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Chapter 6

Forest restoration in a changing world: complexity and adaptation examples from the Great Lakes region of North America

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Managing Forests as Complex Adaptive Systems: Building Resilience to the Challenge of Global Change

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Introduction

The practice of ecological restoration and the science of restoration ecology have been called "beacons of hope" in sustaining biological diversity of degraded environments (e.g., Dobson et al. 1997). Due to its potential to provide guidance for land and water management and facilitate innovative new techniques, restoration ecology has more recently been aligned with silviculture among other applied disciplines (Sarr et al. 2004; Sarr and Puettman 2008). However, our developing understanding of the potential impacts of global climate change on local biota has thrown into question the concept of restoration of a particular condition, especially one based solely on historical information. Is ecological restoration still a valid construct in a changing world?

Complex Adaptive Systems (CAS) offers a framework by which practitioners, including silviculturists and forest managers, may conceptualize desired outcomes for restoration in forested ecosystems. Land-use change has caused dramatic shifts in forest conditions at a global scale. In North America, many of these changes were associated with post- European settlement land uses that altered natural disturbance regimes (Whitney 1994). Because of these changes we lack true analogues for today's forest conditions. A CAS framework can offer a new lens for goal-setting in light of novel conditions. Although managing specifically for "complexity" may seem nebulous, managing for the attributes that together constitute a CAS is feasible.
Anand et al. (2010) present a number of attributes that help reframe our thinking about forests as CAS (see Chapters 1 and 2, this volume). CAS represents a promising new direction for the science and practice of restoration in a changing world. Striving to restore a set of CAS attributes, as opposed to a particular species composition or age structure reframes the objective of land management as one of sustaining functional forest ecosystems into the future. Central to

the practice of forest restoration is the CAS attribute of self-organization, whereby the restorationist acts as an agent of energy dissipation. The restorationist re-introduces one or more elements, such as a species or process, thereby facilitating the ability of the system to maintain its current state or reorganize to another desired state. Alternatively, the restorationist might remove a stressor, such as a toxin or a recurring disturbance that interferes with a system's ability to reorganize.

Other CAS attributes are invoked upon restoration of the capacity to self-organize. For instance, cross-scale interactions and the legacy of past management (*sensu* Franklin et al. 2000) influence the ability to self-organize. Self-organization following one or more management interventions may result in a system that exhibits adaptation in the face of emerging stressors, such as climate change, invasive species, and outbreaks of insects and diseases. The structure and composition of future forests may bear little resemblance to those of the present. However, CAS offers hope of maintaining continuity of other attributes that may sustain important services over time (e.g., Holling 1973; Walker 1995; Holling and Meffe 1996; Naeem and Li 1997; but see Côté and Darling 2010).

We suggest that although objective-setting for restoration in a CAS context must necessarily be forward-focused, lessons and information from the past should also be incorporated. Frelich and Reich (2009) conclude that sustaining forests in the northern Great Lakes region will require enabling a "graceful transition" from their present condition to a desired future condition – as opposed to some less desirable condition. Although much uncertainty surrounds potential ecosystem responses to global change, setting flexible objectives for desired future conditions in forests has never been more critical. An analogy lies in the renovation of an historic building to accommodate modern uses. The original blueprints may be inappropriate, but may provide valuable insights regarding compatible modifications. The builder may preserve the structural foundation, architectural features, and overall character but choose to update light fixtures, add insulation, and install energy-efficient heating and cooling. Restoration in the context of CAS implies a mingling of new with old to foster self-organization and adaptability in the face of major uncertainties.

This chapter presents examples of restoration forestry projects in the Great Lakes region of North America. Management objectives and outcomes are recast in CAS terms, highlighting one or two attributes of complex adaptive systems in each case. For the sake of simplicity, we draw our examples from reserves and protected, public lands due to the importance of these lands in maintaining complexity and adaptability of forest ecosystems. Left undisturbed, traditional reserves provide habitat refugia and can serve as models for understanding natural processes and also have a role as controls for comparison with managed forests (Frelich et al. 2005). However, reserves also serve as experimental or demonstration sites for new methods that, though well-supported by science, may be too controversial to implement on other lands. For example, forest land owned by The Nature Conservancy in northern Minnesota has been used to demonstrate ecological approaches for managing productive lowland black spruce (*Picea mariana* (Miller) BSP) forest that have since been replicated by agencies managing adjacent lands. The five case studies that follow illustrate CAS attributes of restoration in a variety of reserve settings.

Case studies: restoring the adaptive capacity of forest ecosystems

Geophysical setting

The Great Lakes region of North America is the setting for the five case studies presented (Figure 1). A glacial landscape dominated by Wisconsonian-age glacial drift and landforms, the region includes lacustrine features such as glacial lake plains and morainal landforms. Sandy outwash plains and channels are also common. The climate is characterized by long, cool winters and short, mild summers. This region encompasses a broad transition between temperate forests to the south and boreal forests to the north (McNab and Avers 1994). Forest ecoregions within the area can be further distinguished by the degree Lake Superior influences the regional climate (Fig. 1; Superior Mixed Forest Ecoregional Planning Team 2002). Like forests around the world, Great Lakes forests provide a suite of key ecosystem services including economic benefits through the forest products industry and tourism, as well as environmental benefits such as water quality, air quality, carbon storage, wildlife habitat and biological diversity.

Great Lakes forests have been significantly altered before and since the pre-European settlement era. Forest composition and structure (Schulte et al. 2007) as well as landscape patterns (White and Host 2008) have become dramatically more homogeneous. Natural disturbance historically interacted with landforms, soils, and climate to create significant variability in spatial patterns across the Great Lakes region. Landscape structure varied from fine scale patterns in landscapes with a low frequency of stand replacing disturbances to areas of high frequency of severe fire with large disturbance initiated patches (> 5000 ha) (White and Host 2008). The legacy of extensive logging and intense slash-fueled fires in the late 19th early 20th centuries was a shift from later successional forests dominated by conifers such as white spruce (*Picea glauca* [Moench] Voss), white pine (*Pinus strobus* L.) and northern white cedar (*Thuja occidentalis* L.) to an early successional forest landscape dominated by sprouting, shade intolerant hardwood species, primarily quaking aspen (*Populus tremuloides* Michx.) and paper birch (*Betula papyrifera* Marsh.). As short-rotation, even-aged timber harvest replaced fire as the dominant disturbance from the 1930s to 1950s, similar management practices across the region imposed a more homogeneous pattern dominated by small (10-25 ha) patches (White and Host 2008). As currently practiced, short-rotation, even-aged forest management in this region will compound these changes in composition, structure and spatial patterns (White and Host 2008).

