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Regional climate change adaptation strategies for biodiversity conservation in a midcontinental region of North America

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ABSTRACT

Scenario planning should be an effective tool for developing responses to climate change but will depend on ecological assessments of broad enough scope to support decision-making. Using climate projections from an ensemble of 16 models, we conducted an assessment of a midcontinental area of North America (Minnesota) based on a resistance, resilience, and facilitation framework. We assessed likely impacts and proposed options for eight landscape regions within the planning area. Climate change projections suggest that by 2069, average annual temperatures will increase 3 °C with a slight increase in precipitation (6%). Analogous climate locales currently prevail 400–500 km SSW. Although the effects of climate change may be resisted through intensive management of invasive species, herbivores, and disturbance regimes, conservation practices need to shift to facilitation and resilience. Key resilience actions include providing buffers for small reserves, expanding reserves that lack adequate environmental heterogeneity, prioritizing protection of likely climate refuges, and managing forests for multi-species and multi-aged stands. Modifying restoration practices to rely on seeding (not plants), enlarge seed zones, and include common species from nearby southerly or drier locales is a logical low-risk facilitation strategy. Monitoring "trailing edge" populations of rare species should be a high conservation priority to support decision-making related to assisted colonization. Ecological assessments that consider resistance, resilience, and facilitation actions during scenario planning is a productive first step towards effective climate change planning for biodiversity with broad applicability to many regions of the world.

1. Introduction

Climate change resulting from CO_2 emissions will continue over the next century regardless of the scope and magnitude of mitigation efforts (IPCC, 2007). The rapid rate of climate change, coupled with other anthropogenic stresses, will deplete species diversity in some regions if habitats become unsuitable and migration is insufficient. Although climate change predictions are derived from global models, strategies to minimize effects on biodiversity need to be formulated at local and regional scales to account for land-use differences, extent of natural ecosystems, and ecology of the indigenous flora and fauna. The adjustments humans make in response to climate change, or that natural systems make unassisted, has been called adaptation by IPCC (2001). Scenario planning will likely be a crucial tool for developing these climate adaptation strategies, given the high uncertainty of ecological responses to anticipated changes and the complexity of addressing multiple stressors (Peterson et al., 2003; Brooke, 2008). Scenarios are projections of plausible alternative futures for a specific purpose, developed deliberatively and based on a shared understanding of system dynamics and how actions may alter the future trajectory of ecosystems. The foundation for scenario planning is an assessment that identifies key drivers of system dynamics, uncertainties with potential to have large impacts, and external changes most likely to influence the system in the future (Peterson et al., 2003). The challenge of converting highly context- or case- specific research results into assessments has hindered the incorporation of ecological information into climate change adaptation conservation planning (Brooke, 2008).

Climate change adaptation conservation planning, using a variety of conservation tools, is underway for some countries (e.g., UK, South Africa, Australia), groups of countries (i.e., Small Island Developing States (SIDS), European Union (EU)), and states/provinces within countries (e.g., Queensland, Australia; Alaska and Florida, USA) (IPCC, 2002; Hannah et al., 2005; Ferris, 2006; Von Maltitz et al., 2006; Pew Center on Global Climate Change, 2007; QCCCE, 2008). Some of these efforts have identified key ecosystems

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or species likely to be most threatened by climate change and compare adaptation options, but most are more general; scoping impacts, identifying major barriers to action, and discussing key issues needed for decision-making. Even when highly vulnerable species and ecosystems have been identified, conservationists have been reluctant to commit to specific adaptation plans (Heller and Zavaleta, 2009). This reluctance often stems from a lack of climate change predictions for specific regions, uncertainty about how species will actually respond, and limited evidence that the proposed actions will have the desired effects. When these uncertainties are informally weighed against the risk of actions being counterproductive and the costs of implementation, plans stall (McLachlan et al., 2007). This inaction or "paralysis by analysis" is not new to conservation biology and is one of the primary reasons scenario planning has been used to approach other problems with high uncertainty and complexity (Peterson et al., 2003). Scenario planning has the advantage of explicitly incorporating different assumptions about specific policies and actions when envisioning alternative futures (Nassauer and Corry, 2004). Ecological assessments need to be developed that can effectively serve as a basis for scenario planning.

