

Frontiers in Ecology and the Environment

Management of novel ecosystems: are novel approaches required?

Timothy R Seastedt, Richard J Hobbs, and Katharine N Suding

Front Ecol Environ 2008; 6, doi:10.1890/070046

This article is citable (as shown above) and is released from embargo once it is posted to the *Frontiers e-View* site (www.frontiersinecology.org).

Please note: This article was downloaded from *Frontiers e-View*, a service that publishes fully edited and formatted manuscripts before they appear in print in *Frontiers in Ecology and the Environment*. Readers are strongly advised to check the final print version in case any changes have been made.



Management of novel ecosystems: are novel approaches required?

Timothy R Seastedt^{1*}, Richard J Hobbs², and Katharine N Suding³

Most ecosystems are now sufficiently altered in structure and function to qualify as novel systems, and this recognition should be the starting point for ecosystem management efforts. Under the emerging biogeochemical configurations, management activities are experiments, blurring the line between basic and applied research. Responses to specific management manipulations are context specific, influenced by the current status or structure of the system, and this necessitates reference areas for management or restoration activities. Attempts to return systems to within their historical range of biotic and abiotic characteristics and processes may not be possible, and management activities directed at removing undesirable features of novel ecosystems may perpetuate or create such ecosystems. Management actions should attempt to maintain genetic and species diversity and encourage the biogeochemical characteristics that favor desirable species. Few resources currently exist to support the addition of proactive measures and rigorous experimental designs to current management activities. The necessary changes will not occur without strong input from stakeholders and policy makers, so rapid information transfer and proactive research–management activities by the scientific community are needed.

Front Ecol Environ 2008; 6, doi:10.1890/070046

In this era, historically authentic, co-evolved biotic assemblages are increasingly rare; instead, we are confronted with a greater incidence of native and introduced species living under new environmental conditions and new or altered disturbance regimes (Suding *et al.* 2004; Hobbs *et al.* 2006; Figure 1). Chapin and Starfield (1997) use the term “novel ecosystem” to recognize the response of the boreal forest to current and anticipated climatic changes. In an attempt to address sustainability issues for Alaskan forests, Chapin *et al.* (2006) proposed four broad policy strategies: (1) enhance human adaptability, (2) increase ecosystem resilience by strengthening negative

feedbacks and increasing options for adaptation, (3) advocate human activities to reduce climate change, and (4) facilitate transformation to new, potentially more beneficial ecosystem conditions. We believe that similar activities are warranted across the globe; here, we explore some of the management considerations required to increase ecosystem resilience and promote desirable outcomes.

In theory, adaptive ecosystem management offers tools and procedures for enhancing the resilience of desired states and facilitating transformations from undesirable states. However, such proactive responses are the exception to what is, in our opinion, a more common, reactionary approach to addressing the rapid transformation of landscapes. In arguing that systems are in novel states, we recognize that what constitutes an acceptable course of action remains open for scientific debate. Here, we provide several examples of “desirable” novel ecosystems and offer suggestions about management actions, recognizing that these are neither complete nor universally applicable.

In a nutshell:

- Novel ecosystems composed of new combinations of species under new abiotic conditions are increasingly common, and adaptive ecosystem management approaches must explicitly acknowledge the current status and predict the future conditions of these systems
- Old styles of management, which focused on removing undesirable species or conditions from ecosystems to return them to a prior condition, may no longer be sufficient
- We need to consider, and experiment with, novel approaches to ecosystem management that focus on desired outcomes or trajectories, rather than simply taking preventative or therapeutic measures

Theoretical underpinnings of novel ecosystems

The overarching theoretical framework for understanding novel ecosystems, as well as a compelling argument for an adaptive management stance, comes from the “panarchy paradigm” developed by Holling and colleagues (eg Gunderson and Holling 2001; Holling 2001). This synthesis of ecosystem and hierarchy theories takes account of the fact that, over time, ecosystems pass through different states with different characteristics, and that some stages are much more vulnerable and less