In their current, more homogeneous state, the forests of the Great Lakes region may be vulnerable to a number of stressors including climate change, forest insects and disease, invasive plants, and wildfire (Galatowitsch et al. 2009; Frelich and Reich 2009). Central to the natural resource-based economy of this region, sustaining these forests and the services they provide is critical for the viability of local communities. With a timber industry struggling in the face of global competition, dwindling mineral resources, and increasing pressure from recreational users, the need for ecological solutions that also meet society's needs is clear. The simplified condition of northern forests leaves them vulnerable to emerging stressors and underscores the importance of policies that integrate socio-ecological systems.

Hierarchy and scaling

As addressed in Chapters 1 and 2, a complete CAS functions within a hierarchy of scales with multiple dimension, e.g., temporal and spatial. Since most land management decisions are made at the stand level, the hierarchical nature of CAS is one of the most difficult to address whether a project has a restoration, commercial, or other focus. In the following example, we illustrate the ways in which scaling, as an example of a characteristic of CAS may be used to guide restoration projects in forests of northern Minnesota, USA. We highlight a project designed to restore patch structure at three scales: within-patch (fine-scale), conservation-area (across a focal area of approximately 40,000 ha), and landscape-level patch structure, across the entire Minnesota portion of the LMF, an ecological section of approximately 2.5 million ha.

The current landscape structure dominated by small forest patches leads to high edge density and low interior forest area (Wolter and White 2002) that favors game species such as white-tailed deer (*Odocoileus virginianus*) but negatively impacts edge-sensitive forest birds, tree regeneration, and persistence of other plants due to deer herbivory. Late-successional forest covers only a small fraction of its pre-European settlement area (Frelich 1995). Due to the rarity of large patches and later successional forest, larger forest patch sizes with mature- or late-successional characteristics can increase landscape scale heterogeneity in spatial patterns, species composition and vertical structure thereby improving adaptive capacity and response diversity.

Amidst growing concerns about impacts of the homogenized forest landscape on sustaining biological diversity, land managers and scientists in northeastern Minnesota have developed regional landscape plans. The plans specify long-term desired future conditions for composition, structure, and spatial patterns (MFRC 2003). Here we focus on goals related to restoring variability of patch size across spatial scales, a challenging aspect of landscape structure to address in areas of the Great Lakes where forest land may be owned by multiple units of federal, state, and local governments.

A collaborative landscape group composed of public agencies and private land managers developed a project to increase patch size and restore variability within the 42,000 ha Manitou Forest landscape of northeastern Minnesota (Figure 2). The group selected an area of approximately 450 ha to demonstrate the ability of timber harvests to be coordinated across multiple public ownerships in order to achieve patch restoration objectives. Over the long term (>100 years), the group envisions that the project area will result in a large, late successional forest patch dominated by long-lived conifers such as white pine, white spruce, and white cedar. Although at the patch level there may be lower response diversity with late successional conditions and lower species diversity (D'Amato et. al. 2011), at the landscape scale, this patch may increase response diversity due to an increase in habitat heterogeneity and seed sources for long-lived conifers, as large patches (> 100 ha) of mature-late-successional forest occur infrequently on the landscape (Frelich 1995; Wolter and White 2002).

Silvicultural prescriptions were based on moderate severity natural disturbances characteristic typically found in this region (40-70 % canopy removal) and include shelterwood with reserves and seed tree with reserves. Both prescriptions include summer and frozen ground harvest. The summer harvest allows for soil scarification through whole tree skidding to expose mineral soil and promote seedling establishment by seed rain from paper birch and conifer species. Winter harvest may limit the introduction of invasive plant species and protect sensitive soils from compaction and allow entry into stands with wet soils that otherwise would not be suitable for harvest. In addition, white pine and white cedar will be planted at variable densities to take advantage of mineral soil seedbeds and areas with less sprouting hardwood and shrub competition. White pine and white cedar are both important elements of compositional and structural diversity that decreased significantly with Euro-American land use changes.

The retention of biological legacies (Franklin et al. 2007) within the large patch (450 ha) is intended to contribute to an increase in heterogeneity at the fine scale as well; 30% of the forest cover is retained in reserve patches, including late-successional forest. To influence the condition of the greater LMF landscape across northeastern Minnesota will require numerous installations of "large patch" projects spanning multiple ownerships. The Manitou example is a start, and illustrates the potential to use an understanding of past landscape patterns to inform management objectives for heterogeneity at multiple scales as part of a CAS (Figure 2).

Emergence

An attribute central to CAS is that of emergent properties and processes. The implication of emergence for ecological restoration is the necessity of anticipating multiple potential future trends and interactions that today's course of action might set into motion. In contrast, many public agencies and private land managers across North America have adopted historical variability, or the range of natural variability (RNV), as a benchmark to assess departure from reference conditions of forest ecosystems under human influence (Landres et al. 1999).

Over the last few decades, restoration forestry has promoted the implementation of natural disturbance-based management, which uses silviculture to emulate effects of natural disturbances (e.g. fire and windthrow) to move forest ecosystems toward RNV (Drever et al. 2006). However, changes in the global environment indicate a significant mismatch will emerge between RNV forest conditions and conditions of the future, suggesting a need for new tools for goal-setting in forest restoration – tools that can simulate potential emergent properties to compare management strategies within a forest CAS (Seastedt et al. 2008; Puettmann 2011). Although natural disturbance-based management strives to maintain a diversity of species, a CAS framework may help managers evaluate the likelihood of species persistence under different change scenarios.

To better understand how changing climate conditions might interact with forest management in northern Minnesota, Ravenscroft et al. (2010) used a spatially dynamic simulation model, LANDIS II with three climate scenarios (current, low emissions, high emissions) and three management scenarios (no management, current management, natural disturbance-based management). The 2 million ha landscape is part of the north-temperate-southern boreal forest transition zone (Figure 1), where significant changes to forest ecosystems are expected as climate warms over the next century (Frelich and Reich 2009). The Landis-II model independently simulates key ecological processes (fire, wind throw, seed dispersal, tree establishment and growth) as well as anthropogenic processes such as forest management. The interactions of these processes lead to emergent properties in the model results (Mladenoff 2004; Gustafson et al. 2010). In northern Wisconsin, fragmentation, seed dispersal and interspecific competition may interact to limit tree species migration to suitable habitat under climate change (Scheller and Mladenoff 2008). The RNV-natural disturbance-based management restoration scenario used management prescriptions based on the frequency, severity, and size of historical wind and fire regimes including: stand-replacing fire, moderate surface fire, catastrophic windthrow, and patchy windthrow. The current management scenario emphasized even-aged management based on agency specific management plans (Ravenscroft et al. 2010).

Over the first 100 years of simulation, tree species currently present in the landscape varied in their responses to climate change and forest management. However, regardless of management approach, species at the southern edge of their range limits declined substantially under both high and low emissions scenarios (e.g., paper birch, white spruce, black spruce, and balsam fir (*Abies balsamea* (L.) Miller)) (Figure 3). Species closer to their northern range limits increased across all treatments (e.g., sugar maple (*Acer saccharum* Marshall) and red maple (*Acer rubrum* L.)).

