to track change. RBM strategies can directly introduce novel elements into a system that both increase the adaptive capacity and modify the historic identity and function of the state. For example, forest pests and pathogens can be more adapted to warming temperatures than their hosts and cause extensive tree mortality [52,53]. The introduction of appropriate biocontrols [54] to constrain pest population growth or planting climate-adapted genotypes [55] are possible management strategies that could help to prevent undesirable forest shifts. While these interventions can modify trophic interactions and the genetic composition of the forest they can ultimately help to sustain much of the historic structure and function of the state. Such RBM approaches that actively introduce novelty, however, are dependent on clear definitions of the type of resilience being managed for, as well what type of change is acceptable (e.g., only native species).

Enable Transformation

In some cases, environmental conditions could change to such an extent that the system can no longer support the historic identity and function (Figure 2D). Managers can decide if interventions to preserve desired system characteristics, such as specific ecosystem services or native species, are worth the risks. For example, recent studies suggest that some plants will not be able to keep pace with changing climatic conditions [56–58]. To prevent an undesirable state-shift or species extirpation, managers can translocate a dispersal-limited species [59,60] or enable a shift to a novel forest that sustains desirable characteristics and functions [3,61].

Similarly, introducing stress-tolerant corals, breeding heat-tolerant dinoflagellate communities, or hybridizing corals [30,62] to increase the resilience of **vulnerable** reefs might lead to the emergence of desirable novel ecosystems (Figure 2D, E_1). Such strategies typically embrace greater levels of novelty in ecosystems [11], and are associated with risks of unintended outcomes as a result of the management intervention itself [11]. Risk–benefit analyses and plans for failure, including reduced diversity or increased vulnerability to disease [63,64], are therefore necessary to improve management outcomes.

Concluding Remarks

Resilience theory is a helpful tool to guide management of dynamic and often unpredictable systems. However, given the ambiguities of resilience, the uncertainties of future global change impacts, and the capricious human behavior that drives global change, a tremendous amount of humility is required in RBM applications (see Outstanding Questions). Because RBM approaches have dramatically different relationships with change and novelty, greater specificity is needed in goal-setting that clearly aligns with underlying values. RBM should also foresee risks that management itself can lead to undesirable outcomes. By drawing direct links between RBM interventions and novelty, management strategies can be improved.

Outstanding Questions

How will differences in recovery time across ecosystems reduce the efficacy of RBM applications?

What guidelines can help managers to interpret the disirability of an ecosystem shift that results in an altered, more climate-adapted system?

How will climate change shift the structure and function of alternative stable states?

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Appendix A Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.tree.2018.08.012.

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