¹Department of Ecology and Evolutionary Biology and INSTAAR, University of Colorado, Boulder CO 80309 * (timothy.seastedt@colorado.edu); ²School of Environmental Science, Murdoch University, Murdoch, West Australia 6150, Australia; ³Ecology and Evolutionary Biology, University of California–Irvine, Irvine, CA 92697



Courtesy of T. Vablen

Figure 1. Extensive beetle damage in forests is a natural phenomenon, but is now occurring at unprecedented spatial scales. Post-beetle kill recovery of these areas will produce novel ecosystems, influenced by new climates and new biota.

resilient to change. When a disturbance affects a system in a sensitive state, restructuring occurs; the extent of this restructuring is influenced both by the state of the system and the spatial scale at which the disturbance occurs. Historically, these interactions produced sustainable cycles. However, in the era of new climates, new and modified chemical inputs, and new species, disturbances function as mechanisms for the generation of novel ecosystems, involving whatever abiotic and biotic materials are at hand. Holling (2001) concluded his overview by stating that “the era of ecosystem management via incremental increases in efficiency is over. We are now in an era of transformation, in which ecosystem management must build and maintain ecological resilience, as well as the social flexibility needed to cope, innovate, and adapt.”

Panarchy theory does not provide a road map for policy makers and managers, who have specific wants and needs. Other compatible and more intuitive conceptual models can be nested within the panarchy framework to help explain the novel ecosystem concept and provide additional focus. Landres *et al.* (1999) emphasize the importance of the magnitude and frequency of disturbance variables that drive the state and cycles of ecosystems. Managers understand that ecosystems are greatly influenced by fire, flood, disease outbreaks, and other disturbances, and many recognize the importance of these in determining ecosystem structure. Landres *et al.* (1999) defined the historical range of variability of ecosystems as “the ecological conditions, and the spatial and temporal variation in these conditions, that are relatively unaffected by people, within a period of time and geographical area appropriate to an expressed goal”. This goal is often the characterization of the current state of the ecosystem and landscape mosaic in terms of its biotic diversity and functional characteristics. The historical range of variability

(HRV) characterizes ecosystems at defined spatial and temporal scales. Landres *et al.* (1999) recognized that some human activities were a part of such systems, but, in the past few centuries and particularly in the past few decades, human activities and indirect effects resulting from these activities have shifted what we consider to be natural ecosystems outside of their historical range of variability.

■ An era of increasingly rapid change

The overwhelming majority of environmental scientists agree that biotic change will dominate the 21st century (MA 2005), producing both novel climates (Williams *et al.* 2007) and “no-analog futures” (Fox 2007). Our ability to respond to this change remains limited.

The compartmentalized nature of our educational systems and the reductionist approach to experimentation contribute to a deleterious lag time between acquisition of scientific knowledge and its use in management applications. Current environmental problems, often resulting from past mistakes (eg failure to control invasives before they became regional problems, failure to maintain fuel loads to mimic natural fire conditions) are consuming the time and budgets of managers, so that proactive management strategies to deal with emerging problems are relatively rare and certainly underfunded (Hobbs *et al.* 2003). Managers attempt to achieve success in management activities, but what constitutes success?

Factors that move terrestrial ecosystems outside of their historical range of variability include CO₂ and atmospheric nitrogen enrichment, altered disturbance regimes, climate change, invasions, local or global extinctions (particularly of keystone species or ecosystem engineers), and fragmentation effects. The historical ecosystem, as identified by the theoretical framework discussed above, possesses a range of biotic and abiotic characteristics (Figure 2). Directional shifts caused by climate change, fire suppression, enhanced CO₂, or atmospheric nitrogen deposition push the system outside of its historical range of geochemical conditions. Species additions or subtractions move the system to a new configuration. With changes in biotic composition, measurable changes in geochemical processes are also likely (eg Ehrenfeld 2003). Similarly, once a system has been removed from its historical range of variation due to abiotic changes, subsequent changes in species composition and biogeochemical cycling are almost certain. The causal mechanisms for change can be either biotic or abiotic in origin, but the outcome may be very similar.