Different types of forest management altered the direction of climate-induced compositional changes by influencing abundance of shade intolerant species. The scenario that merely continued current management maintained higher levels of quaking aspen but red maple showed the greatest increase in this scenario, as it responds well to disturbance but also has moderate shade tolerance. The restoration scenario limited the expansion red maple and sugar maple and maintained the greatest species diversity across the landscape by increasing pine species and slowing the loss of shade tolerant boreal conifers.

By year 200, as an emergent property of a warming climate, most of the boreal tree species were effectively extirpated from the landscape coinciding with a strong shift to *Acer* dominance and a more homogenous landscape (Ravenscroft et al. 2010). As the climate warmed over time the restoration strategies became less effective in maintaining species diversity. A mismatch between climate conditions, tree species, and disturbance regimes also emerged over time, such that the model projected a 30% loss in forested land due to regeneration failures and low productivity of *Acer* species in large harvest patches that emulated natural fire disturbance. This emergent process of forest loss was the product of the interaction of biotic and abiotic factors that could not have been predicted without a modeling platform that allows for complex, multi-scale interactions.

Although restoration interventions such as natural disturbance-based management may help stem the tide of homogenization and maintain key elements of forest variability, in this era of emerging stressors it can only accomplish so much. If climate change trends are similar to those projected in general circulation models, there will be an increasing mismatch between tree species, habitat conditions, and management which could lead to decreased productivity and a loss of adaptability. With the high projected rates of climate change, more southerly distributed species such as bur oak (*Quercus macrocarpa* Michx.) bitternut hickory (*Carya cordiformis),*and black cherry (*Prunus serotina* Ehrh.) that may be well suited to these future habitats may not have sufficient time to migrate to available habitat (Scheller and Mladenoff 2005).

Although there is significant uncertainty both in climate projections from general circulation models and forest model projections using simulated climate data, these results suggest that the historical range of variability, while a useful starting point, may be useful only over relatively short time frames (e.g., 50-100 years). A natural disturbance-based management approach could help sustain those species with the capacity to persist over time, and might be complemented by transitional strategies that facilitate establishment of tree species better suited to future climates. A blended approach may be most effective at maintaining the key elements of heterogeneity and resulting adaptability in a time of rapid environmental change.

Self-organization and uncertainty

As attributes of complex adaptive systems, self-organization and uncertainty are closely intertwined. Levin (2005) makes the case that "the process of self-organization is indeterminate." Like a novel begun by an author with only a general sense of the plot, the trajectory of relationships among today's species and environments may lead to a number of different future outcomes. The warming climate merely underscores this uncertainty (Messier and Puettmann 2011).

To illustrate the interplay of self-organization and uncertainty in forest restoration, we turn to a 2.1 million ha landscape of international significance: the Border Lakes region of northeastern Minnesota and northwestern Ontario. Roughly 43% of the landscape is designated wilderness within the Boundary Waters Canoe Area Wilderness (BWCAW) and Quetico Provincial Park (hereafter, Quetico) with an additional 52% in other forms of public ownership (Shinneman et al. 2010). The BWCAW and Quetico were established decades ago as protected areas to address the critical threats of the time: habitat loss, fragmentation, and ecologically incompatible forest management. Although the foresight of creating an extensive wilderness area represented a great advancement for conservation in the region, it fell short of anticipating two major future threats to the area's biological diversity: further alteration of natural disturbance regimes and climate change. Even the most extensive preserve is not immune to such powerful forces.

The forests of the Border Lakes region are largely considered fire-dependent. (For an overview of historical fire regimes within the Border Lakes see Shinneman et al. 2010). A century of fire suppression and timber management in the greater Border Lakes region has simplified the landscape, resulting in strongly-contrasting successional expressions of the boreal forest. Today, fire-intolerant species such as white spruce and balsam fir are increasingly common within wilderness areas of the Border Lakes. Early successional forests under short-rotation, even-aged management are most prevalent on lands managed for timber production, a bifurcation that reflects political rather than biophysical forces (Shinneman et al. 2010). The bifurcation of the landscape has been reinforced by contemporary fire management policies and socio-economic constraints, which have disrupted the fire regime within the BWCAW (Frelich and Reich 2009). Only a small number of wildfires are permitted to burn without intervention and no prescribed fire is conducted to achieve ecological objectives alone. Like much of the Great Lakes region, the forests of the Border Lakes now enter the climate change with a legacy of nearly a century of cumulative land management decisions.

The use of prescribed fire to achieve ecological objectives has been viewed for decades as beneficial to historically fire-dependent ecosystems. In the Border Lakes, we propose reframing the use of fire as a way of bolstering the system's ability to self-organize. Fire regimes in other ecosystems (e.g., mixed conifer forests of Yosemite National Park in California (USA)) also exhibit self- organizing behaviors, which in turn influence the spatial configuration of subsequent fires (Scholl and Taylor 2010). Although the fire regimes introduced today may only vaguely resemble those of the past, capitalizing on the ability of BLR forests to self-organize post-fire may strengthen other aspects of complexity, such as adaptability.

Shinneman et al. (2010) caution that even under well-coordinated, landscape-level restoration, the decline of some underrepresented forest types, such as white pine and red pine, may be inevitable, with resulting losses of heterogeneity at multiple scales. Assuming a stable climate, the group simulated several combinations of prescribed fire, wildland fire and forest management. The authors posit that, if continued over the next two centuries, current uncoordinated timber management and near-total fire suppression will likely result in a further simplification of the BLR landscape (Shinneman et al. 2010). In contrast, a broader use of fire in the landscape could result in greater heterogeneity of forest types and fuel distribution, potentially rendering the region less vulnerable to the stand-replacing fires that are otherwise anticipated to increase in frequency as the climate warms.

Under a scenario in which CO_2 emissions double from pre-industrial levels, uncertainty about the ability of BLR forests to self-organize increases. As noted in the emergence example above (Ravenscroft et al. 2010), boreal tree species within the BLR are anticipated to give way to species with greater tolerance for warmer, drier conditions. Although Ravenscroft et al. (2010) modeled trees, other boreal species will have to cope with the same set of circumstances. Species are expected to move individualistically, and today's plant communities will likely lack comparable analogs in the future (Seastedt et al. 2008; Heller and Zavaleta 2009). Over the next several decades, ecological systems and plant communities will self-organize in large part depending on which new species are the first to arrive, then cycle through a complex array of compositional and functional states (e.g., Lockwood et al. 1997). Facilitating colonization by a suite of desired species represents one of the key leverage points for restorationists as self-organization plays out in the BLR landscape. For example, if warming is moderate, Frelich and Reich (2009) recommend a combination of restoring locally extirpated tree species, such as white pine and facilitated colonization by currently uncommon species, such as bur oak and red oak (*Quercus rubra* L.), that could capitalize on newly-favorable growing environments but have limited dispersal ability.