For over 20 years, challenges to sustaining species and ecosystem diversity in remnant natural areas generated key conservation planning principles that are relevant to the new challenge we face with climate change. As with traditional conservation planning, a "coarse-filter approach" of prioritizing reserve selection of communities and ecosystems will provide more efficiency than attempting to build scenarios for every vulnerable species (Hunter et al., 1988). Connecting these reserves with corridor systems, stepping stone reserves, and buffer zones will be crucial to allow species' ranges to adjust to new climatic conditions (Halpin, 1997). However, as predictions of warming have become increasingly dire, there is recognition that these planning frameworks need to be supplemented to facilitate regional planning under a greater array of environmental and socio-economic situations (Halpin, 1997; Heller and Zavaleta, 2009). Millar et al. (2007) identified three kinds of adaptation actions for forest ecosystems: defensive actions intended to resist the influence of climate change; practices aimed at promoting resilient ecosystem responses to climate change; and active involvement in facilitating change to ecosystems or particular species. Distinguishing between resistance, resilience and facilitation options during ecological assessments and scenario planning is important for two reasons. First, conservation actions reflect assumptions about species and ecosystem responses to climate change and so recognizing these options can help ecologists comprehensively assemble the information needed for assessments. Second, developing scenarios that variably depend on resistance, resilience and facilitation actions allow regional conservation planning teams to compare the feasibility, risks, and potential outcomes without needing to reach consensus on aspects of climate change that are too uncertain to resolve. The resistance/resilience/facilitation framework is potentially applicable to many kinds of ecosystems and regional landscape contexts, although this has not yet been applied to systems other than forests.

We used the state of Minnesota (USA) as a case study for regional climate change adaptation ecological assessments using the resistance/resilience/facilitation framework. At the convergence of three major biomes—boreal forest, hardwood forest, and Great Plains grasslands—Minnesota is a good test case for this framework and for regional adaptation planning in general. In addition, approximately 50% of Minnesota's landscape has been converted for agriculture, industry and urbanization, but the state has an extensive protected areas network (Fig. 1), ranging from the 400,000 ha Boundary Waters Canoe Wilderness Area to small (<10 ha) remnant grasslands and wetlands surrounded by agriculture. Specifically, our objectives were to: (1) develop climate projections for different regions of the state, (2) assess likely impacts to wetland, forest and prairie ecosystems, and (3) propose a range of key adaptation strategies for each region based on the resistance/resilience/facilitation framework. How Minnesota's conservation practices need to change so its protected areas network continues to support the state's biodiversity should provide insights for many other midcontinental locales. As importantly, we report this ecological assessment as an example of information assembly that would ideally be part of scenario planning for climate change adaptation.

2. Regional projected climate change

To initiate the ecological assessment for Minnesota, we created climate change projection maps using the LLNL-Reclamation-SCU downscaled climate projections derived from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset, stored and served at the LLNL Green Data Oasis (LLNL et al., 2008). These simulations use general circulation models (GCMs) produced for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), scaled to a finer resolution (i.e., "downscaled") using bias-correction to eliminate discrepancies between the GCM and historical observations, and spatial interpolations to merge course-resolution (2° grid squares, or approximately 200 km by 200 km) GCM values with observed spatial patterns at a 1/8° grid square resolution (approximately 12 by 12 km).

Using averaged results from a single run of all 16 models in the CMIP3 archive, we produced projections of changes in annual and summer temperature and precipitation for two time periods, 2030–2039, and 2060–2069, relative to a baseline period (1970–1999) (data from Maurer et al., 2002; cited in LLNL et al., 2008), for the A2 (upper mid-range) emissions scenario (IPCC, 2001). Model ensemble averages are viewed with greater confidence than individual climate models, because they neutralize extreme results for given regions, and illustrate agreed-upon trends.

Climate change projections were evaluated for eight landscape regions in Minnesota (Fig. 2). These regions were based on Minnesota's Ecological Classification System (MN DNR, 2003), Forest Resources Council Regional Landscape Classification (MFRC, 2008), and Wetland Ecological Units (MN DNR, 1997) so that they reflect major differences in landform and natural vegetation and generally follow political boundaries. For each region, the minimum and maximum average annual temperature and precipitation was determined for the recent past, 2030–2039, and 2060–2069. To estimate current analogs for future conditions, the four coordinate pairs for each region and time were located on maps showing isopleth lines for the US 1961–1990 average annual temperature and precipitation (Owenby et al., 1992). Average summer (June–August) temperature and precipitation were also calculated for each region and time. However, climate maps for summer averages were not available, so we plotted potential analog locations using maps for July averages (High Plains Regional Climate Center, 2008).