In managing novel ecosystems, the point is not to think outside the box, but to recognize that the box itself has moved, and in the 21st century, will continue to

move more and more rapidly (Harris *et al.* 2006). While we can usually predict the impact of individual drivers on local ecosystems, the impacts of combinations of these changes, at varying levels of intensity across the globe, generate a lot of uncertainty. This presents a conundrum for managers and necessitates a more active partnership with researchers who are now engaged in attempts to measure impacts of complex changes on ecosystems. There is a compelling need to adopt a more dynamic framework that explicitly acknowledges and embraces change as a fundamental process that occurs in all ecological systems. Scientists must initiate and maintain dialogues with managers and policy makers, given that the ecosystems they manage have already been altered in ways that predispose them to further change and reduced resilience. Management activities should not only anticipate change, but should acknowledge that current systems have already been transformed and are in the process of transforming further.

■ Implications for management

Classical management of natural ecosystems often involves maintaining the system within the historical range of variability of abiotic and biotic drivers. Even in those ecosystems that have not experienced direct human alterations, the “indirect effects” of climate change, atmospheric chemistry changes, and introduced species have affected or will shortly transfigure these systems. Thus, traditional approaches may prove to be unproductive; HRV conditions no longer exist and attempts to restore such conditions are no longer management options.

Chapin *et al.*'s (2006) study of changes in the boreal forest provides a model system relevant to most terrestrial systems experiencing climate warming. This study is also relevant to those systems that are fire prone or have fire suppression issues. In the western US, many forests are currently in the process of being transformed by catastrophic fires or large-scale insect outbreaks, while smaller areas are the subject of novel thinning approaches, with the aim of preventing such disturbances (Noss *et al.* 2006 a,b). All of these developments, in conjunction with fragmentation and road activity, facilitate the spread of non-native plant species (Rumbaitis del Rio 2006). In those forests not altered by fire suppression, historical logging and agricultural activities still affect the structure (Baker *et al.* 2007) and function (McLauchian *et al.* 2007) of these systems. In tropical or more humid forested ecosystems, landscape change, invasive species

(including all trophic components: trees, defoliating insects, earthworms, and pathogens), and wholesale reductions in species and genetic diversity have led to important sustainability issues. While examples of adaptive forest ecosystem management exist (eg Bormann *et al.* 2007), the amount of research, education, and outreach required to mitigate climate change alone (eg Chapin *et al.* 2006) suggests that there are too many problems confronting too few managers with too few resources.

Invasive species are likely to have an increasingly important role in grassland dynamics. While invasive species can be quantified as drivers or “passengers” of change in communities (MacDougal and Turkington 2005), we suggest that these species are also passengers and drivers in novel ecosystems. Major economic and ecological damage has been inflicted by invasive species in grasslands and rangelands, and expenditures to control these species with herbicides or other proactive management techniques are also substantial. However, when the management focus is only on the invader, native species or even desirable non-native species may not necessarily be beneficiaries of management strategies. For instance, in southern California grasslands that have been previously overgrazed, control of a particularly problematic invader, artichoke thistle (*Cynara cardunculus*), may only be a first step in restoration once the native component has been almost completely removed (Figure 3). Within the next few years, millions of hectares of rangeland in the US that are dominated by several species of invasive knapweeds (*Centaurea* spp) will probably be replaced by new dominant plant species, as the knapweeds are reduced in density by biological control agents (Story *et al.* 2006; Seastedt *et al.* 2007). The few studies that have