Unfortunately, effective climate change mitigation seems unlikely under the geopolitical circumstances of 2011. Outcomes of BLR forest self-organization are thrown into greater uncertainty under scenarios of high warming, i.e., very warm and very dry (Frelich and Reich 2009). Under high-emissions scenarios, the BLR forests are likely to undergo further changes. The uncertainty surrounding outcomes suggest that the process may be play out as a total reorganization than a process of self-organization within an existing ecosystem. Over the next two centuries, areas of forest loss may become more pronounced resulting in a more open structure and greater dominance in some cases of non-native and/or invasive species (e.g. Frelich and Reich 2009; Ravenscroft et al. 2010). Greater climate-associated stressors may require greater intervention on the part of restorationists as agents of change, for example active facilitation of colonization by more southerly species outside the region (Frelich and Reich 2009). In this context, the restorationist serves as a director in the BLR theater. The stage remains the same, but the sets, actors, and costumes change several times over the centuries to come (e.g., Anderson and Ferree 2010). Whether wilderness policy would ever permit such active intervention is unclear. To meet the challenges of global change, adaptability in social and political processes may be every bit as important as adaptability in our approaches to land management.

Within the constraints of forest policy, land managers and restorationists have some ability to bolster or weaken an ecosystem’s ability to self-organize. However, this capacity is also bounded by other constraints outside the control of the agent of change. Capitalizing on a forest’s ability to self-organize is a promising conceptual framework for restorationists entering the climate change era. Given the uncertainty inherent to CAS, restorationists may think of themselves as "stacking the deck." By restoring processes and providing a diverse array of potential players, the restorationist tries to anticipate a number of potential acceptable outcomes, allowing the process of self-organization to select among them (Puettmann 2011).

Legacies

The absence of desired legacies, such as nurse logs for regeneration of moisture-sensitive species or seed trees that allow the persistence of uncommon trees in a landscape, is usually one of the major triggers for restoration. The legacy of successive forest management practices may result in a simplified forest ecosystem, one that is vulnerable to emerging threats, or at the least reduce its ability to provide valuable services. To better understand the consequences of missing legacies within particular forest systems, the importance of unmanaged reserves should not be underestimated.

One such example lies in northern hardwood forests of the Great Lakes region. Northern hardwood forests are less disturbance-prone ecosystems than the fire-driven mixed conifer forests that occur throughout the region. Northern hardwoods are driven by fine-scale processes such as gap formation (Frelich et al. 2005). In a direct comparison of primary and secondary northern hardwood forests at the northern edge of sugar maple's native range, Burton et al. (2009) demonstrated a continued legacy of past forest management in secondary stands that originated between 60 and 70 years ago. Compared with primary forest, second-growth had lower densities of conifer species and yellow birch (*Betula alleghaniensis* Britton), lower structural and environmental heterogeneity, and associated differences in understory vegetation. The cumulative legacy of the past several decades of forest management is one of simplification of the system.

In the northern hardwoods example, the role of the restorationist might be that of accelerating natural processes (e.g., gap-phase dynamics) and structure, thereby hastening the development of desirable legacies for the future. Researchers developed silvicultural treatments intended to mimic the variable gap size that might result from centuries of gap-phase dynamics in a northern hardwood forest in northern Minnesota (Sarr et al. 2004). By creating structural heterogeneity, silviculturists predicted that yellow birch would respond to greater heterogeneity, especially open conditions and associated availability of resources by increasing as a component of second-growth forests, which now dominate over 85% of the northern hardwoods forest ecosystem in the region.

In all, 46 gaps were created within six different secondary forest stands and measured >5 years post-treatment (Bolton 2010). Study sites were located on land owned and managed by the Lake County Land Department in northeastern Minnesota. Although the project succeeded in creating a gap structure more reminiscent of the reference conditions, forest composition did not respond as predicted. This example clearly illustrates that superficial structural changes do not necessarily effect desired changes in function or process. In particular, yellow birch regeneration did not increase in or near the newly-created gaps, although gaps were purposefully placed near seed trees. Inhospitable seedbed conditions for yellow birch germination and establishment are suspected to have led to the regeneration failure. In particular, harvesting took place in the winter, with little resulting scarification of the soil that may have provided an advantage in some cases to yellow birch. Furthermore, a dearth of nurse logs was prevalent throughout secondary stands, a cumulative legacy of past forest management. Yellow birch relies on nurse logs as sites for germination and establishment (Bolton 2010). As a result, sugar maple continues to dominate the gaps at this site, although structural heterogeneity has been introduced via management.

In a CAS, legacies can lead to either reinforcing or negative feedbacks that can in turn vary across scales. In the northern hardwoods example, restorationists tested the potential of silvicultural tools to jump start the process of canopy feedbacks that could in turn influence future aspects of age structure and composition. Although in the early stages, as described above, the outcome suggests that the full life-history of desired species must be considered when deciding what legacies to attempt to recreate within a system. Ensuring that a variety of species, growth stages, and functions are present in a given landscape provides pathways to sustaining complexity in ecosystems. Manipulating the forests of today to influence legacies of the future represents a way for restoration to improve the hand we are dealt. Legacy management, if viewed in terms of scales and varying amounts, is an approach by which restorationists can enhance attributes of CAS, such as adaptability.

Adaptability

The most effective role of ecological restoration in today's world may be the development, testing, and widespread implementation of adaptation strategies. Adaptation strategies have been grouped into three major categories: resistance, resilience, and response (Millar et al. 2007), or transformative (Heller and Zavaleta 2009). In the forested ecosystems of the Great Lakes, we propose an emphasis on resilience strategies, but with a gradual transition toward transformative strategies. Given the uncertainties associated with climate change and various interacting factors such as CO_2 fertilization, phytophagous insects, and deer populations, increasing the adaptive potential in managed forests may be one of the most important strategies for maintaining long-term resilience. In this example, we draw on a recently-developed set of climate change adaptation strategies created for The Nature Conservancy's 406 ha Caroline Lake preserve in northern Wisconsin.

Great Lakes forests in Wisconsin share many characteristics already described for the northeastern Minnesota portion of the LMF, including similar historical origins and a homogenized landscape resulting from decades of cumulative forest management (e.g. Schulte et al. 2007). Although forests are dominated by a mixture of northern hardwoods and conifers, the presence of eastern hemlock (*Tsuga canadensis* (L.) Carriére) is a distinguishing feature. The forests of Caroline Lake represent a legacy of homogenization via the prevalent silvicultural system used over decades (e.g., Angers et al. 2005). Sugar maple dominates the landscape today, and yellow birch and eastern hemlock have been greatly reduced post euro-American settlement (Schulte et al. 2007).