Changes in average annual temperature and precipitation by 2069 suggest a shift in regional climates equivalent to current conditions approximately 400–500 km SSW (Fig. 3). Average annual and summer temperatures are projected to increase 3 °C (Tables 1 and 2). Average annual precipitation is predicted to increase slightly (4.8–7.8%) over this interval, although average summer precipitation is expected to decrease slightly, up to 4%. These trends are consistent with other published projections, which suggest that analogs are likely to exist for Minnesota's future climates (Williams et al., 2007) in more southerly midwestern US states (Kling et al., 2003).

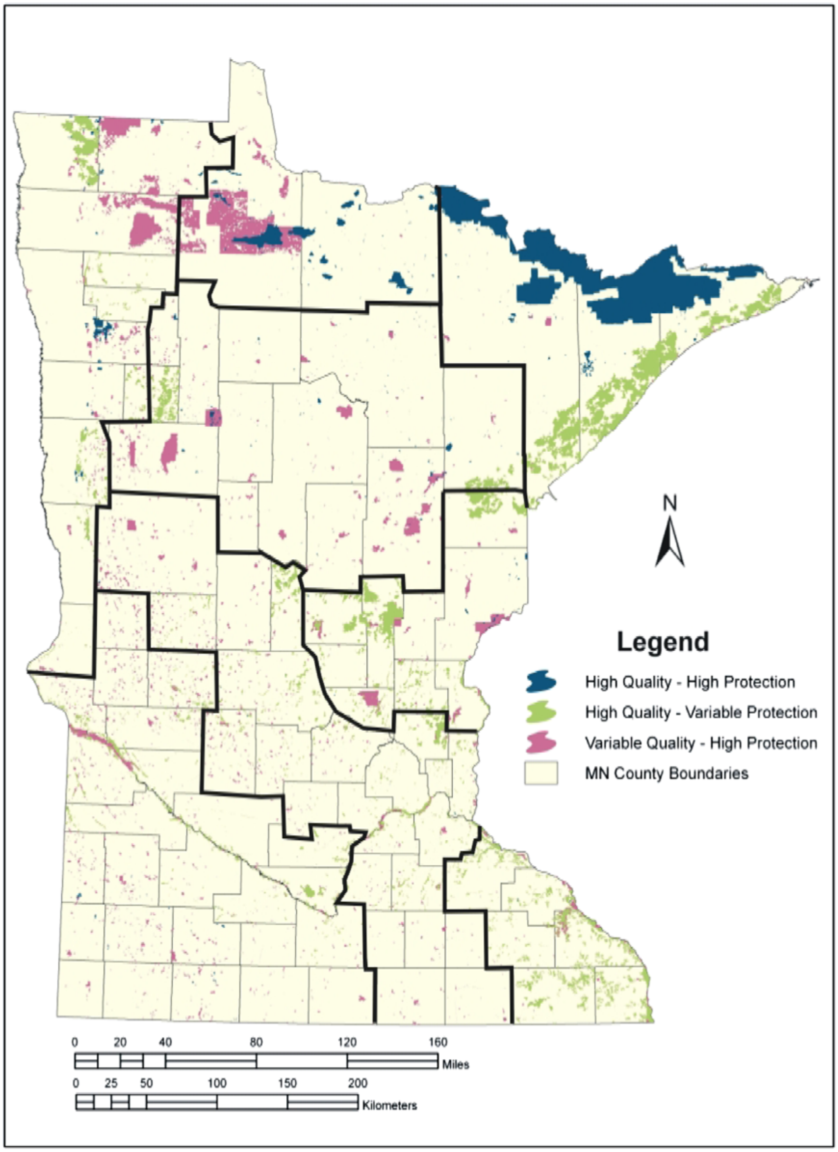

Fig. 1. Protected areas are categorized based on their habitat quality and level of protection. "*High quality – high protection*": Science and Natural Areas, Nature Conservancy preserves, Designated Old Growth Forest, Prairie Bank lands, the BWCA Wilderness and Voyageurs National Park. "*High quality – variable protection*": areas designated as moderate – outstanding quality by the Minnesota County Biological Survey. "*Variable quality – high protection*": State Parks, Wildlife Management Areas, Waterfowl Production Areas, and National Wildlife Refuges. The boundaries of the eight landscape regions are delineated (see Fig. 3 for names and Table 3 for land cover descriptions).