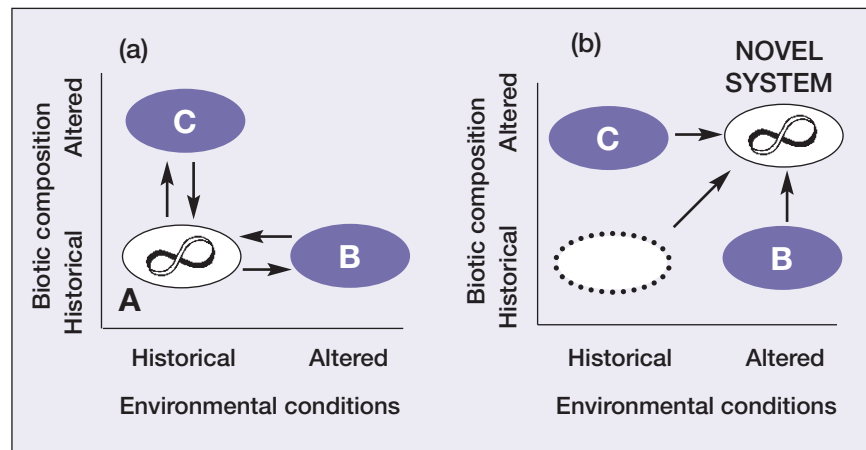


Figure 2. Creation of novel ecosystems via biotic or abiotic change (modified from Suding *et al.* 2004). The “range of variability”, as discussed by Landes *et al.* (1999), and the adaptive four-phase cycle of Holling (2001) of a natural ecosystem are collapsed into the range of values found in zone A. (a) An ecosystem is altered by directional environmental drivers ($A \rightarrow B$) or the addition or loss of an important species ($A \rightarrow C$). (b) Once in the new state (either B or C), internal restructuring due to new biotic and abiotic interactions further alters community composition through changes in abundances or species losses, and through changes in biogeochemical interactions.