The Nature Conservancy acquired Caroline Lake because of its relatively high quality forest plant communities and its importance in maintaining functional wetlands, streams and rivers in the Chequamegon Bay watershed. The Caroline Lake preserve was also acquired to demonstrate sustainable forestry practices consistent with maintaining biological diversity. The current management plan utilizes site-level best management practices, such as retention of biological legacies and riparian buffers. "Climate-smart" updates to the plan in the form of adaptation strategies were developed to augment the adaptability of forests in the watershed. The Caroline Lake example is one of the first attempts in this region to explicitly restore attributes of complexity that may enhance the ability of northern forests to adapt to changing conditions.

As with the previous example from northeastern Minnesota (see section on Emergence), forests in the area are expected to be sensitive to warmer, drier conditions associated with climate change (Ravenscroft et al. 2010). In a separate study, Scheller and Mladenoff (2005, 2008) analyzed potential impacts of a warming climate on individual tree species in northwestern Wisconsin using LANDIS-II. Species tolerant of warmer, drier conditions will likely persist and remain reasonably productive at Caroline Lake over the next 100 years of climate change (Table 1). However, species with lower tolerance for warmer temperatures and drier conditions will likely be extirpated from the region regardless of management over the next 100-200 years (Table 1).

Original management objectives at Caroline Lake focused on creating or maintaining all-aged forests with an emphasis on developing mature-late successional characteristics including increased snags and large diameter coarse woody debris, and greater abundance of eastern hemlock and yellow birch. We modified these goals to include management for a diverse mixture of species with attention to those species with higher tolerance for warmer, drier conditions. Further, we included the possibility of introducing a small number of tree species that would likely expand their ranges northward to the Great Lakes forests of Chequamegon Bay were it not for seed dispersal limitations and human-caused landscape fragmentation (e.g., white oak (*Quercus alba* L.), and bitternut hickory (Scheller and Mladenoff 2005).

In addition, we suggested developing greater structural heterogeneity at Caroline Lake in the form of gap-based management (i.e. group selection). Patterned after wind disturbances that are higher severity but less frequent (e.g. Woods 2004; Angers et al. 2005; Hanson and Lorimer 2008), intermediate-sized silvicultural treatments can create greater heterogeneity with more variable opening sizes creating a greater range of available solar radiation. For example, in northern Wisconsin, Hanson and Lorimer (2008) report that intermediate wind disturbance removed an average of 41% of basal area (range 39-43%) with openings ranging from 10 to 5000

m^2. Typical northern hardwood management systems remove only 20-30% of basal area per entry with gap sizes ranging from 100 to 400 m^2. Intermediate wind disturbances historically occurred at lower rates (rotations of 300-390 years) than finer-scale gap events removing 10-30% of canopy (rotations of 72- 195 years) but still influenced a significant proportion of the landscape (Frelich and Lorimer 1991; Hanson and Lorimer 2008). While single tree and small gap selection harvests will continue to be a part of management, a broader suite of practices, including intermediate-scale disturbances, are required to increase species diversity of climate tolerant species and structural heterogeneity at both stand and landscape scales.

A gradient of management disturbance staged over decades rather than a single year could be utilized in northern hardwood forests ranging from single tree selection to irregular shelterwood or multi-cohort systems that create larger openings with variable levels of retention thereby ensuring variability across spatial scales. Single tree and gap harvest are recommended for shade tolerant species but would allow for appropriate recovery periods to allow for development of late successional characteristics such as large old trees, cavities, and dead wood structures. Larger gap sizes along with irregular shelterwood or multi-cohort management could be used to establish a greater diversity of species, including those requiring higher light levels for establishment. This approach includes longer overstory retention periods as well as permanent biological legacies. We also recommend small-scale scarification that exposes mineral soil. These methods mimic moderate severity disturbances and are compatible with types such as northern hardwoods in which tip-up mounds result from finer scale disturbance patterns (Raymond et al. 2009).

By implementing a more diverse management system that introduces variability across scales, the primary goal of restoration at Caroline Lake is to support the forest's ability to adapt to novel climate conditions and related stressors. Monitoring will be critical to assessing the effectiveness of these recommendations to avoid unintended consequences, such as the expansion of invasive plant species or inadvertently creating habitat more favorable to deer. Although Caroline Lake is a relatively small site in the context of the entire Chequamegon Bay watershed, treatments that enhance complexity by emulating some aspects of intermediate wind disturbances could be incorporated into management prescriptions by other public landowners (e.g., Puettmann et al. 2009).

Summary and recommendations

Rethinking forest ecosystems in a CAS context presents numerous opportunities for the practice and science of restoration. The present era of accelerating climate change has rendered the restoration of a particular condition or expression of a forest ecosystem a moving target at best. As such, striving to restore particular attributes of complexity may be the most promising avenue toward maintaining functional ecosystems and biological diversity, thereby sustaining the ecological services on which life depends.

Although there is no simple restoration prescription for creating a CAS, lessons from the Great Lakes region demonstrate the ways in which various elements of complexity may be reintroduced to forest systems. Restoration of patch structure in mixed conifer-hardwood forests of northern Minnesota at the nested scales of 450 ha, 4,500 ha and 3.5 million ha illustrates the potential of silvicultural influence at a hierarchy of spatial scales. The modeling examples probe the CAS attribute of emergence and the diminishing efficacy of restoration management over time, at least in terms of achieving target conditions defined today. Key among potential emergent outcomes is the likely loss of forest cover throughout the region over the next two centuries. Uncertainty as to how much forest area will be lost and where the losses will occur is not uniquely a CAS attribute, but must be considered together with scaling, emergence, self-organization, legacies, and adaptability.

The future of restoration may lie in the ability of land managers to promote the CAS elements of self-organization, legacies, and adaptation. By acting as agents of change, restorationists might focus e.g., on returning a process, such as fire in the Border Lakes region, and determine from the self-organization response whether further action is needed. The working forest example from Lake County, Minnesota highlights the limitations of attempting to restore structural heterogeneity. Although canopy and age structure were successfully manipulated, other aspects of natural disturbances, such as creation of seedbeds (i.e., nurse logs) were not addressed, hence regeneration and composition did not follow, at least in the short term. A better approach to restoration may consist of comprehensive designing of silvicultural practices specifically to help forests adapt to environmental conditions of the future, as with the case study from northern Wisconsin.

Land managers may influence multiple components of complexity, including hierarchy and scaling, emergence, legacies, self-organization, networks (Simard et al., this volume), and uncertainty. Restoration and management options discussed here range from the conventional to the innovative to the downright controversial. The degree of uncertainty associated with all the cases discussed above is high. Such high stakes and uncertainty call for an increased level of effectiveness monitoring as part of a deliberate adaptive management program. Monitoring has always been important, but the need for rapid learning and adjustment of practices, as in the Lake County example, is more urgent than ever. Adequate measures and communication of results, whether to land managers or policy makers, is critical to the success of making the shift from restoration of a particular cover type to managing for elements of complexity (Tierney et al.