3. Anticipated responses of Minnesota ecosystems to climate change

The likely response to climate change in Minnesota will vary greatly among landscape regions since each differs in the type and extent of remnant ecosystems, land use in the matrix around protected areas, and prevailing environmental conditions (Fig. 1, Table 3). Two of the landscape regions (Agassiz Lake Plain and Southwest Prairie) lie along the eastern edge of Great Plains grasslands. Both regions have been extensively transformed by drainage and cultivation, resulting in losses of prairies and wetlands of >90%. The Boreal peatlands region on the Canadian border is a poorly drained landscape of bogs, tamarack swamps, and fens. Less than 10% of the landscape in this region has been converted for human use (MN DNR, 1997). The remaining five regions are forested landscapes. The Hardwood Hills region spans the prairie-forest border, with remnant oak woodlands and hardwood forests within a matrix of agricultural and urban lands. The Mississippi Blufflands region is a rugged landscape of primarily hardwood forests on high-relief hillsides. Three landscape regions (Western Superior Uplands, Northern Superior Uplands, and Central Lakes) once had extensive coniferous forests that have been replaced by aspen and birch following logging (Friedman and Reich, 2005). After creating the climate projections for Minnesota's landscape regions, we applied relevant literature and local expert knowledge of land-use patterns, vegetation types, soils and hydrology to determine the likely ecosystem responses to climate change within Minnesota's major biomes.

3.1. Wetlands

The effects of climate change on hydrology will determine how wetland ecosystems respond in Minnesota and elsewhere. All but one of Minnesota's landscape regions (Mississippi Blufflands) are predominantly glaciated terrain where interactions between atmospheric moisture and groundwater govern wetland hydrology (Winter, 2000). For these wetlands, a positive water balance is maintained when precipitation and groundwater additions exceed

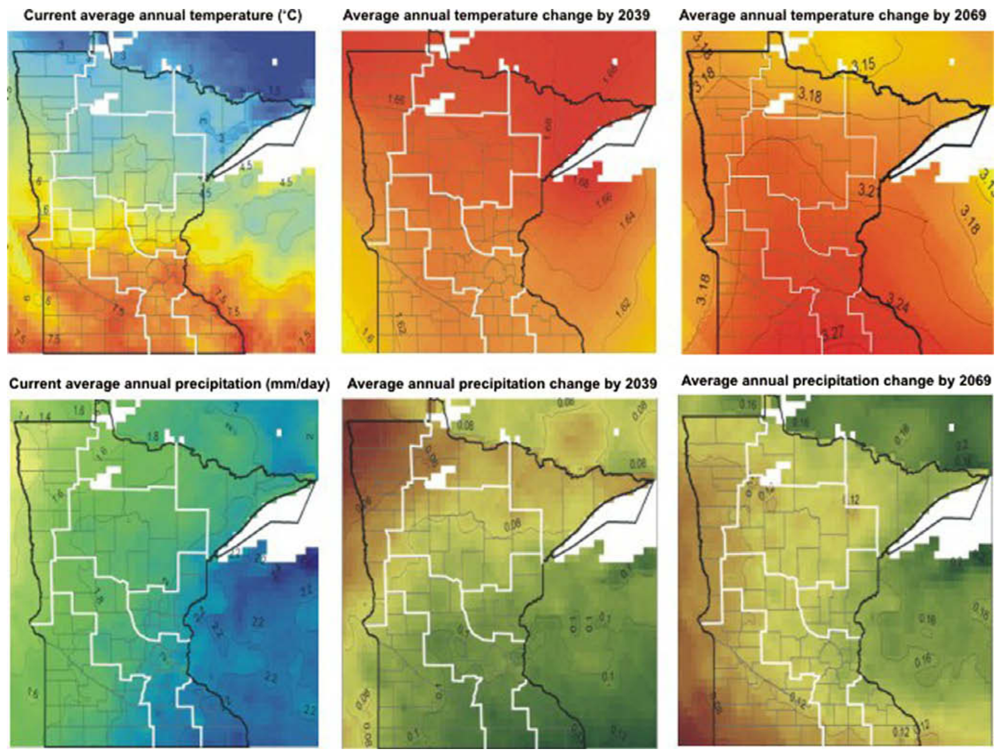

Fig. 2. Projected changes in average annual temperature (C) and precipitation (mm/day) from recent conditions (1970–1999) to 2030–2039 and 2060–2069 based on an ensemble of 16 models under the A2 emissions scenario. Isolines in the projection maps indicate the degree of change relative to the baseline period; color gradient indicates the relative difference in temperature/precipitation across Minnesota within the given decade.

evapotranspiration (ET) losses. Johnson et al. (2005) estimated that a 20% increase in precipitation is needed to compensate for a 3 °C rise in temperature to maintain water balance in wetlands in the eastern Great Plains, including the Southwest Prairie region of Minnesota. Projections from the ensemble model suggest that while Minnesota will experience a 3 °C rise in temperature statewide by 2069, increases in moisture may be only one-third of what is needed to offset ET. Glacial till deposits have low hydraulic conductivity in most landscape regions; consequently, in all but localized areas, wetland ecosystems of Minnesota will likely have shorter hydroperiods.