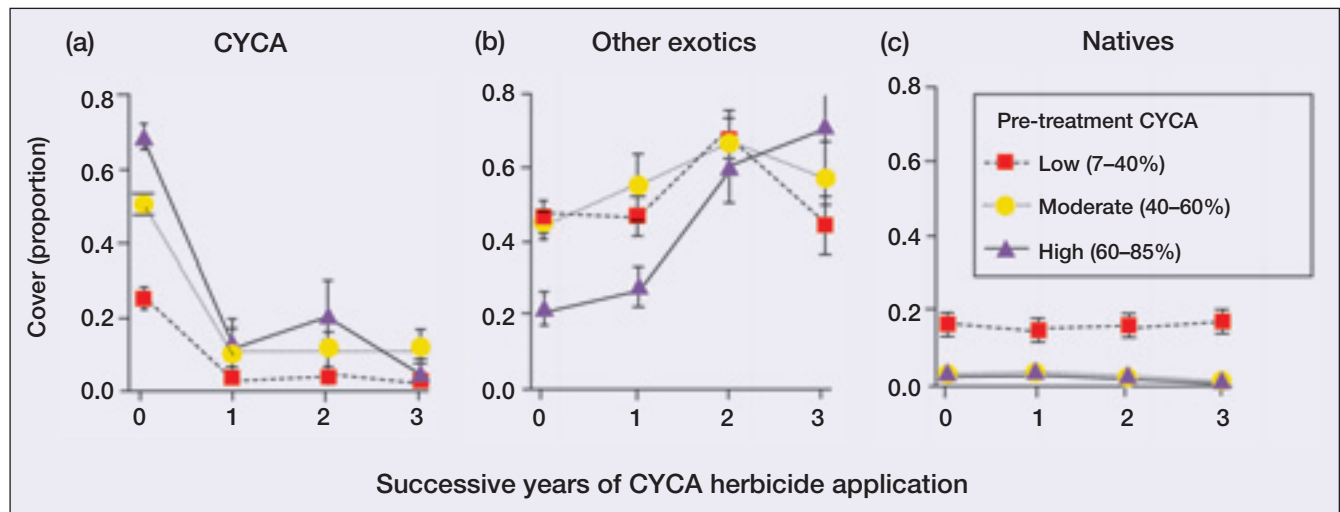


Figure 3. Cover (mean, SE) of (a) artichoke thistle (CYCA), (b) other exotic species, and (c) native species, prior to initiating herbicide treatments (at $t = 0$) and after 1, 2, and 3 years of successive treatment. Sites were grouped by the degree of pretreatment invasion of artichoke thistle. Sample size ranged from 30 sites (pre-treatment and year 1) to 15 (year 3). At sites that were initially highly invaded, with little native cover (triangles), control of the focal exotic has led to increases in other exotics. However, at sites with a lower level of invasion and higher initial abundance of natives (squares), other exotics did not increase. In addition, recruitment of the native bunchgrass appears to be increasing at these sites (results not shown). Data courtesy of the Nature Reserve of Orange County and The Nature Conservancy.

monitored vegetation response to these declines suggest that other non-native species will increase in abundance as a result of the demise of the *Centaurea* spp (Denslow and D'Antonio 2005; Bush *et al.* 2007; Figure 4).

■ Managing under no-analog conditions

In the past, managers have attempted to eliminate processes or components that did not fit the general perception of a desirable system. With these new challenges, managers must re-examine their perceptions and develop management strategies to promote ecosystems that are both feasible and resilient. As indicated in Figure 2 and by an increasing number of examples, removing unwanted species, or the consequences of unwanted species (such as high fuel loads or high nutrient loading from human activities), will not necessarily restore the ecosystem to its historical state and may not move the system to a desirable, new state. While climate change may impose limitations on our ability to restore the biogeochemical configuration of ecosystems, reversing or negating trends caused by other directional drivers is possible. If changes produce geochemical conditions that cannot be reversed without unacceptable cost, stakeholders must select from among those management activities that can enhance resilience and provide the biotic structure and ecosystem services they are willing to accept and support.

While emphasizing that “one size does not fit all”, resource managers must either find species capable of persisting in spite of these directional shifts, or must identify mechanisms that can provide sufficient resilience to allow for the persistence of desired species in the face of these changes. Here, we present an example of a non-tra-

ditional management strategy that has maintained a relict, desirable native community despite the absence of a key driver, and of a novel grassland generated by a less-than-traditional restoration effort. These examples demonstrate that biotic and abiotic manipulations can be used to generate “what we want” under conditions outside the HRV of the pre-existing systems.

Maintaining a relict tallgrass prairie without frequent fire

At the base of the Front Range of Colorado, a relict tallgrass prairie composed of thick stands of big bluestem, switchgrass, and Indian grass can be found on portions of land owned and managed by the city of Boulder. These species generally require 800 mm of precipitation per year to maintain dominance, yet, at this site, they persist in an area that receives about 500 mm of precipitation. This grassland is arguably the rarest terrestrial ecosystem type in Colorado. The fire return interval for this region was estimated at one fire every 7–12 years (Veblen *et al.* 2000), and fire is viewed as essential to the maintenance of this type of grassland (eg Knapp *et al.* 1998). These systems are also vulnerable to almost all of the previously discussed drivers of environmental change.

Burning portions of this area is now considered unacceptable due to an adjacent highway. For more than 20 years, a bottomland tallgrass site has been maintained by short-duration, intensive spring grazing by cattle. The animals seek out and consume whatever is green on these sites and avoid eating the standing dead material from the warm-season grasses. Importantly, such green plants include numerous non-native species, including Canada

thistle, and a number of cool-season grasses. The cattle heavily graze the cool-season plants and trample the previous year's standing dead vegetation, exposing the soil surface to sunlight. Following the removal of the animals in late May, the trampling allows for the rapid emergence of warm-season grasses into full sunlight. These species then dominate the water, light, and nutrient resources of the site. While fecal material and urine from the cattle increase plant-available nitrogen, the timing of the fertilization activity produces a lush stand of tallgrass species instead of stimulating more nitrogen-demanding cool-season grasses or weedy species. To date, this unconventional management approach has sustained the tallgrass species, in marked contrast to traditional effects of grazing on tallgrass prairie (eg Towne *et al.* 2005), where year-round or growing-season grazing activity reduces the abundance of these plant species.