2009). As with the restoration goals themselves, an effectiveness monitoring program must parallel the array of CAS attributes, particularly those that restoration practices aim to influence. For example, monitoring response to management at both the landscape and stand level goes a long way toward addressing hierarchy and scaling. Tracking both composition and the distribution of legacies, such as snags and nurse logs, will help generate a working set of indicators that can help determine whether management strategies need minor adjustments or to change course altogether. As an emerging framework, restoration of adaptability will require a commitment to research and monitoring to sustain forests for the future.

Literature Cited

Anand, M., Gonzalez, A., Guichard, F., Kolasa, J., and Parrott, L. 2010. Ecological systems as complex systems: challenges for an emerging science [online]. Diversity **2**:395-410. doi:10.3390/d2030395.

Anderson, M.G. and Ferree, C.E. 2010. Conserving the stage: climate change and the geophysical underpinnings of species diversity [online]. PLoS One **5**(7):e11554. doi:10.1371/journal.pone.0011554.

Angers, V.A., Messier, C., Beaudet, M. and Leduc, A. 2005. Comparing composition and structure between old-growth and selectively harvested stands in hardwood forests in eastern Canada. For. Ecol. Manage. **217**:275-293.

Bolton, N.W. 2010. The influence of natural disturbance-based silviculture treatments on northern hardwood forests in northeastern Minnesota, USA. M.Sc. thesis, Department of Forest Resources, University of Minnesota.

Burton, J.I., Zenner, E.K., Frelich, L.E., and Cornett, M.W. 2009. Patterns of plant community structure within and among primary and second-growth northern hardwood forest stands. For. Ecol. Manage. 258(11):2556-2568.

Côté, I.M., and Darling, E.S. 2010. Rethinking ecosystem resilience in the context of climate change [online]. PLoS Biol. **8**(7) e1000438. doi:10.1371/journal.pbio.1000438.

Dobson, A.P., Bradshaw, A.D. and Baker, A.J.M. 1997. Hopes for the future: restoration ecology and conservation biology. Science **277(5325)**:515-522. doi:10.1126/science.277.5325.515 .

Drever, C.R., G. Peterson, C. Messier, Y. Bergeron, and M. Flannigan. 2006. Can forest management based on natural disturbances maintain ecological resilience? Can. J. For. Res. **36**:2285-99.

Franklin, J.F., Lindenmayer, D., MacMahon, J.A., McKee, A., Magnuson, J., Perry, D.A., Waide, R., and Foster, D. 2000. Threads of continuity. *Conservation Magazine* **1**(1). Available from http://www.conservationmagazine.org/2008/07/threads-of-continuity [accessed 13 August 2010].

Franklin, J. F., Mitchell, R. J., Palik, B. J. 2007. Natural disturbance and stand development principles for ecological forestry. USDA For. Serv. GTR NRS-19.

Frelich, L.E. 1995. Old forest in the Lake States today and before European settlement. Nat. Areas J. 15:157-167.

Frelich, L.E., and Lorimer, C.G. 1991. Natural disturbance in the hemlock–hardwood forests of the upper Great Lakes region. Ecol. Monogr. 61: 145–164.

Frelich, L.E., Cornett, M.W. and White, M.A. 2005. Controls and references in forestry: the role of old growth and retrospective studies. J. For. **103**(7):339-344.

Frelich, L.E., and Reich, P.B. 2009. Will environmental changes reinforce the impact of global warming on the prairie-forest border of central North-America. Front. Ecol. Env. Doi:10.1890/080191

Frelich, L.E., and Reich, P.B. 2009. Wilderness conservation in an era of global warming and invasive species: a case study from Minnesota's Boundary Waters Canoe Area Wilderness. Nat. Areas J. **29**:385-393.

Gustafson, E.J., Shvidenko, A.Z., Sturtevant, B.R., and Scheller, R.M. 2010. Predicting global change effects on forest biomass and composition in south-central Siberia. Ecol. Appl. **20**(3):700–715. [doi:10.1890/08-1693.1].

Hanson, J.J., and Lorimer, C.G. 2008. Forest structure and light regime following moderate wind storms: implications for multi-cohort management. Ecol. Appl. **17**(5):1325-1340. doi:10.1890/06-1067.1

Heller, N.E., and Zavaleta, E.S. 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. Biol. Conserv. **142**(1):14-32. doi:10.1016/j.biocon.2008.10.006.

Holling, C.S. 1973. Resilience and stability of ecological systems. Annu. Rev. Ecol. Syst: 4:1-23.

Holling, C.S. and G.K. Meffe. 1996. Command and control and the pathology of natural resource management. Conserv. Biol. **10**(2):328-337.

Landres, P.B., Morgan, P., and Swanson, F.J. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecol. Appl. **9**:1179-1188. [doi:10.1890/1051-0761(1999)009[1179:OOTUON]2.0.CO;2]

Levin, S.A. 2005. Self-organization and the emergence of complexity in ecological systems. Bioscience **55**(12):1075-1079.

Lockwood, J.L., Powell, R.C., Nott, M.P., and Pimm, S.L. 1997. Assembling ecological communities in time and space. Oikos **80**:549-553.

McNab, W.H., and Avers, P.E. 1994. Ecological subregions of the United States: Section descriptions. Washington, DC. U.S. Department of Agriculture, Forest Service. Publication WO-WSA-5.

Messier C. and Puettmann K.J. 2011. Forests as complex adaptive systems: implications for forest management and modeling. L'Italia Forestale e Montana **66**:249-258.

Millar, C.I., Stephenson, N.L., Stephens, S.L. 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecol. App. **17**:2145-2151.

Minnesota Forest Resources Council (MFRC). 2003. Recommended desired outcomes, goals and strategies: northeast landscape region. LP-0303a. Available from http://www.frc.state.mn.us/documents/council/landscape/NE%20Landscape/MFRC_Northeast_LA_Plan_1.25_2003-03-25.pdf

Mladenoff, D.J. 2004. LANDIS and forest landscape models. Ecol. Modell. **180**(1):7-19. doi:10.1016/j.ecolmodel.2004.03.016.

Naeem, S. and Shibin, L. 1997. Biodiversity enhances ecosystem reliability. Nature 390: 507-509.

Puettmann, K.J. 2011. Silvicultural challenges and options in the context of global change: "simple" fixes and opportunities for new management approaches. J. For. 321-331.

Puettmann, K.J., Coates, K.D., and Messier, C. 2009. A critique of silviculture: managing for complexity. Island Press, Washington, D.C.

Ravenscroft, C., Scheller, R.M., Mladenoff, D.J. and White, M.A. 2010. Forest restoration in a mixed ownership landscape under climate change. Ecol. Appl. **20**: 327-346.

Raymond, P., Bedard, S., Roy, V., Larouche, C., and Tremblay, S. 2009. The irregular shelterwood system: review, classification, and potential application to forests affected by partial disturbances. J. For. **107**:405-413.