Decreases in water supply to Minnesota wetlands will likely cause significant shifts in plant communities either as direct responses to water level changes or indirectly through altered soil and water chemistry, decomposition, and disturbance regimes. The decreased hydroperiod expected under a warmer climate will favor several invasive species, especially reed canary grass (*Phalaris arundinacea*) (Galatowitsch et al., 1999). The rate of colonization and spread of reed canary grass greatly exceeds that of native graminoids and forbs in newly created habitats, such as in drawdowns, after fire and in restorations. Of critical conservation concern is the anticipated impacts to calcareous fens which are sustained by mineral-rich groundwater discharge and support a relatively large proportion of rare plant species. There are approximately 100 fens in the state, 20% of the total known for North America (MN DNR, 1997). Lower hydraulic head in the groundwater recharge will reduce flow to fens, favoring non-calciphitic vegetation (Siegel, 2006). Across western Minnesota, freshwater marshes and meadows may become brackish to alkaline as potential ET increases. Currently, potential ET exceeds average annual precipitation in the Agassiz Lake Plain and Southwest Prairie, with brackish wetlands occurring along their western edge. By 2069, ET will exceed precipitation across the state; the conditions in these landscape regions will be more similar to the Rainwater Basin of Nebraska and northern Kansas.

Boreal peatlands, which occupy more than 2,400,000 ha of northern Minnesota and dominate an entire landscape region, may experience the most radical changes of the state's wetland ecosystems. With decreasing water levels and warmer temperatures, shrub growth is expected to increase at the expense of graminoids in ombrotrophic bogs (Weltzin et al., 2000). Lower water tables would also favor the spread of peat fires (Woodwell et al., 1995), likely changing the bog surface and vegetation composition. If the climate of this landscape region becomes similar to Sioux Falls, South Dakota by 2069, the response of peat deposits and vegetation is unclear.

3.2. Forests

Climate effects for Minnesota forests will include warmer summers with more frequent and longer droughts. Because Minnesota is situated on the prairie-forest border, summer precipitation is already marginal for forests on some soils. Many contemporary forests are projected to become savannas (Heinselman, 1996), with forests restricted to cooler, wetter refuges, such as silty soils, lowlands, and north slopes. The boreal biome will likely be lost from Minnesota, while cold-temperate deciduous forests may persist only on north slopes in northern Minnesota. Black spruce (*Picea mariana*), white spruce (*Picea glauca*), balsam fir (*Abies balsamea*), tamarack (*Larix laricina*), and paper birch (*Betula papyrifera*) are likely to exit the state under high emissions scenarios (i.e., A1F1) (Prasad et al., 2008). Boreal red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*) will also likely be lost, but the species may persist in a mixture with oaks (*Quercus macrocarpa*, *Quercus alba*, *Quercus rubra*) and red maple (*Acer rubrum*) on nutrient poor sites.

Large-scale mortality due to a combination of drought stress, blowdown, fire, and insect damage is likely, and has led to rapid and widespread forest change in the past (Camill and Clark, 2000; Foster et al., 2006). Severe thunderstorms, the predominant