Revegetating a gravel pit

Near the area discussed above, gravel was mined from a ~ 100 hectare bottomland site (originally a relict tallgrass area) for over 40 years. State regulations required that the site be revegetated, and rocks from construction sites were used to refill the excavations. The topsoil removed from the site prior to the extraction of gravel was used in this revegetation. The fact that much of this soil had been stockpiled for an unknown interval meant that what was returned and spread over the surface was very different from what had originally been removed. Measurements of organic matter and organic nitrogen indicated that the soils on the revegetated site were more characteristic of arid shortgrass steppe than of a mesic, bottomland tallgrass prairie (Cherwin *et al.* in press).

Only native grasses were seeded onto this site in 1998. Following the seeding, the area experienced a relatively wet year (128% of the 30-year average), while the next 3 years brought 79%, 90%, and 69% of average precipitation, respectively. Foliage production in this area was severely limited during this 3-year drought. Low organic matter soils and low precipitation during the early stages of grass recovery would have doomed a restoration effort focused at rebuilding a tallgrass prairie. However, the seed mixture used nine grass species whose moisture demands spanned a 500-mm rainfall gradient. The plant community that emerged (Figure 5) was dominated by a warm-season plant, salt sacaton (*Sporobolus airoides*), a species usually abundant only in alkaline or dry saline soils. To our knowledge, no such soils occur naturally in this area. Salt sacaton was solely responsible for about half of the vegetation cover. Other warm-season grasses common in mixed-grass and shortgrass steppe provided another 25%



Figure 4. Effects of invasive plant removal without re-seeding. Spotted knapweed, the purple flowered plant on the left, has been replaced by Dalmatian toadflax, the yellow flowered plant on the right. The right side of the field had been treated with herbicides.

of relative vegetation cover. Particularly remarkable was the fact that planted species constituted over 90% of the vegetation cover and the site appeared largely resistant to invasions by other native and non-native plants (Cherwin *et al.* in press).

This successful revegetation effort resulted from the selection of a seed source containing representatives of short-, mixed-, and tallgrass species. Had the original soils been in place and had precipitation been adequate, a prairie dominated by tallgrass species might have emerged. Instead, the resulting vegetation is dominated by mixed-grass prairie species capable of surviving a 3-year drought. The diverse seed mix used by the revegetation team interacted with the climate conditions and unusual soil characteristics to select the community type and produced an impressive, albeit novel, grassland community.

■ The bottom line

In the first example above, managers used a spring-only grazing regime to maintain a tallgrass relict without frequent fire. In the second example, a low-budget soil and a creative seed mix produced a native grassland that contained a “new” dominant plant species, and was largely devoid of invasive species. This grassland will now provide locally important ecosystem services, such as enhancement of water quality in an adjacent stream. In addition, carbon and nitrogen will be sequestered as these soils increase in carbon and nitrogen content, and the area could be used as a platform for desired species introductions, especially those that favor a low nitrogen environment. These successes involved recognition of the



Figure 5. Revegetation site (foreground). What was a tallgrass prairie until the 1950s and then a gravel pit until the mid 1990s is now a mixed-grass prairie.

fact that traditional management approaches could not be used and/or were not likely to achieve management goals. In the first example, we have a novel management approach maintaining a highly desirable relict system which appears capable of persisting outside its HRV, and in the second example, the managers used an “uncertain climate seed mix” to generate a novel ecosystem that appears to be both drought and weed resistant.