Sarr, D.A. and Puettman, K.J. 2008. Forest management, restoration, and designer ecosystems: integrating strategies for a crowded planet. Écoscience **15**:17-26.

Sarr, D., Puettmann, K., Pabst, R., Cornett, M., and Arguello L. 2004. Restoration ecology: new perspectives and opportunities for forestry. J. For. **102**:20-24.

Scheller, R.M. and Mladenoff, D.J. 2005. A spatially interactive simulation of climate change, harvesting, wind, and tree species migration and projected changes to forest composition and biomass in northern Wisconsin, USA. Glob. Change Biol. **11**: 307-321.

Scheller, R.M. and Mladenoff, D.J. 2008. Simulated effects of climate change, fragmentation and inter-specific competiation on tree species migration in northern Wisconsin, USA. Climate Res. **36**: 191-208.

Scholl, A.E. and Taylor, A.H. 2010. Fire regimes, forest change and self-organization in an old-growth mixed conifer forest, Yosemite National Park, USA. Ecol. Appl. **20**: 362-380.

Seastedt, T.R., Hobbs, R.J., and Suding, K.N. 2008. Management of novel ecosystems: are novel approaches required? Front. Ecol. Environ. **6**: 547-553.

Shinneman, D.J., Cornett, M.W., and Palik, B.J. 2010. Simulating restoration strategies for a southern boreal forest landscape with complex land ownership patterns. For. Ecol. Manage. **259**: 446-458.

Schulte, L.A, Mladenoff, D.J. Crow, T.R. Merrick, L.C., and Cleland, D.T. 2007. Homogenization of northern U.S. Great Lakes forests due to land use. Landscape Ecol. **22**:1089-1103.

Superior Mixed Forest Ecoregional Planning Team. 2002. The Superior Mixed Forest ecoregion: a conservation plan. The Nature Conservancy. Madison, Wisconsin. 115 pp.

Tierney, G.L., Faber-Langendoen, D., Mitchell, B.R., Shriver, W.G., and Gibbs, J.P. 2009. Monitoring and evaluating the ecological integrity of forest ecosystems. Front. Ecol. Environ. **7**(6):308-316. doi:10.1890/070176.

Walker, B. 1995. Conserving biological diversity through ecosystem resilience. Conserv. Biol. **9**: 747-752.

White, M.A. and Host, G.E. 2008. Forest disturbance frequency and patch structure from pre-European settlement to present in the Mixed Forest Province of Minnesota, USA. Can. J. For. Res. **38**: 2212–2226.

Wolter, P.T., and White, M.A. 2002. Recent forest cover type transitions and landscape structure changes in northeast Minnesota. Landscape Ecol. **17**:133-155.

Woods, K.D. 2004. Intermediate disturbance in a late-successional hemlock-northern hardwood forest. J. Ecol. **92**: 464-476. doi:10.1111/j.0022-0477.2004.00881.x.

Table 1. Current mean percentage of basal area for tree species currently present at Caroline Lake preserve classified by tolerance for warmer, drier conditions (low, medium, high) (Climate tolerance classification adapted from Scheller and Mladenoff (2008)).

Species	**Mean percent basal area**
Low tolerance	
A. balsamea	5.4
P. glauca	1.4
B. papyrifera	1.2
T. occidentalis	1.6
Medium tolerance	
A. saccharum	36.7
B. alleghaniensis	7.3
Q. rubra	5.8
P. tremuloides	9.6
T. canadensis	2.4
T. americana	4.1
P. strobus	0.6
High tolerance	
A. rubrum	19.9
P. serotina	0.2

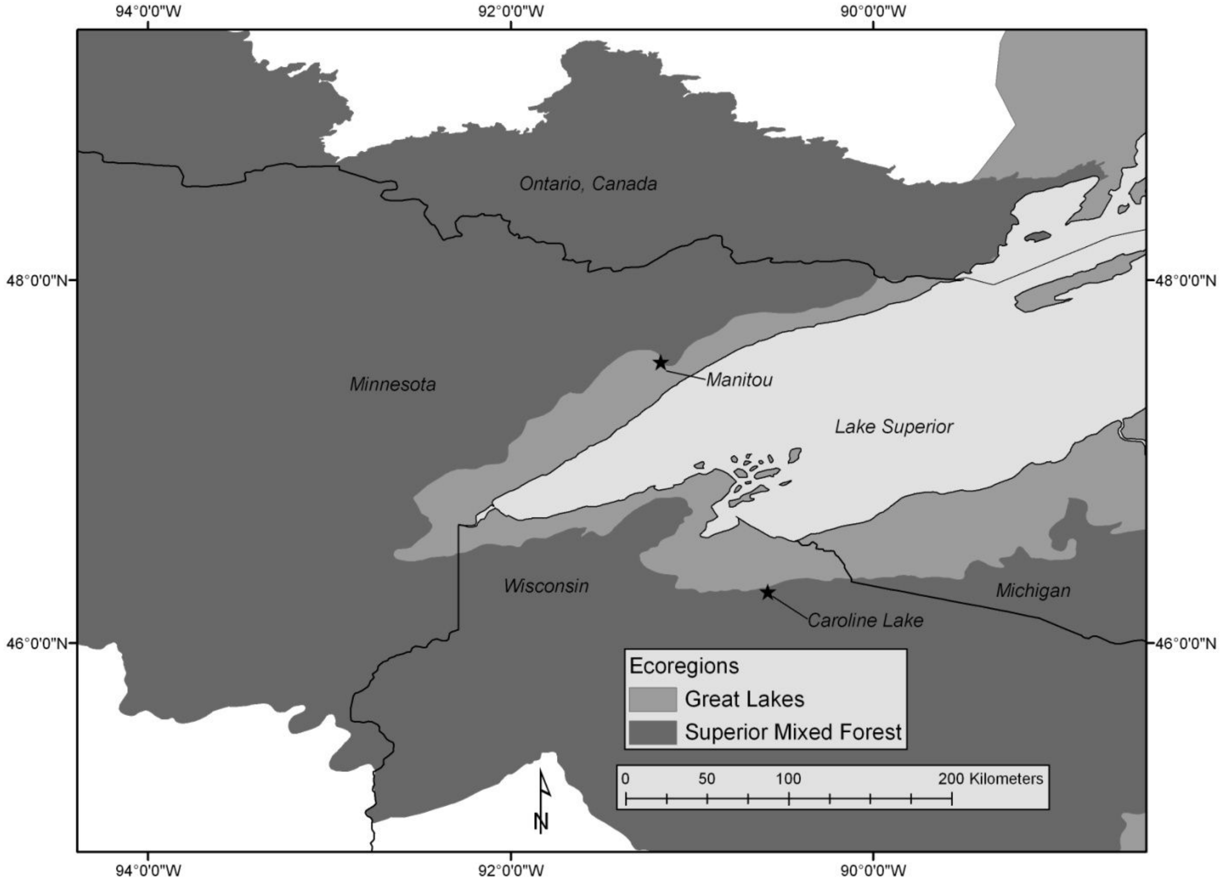

Figure 1. The Great Lakes region of North America Southern boreal forest transition zone