Under novel conditions, all management activities represent experiments, and more proactive scientist–manager collaborations are needed to develop procedures for achieving management goals for these systems (Landres *et al.* 1999). Our interactions with managers have revealed that this group is already besieged by environmental problems. Monitoring, the cornerstone of ecosystem management, has yet to achieve its true level of importance. Furthermore, managers need protection from the public and policy makers, who are quick to condemn when activities designed to produce long-term results do not produce short-term benefits. Scientists provide an appropriate interface between stakeholders and managers, and function as educators for both groups.

The recognition that novel ecosystems require novel management approaches and goals does not imply that “anything goes”. Our conclusions could be interpreted as espousing a free-for-all of outlandish, stab-in-the-dark approaches in order to achieve desired conditions, without due consideration of the probable consequences. Clearly, this is not our intent. However, we must consider how to tackle this new and rapidly changing situation. Outlandish approaches are more likely to be adopted if we ignore the problem than if we engage in open debate about it. We would be foolish to suggest that there are simple answers.

A search for general rules that can be used to manage novel ecosystems is likely to be a long and possibly unpro-

ductive exercise. A logical approach would be to maximize genetic, species, and functional diversity wherever possible, to increase the viability of communities and ecosystems under uncertain climate regimes. Monitoring responses to any action, or lack of action, remains the key activity. In the above examples, management actions produced what were perceived as desirable outcomes by manipulating mechanisms that enhanced desirable system components, rather than by removing or suppressing undesirable species. Although this statement may appear obvious to ecologists, it has not necessarily been translated into the activities that currently dominate the time and financial budgets of land managers. In addition to enhanced monitoring, attention to a rigorous “experimental” design, including reference areas wherever possible, is appropriate if not essential to a defensible, informative, and publicly acceptable management program for novel systems. Awareness among stakeholders, policy makers, and managers of the realities of current and future ecosystem changes is essential to generate management strategies that have positive rather than neutral or negative outcomes. The participation of ecologists in adaptive management activities has been advocated for over a decade (eg Christensen *et al.* 1996), but this call to action deserves to be re-emphasized due to the complexities and urgency of global environmental changes affecting the structure and function of ecosystems. If we are to effectively manage existing and potentially novel ecosystems, we need to put some serious thought into what the goals and approaches should be.

Acknowledgements

We thank T Veblen and N Breiter for use of their photographs. L Riedel provided input on City of Boulder management activities. We thank N Breiter, V Cramer, and K Cherwin for reviewing an earlier draft of this manuscript.

References

- Baker WL, Veblen TT, and Sherriff RL. 2007. Fire, fuels and restoration of ponderosa–Douglas fir forests in the Rocky Mountains, USA. *J Biogeogr* **34**: 251–69.
- Bormann BT, Haynes RW, and Martin JR. 2007. Adaptive management of forest ecosystems: did some rubber hit the road? *BioScience* **57**: 186–91.
- Bush RT, Seastedt TR, and Buckner D. 2007. Plant community dynamics in response to the decline of a dominant invasive plant, *Centaurea diffusa*, in a Colorado grassland. *Ecol Restor* **25**: 169–74.
- Chapin III FS and Starfield AM. 1997. Time lags and novel ecosystems in response to transient climate change in Arctic Alaska. *Climatic Change* **35**: 449–61.

- Chapin III FS, Lovcraft AL, Zavaleta ES, *et al.* 2006. Policy strategies to address sustainability of Alaskan boreal forests in response to a directionally changing climate. *P Natl Acad Sci USA* **103**: 16637–43.
- Cherwin KL, Seastedt TR, and Suding KN. Effects of nutrient manipulations and grass removal on cover, species composition, and invasibility of an adventive grassland in Colorado. *Restor Ecol.* In press.
- Christensen NL, Bartuska AM, Brown JH, *et al.* 1996. The report of the Ecological Society of America committee on the scientific basis for ecosystem management. *Ecol Appl* **6**: 665–91.
- Denslow JS and D'Antonio CM. 2005. After biocontrol: assessing indirect effects of insect releases. *Biol Control* **35**: 307–18.
- Fox D. 2007. Back to the no-analog future? *Science* **316**: 823–25.
- Ehrenfeld JG. 2003. Effects of exotic plant invasions on soil nutrient cycling processes. *Ecosystems* **6**: 503–33.
- Gunderson L and Holling CS (Eds). 2001. Panarchy: understanding transformations in human and natural ecosystems. Washington, DC: Island Press.
- Harris JA, Hobbs RJ, Higgs E, and Aronson J. 2006. Ecological restoration and global climate change. *Restor Ecol* **14**: 170–76.
- Hobbs RJ, Cramer VA, and Kristjanson LJ. 2003. What happens if we can't fix it? Triage, palliative care, and setting priorities in salinising landscapes. *Aust J Botany* **51**: 647–53.
- Hobbs RJ, Arico S, Aronson J, *et al.* 2006. Novel ecosystems: theoretical and management aspects of the new ecological world order. *Global Ecol Biogeogr* **15**: 1–7.
- Holling CS. 2001. Understanding the complexity of economic, ecological, and social systems. *Ecosystems* **4**: 390–405.
- Knapp AK, Briggs JM, Hartnett DC, and Collins SC (Eds). 1998. Grassland dynamics: long-term ecological research in tallgrass prairie. New York, NY: Oxford Press.
- Landres PB, Morgan P, and Swanson FJ. 1999. Overview of the use of natural variability concepts in managing ecological systems. *Ecol Appl* **9**: 1179–88.
- MacDougall AS and Turkington R. 2005. Are invasive species the drivers or passengers of change in degraded ecosystems? *Ecology* **86**: 42–55.
- McLauchian KK, Craine JM, Oswald WW, *et al.* 2007. Changes in nitrogen cycling during the past century in a northern hardwood forest. *P Natl Acad Sci USA* **104**: 7466–70.
- MA (Millennium Ecosystem Assessment). 2005. Ecosystems and human well-being: synthesis. Washington, DC: Island Press.
- Noss RF, Beier P, Covington WW, *et al.* 2006a. Recommendations for integrating restoration ecology and conservation biology in ponderosa pine forests of the southwestern United States. *Restor Ecol* **14**: 4–10.
- Noss RF, Franklin JF, Baker WL, *et al.* 2006b. Managing fire-prone forests in the western United States. *Front Ecol Environ* **4**: 481–87.
- Rumbaitis del Rio CM. 2006. Changes in understory composition following catastrophic windthrow and salvage logging in a sub-alpine forest ecosystem. *Can J Forest Res* **36**: 2943–54.
- Seastedt TR, Knochel D, Garmoe M, and Shosky S. 2007. Interactions and effects of multiple biological control insects on diffuse and spotted knapweed in the Front Range of Colorado. *Biol Control* **42**: 345–54.
- Story JM, Callan W, Corn JG, and White LJ. 2006. Decline of spotted knapweed density at two sites in western Montana with large populations of the introduced root weevil, *Cyphocleonus achates* (Fahraeus). *Biol Control* **38**: 227–32.
- Suding KN, Gross KL, and Houseman GR. 2004. Alternative states and positive feedbacks in restoration ecology. *Trends Ecol Evol* **19**: 46–53.
- Towne EG, Hartnett DC, and Cochran RC. 2005. Vegetation trends in tallgrass prairie from bison and cattle grazing. *Ecol Appl* **15**: 1550–59.
- Veblen TT, Kitzberger T, and Donnegan J. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. *Ecol Appl* **10**: 1178–95.
- Williams JW, Jackson ST, and Kutzbach JE. 2007. Projected distributions of novel and disappearing climates by 2100 AD. *P Natl Acad Sci USA* **104**: 5738–42.