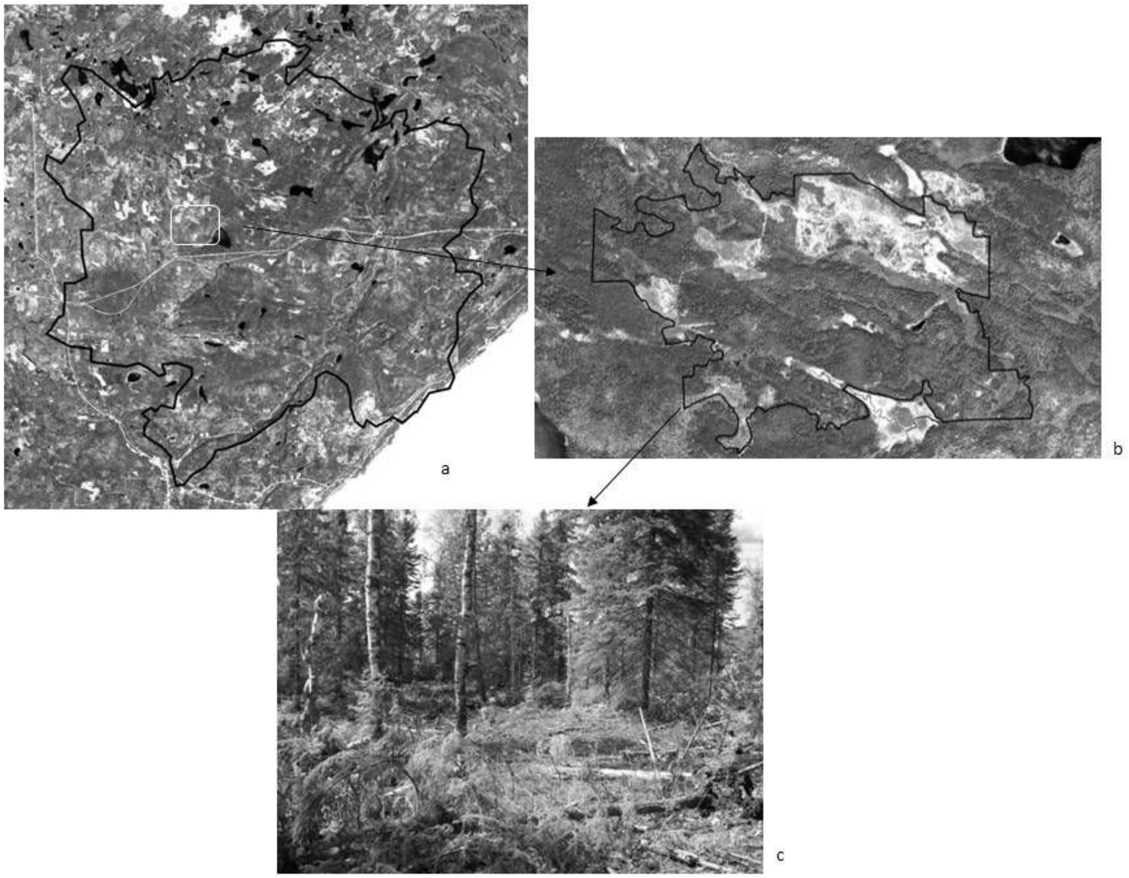

Figure 2. Example of managing for heterogeneity at multiple scales as part of a Complex Adaptive System a) The Manitou Forest Landscape with legacy effects of small, relatively homogeneous patch size (Landsat 2005); b) Outline of cross-ownership patch project designed to restore variability in patch sizes within the Manitou Forest Landscape (450 ha) (Quickbird ™); c) Ground view following shelterwood harvest with 40% of the forest cover reserved. Silvicultural treatments were applied to increase fine-scale heterogeneity in addition to landscape-scale patch structure (Photo © Mark White).

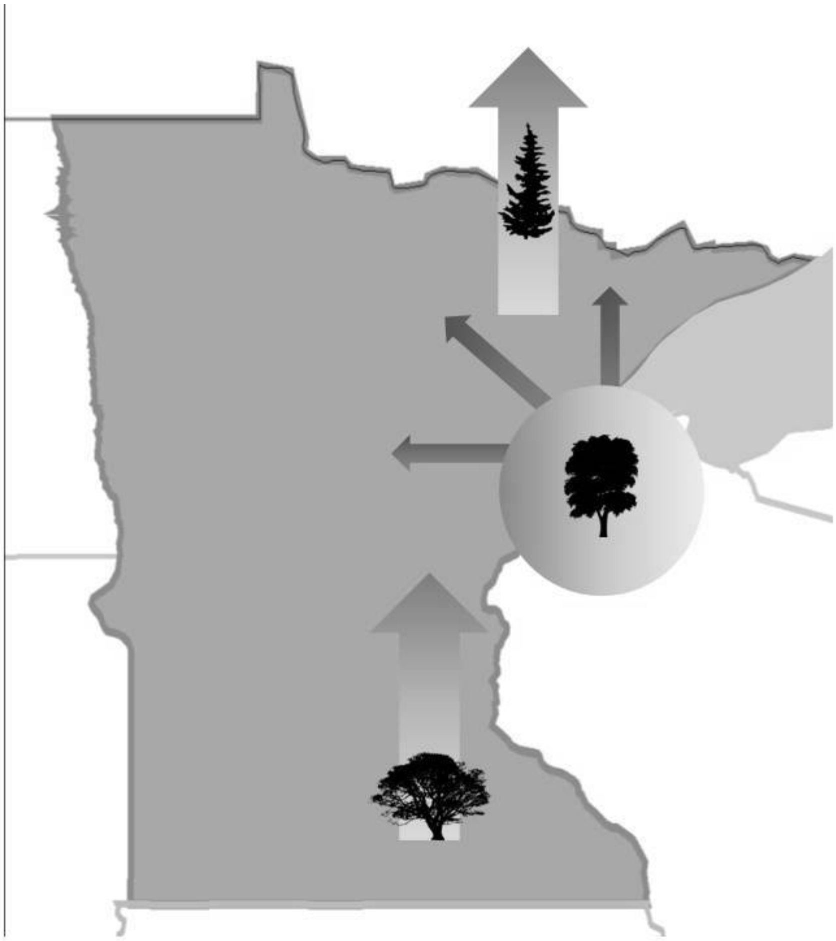

Figure 3. Anticipated migration of tree species in the western Great Lakes Region (adapted with permission from R. M. Scheller):

🌲 boreal conifers (e.g. balsam fir)

🌳 northern hardwoods (e.g. red maple)

🌳 central hardwoods (e.g. white oak)