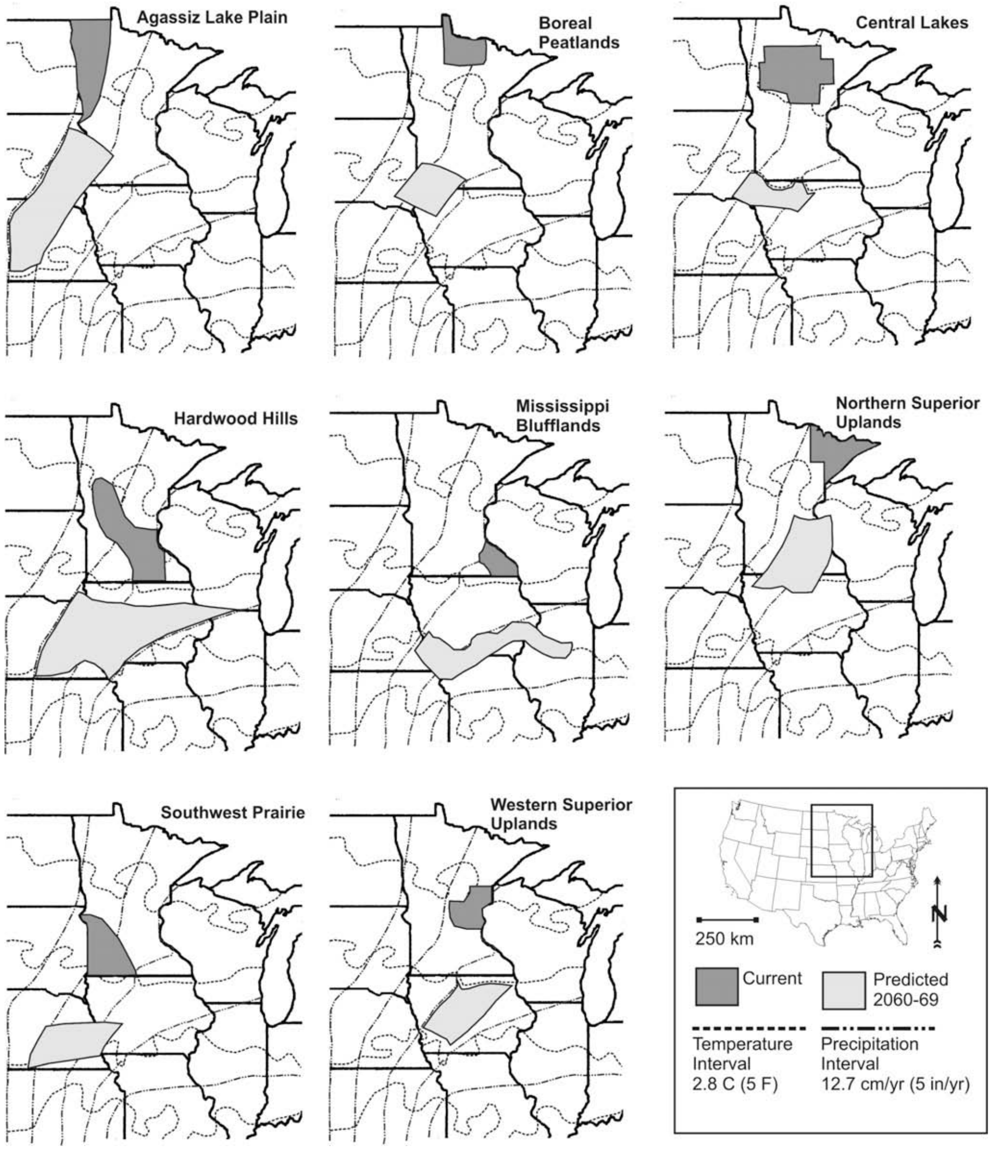

Fig. 3. Analog climate envelopes for each Minnesota landscape region based on projections for 2060–2069 shown on a base map of mean annual precipitation and temperature (1961–1990) (National Climate Data Center – Owenby et al., 1992).

Table 1a
Projected minimum and maximum average annual temperature (°C) for landscape regions in Minnesota, for 1970–1999, 2030–2039, and 2060–2069, based on ensemble modeling (see text for details).

Landscape region	Average annual temperature (°C)					
	1970–1999		2030–2039		2060–2069	
	Min	Max	Min	Max	Min	Max
Agassiz Lake Plain	3.0	6.5	4.7	8.1	6.2	9.7
Boreal Peatlands	3.0	4.5	4.7	6.2	6.2	7.7
Central Lakes	4.0	5.0	5.7	6.7	7.2	8.2
Hardwood Hills	4.5	7.4	6.2	9.0	7.7	10.7
Mississippi Blufflands	6.5	7.5	8.1	9.1	9.8	10.8
Northern Superior Uplands	2.0	4.5	3.7	6.2	5.2	7.7
Southwest Prairie	6.0	7.5	7.7	9.1	9.2	10.8
Western Superior Uplands	4.3	6.5	6.0	8.1	7.5	9.7

cause of forest damage in Minnesota, are expected to increase (Trapp et al., 2007). Blowdowns and warmer, drier weather will lead to more severe fires quickly transforming forests to other forest types or potentially savanna. Tree mortality may increase from insect outbreaks; severe winter cold spells will be less frequent, favoring the establishment and spread of a greater array of insects. For example, the eastern larch beetle (*Dendroctonus simplex*) has caused extensive mortality in recent years—higher population sizes likely the result of lower winter mortality. Likewise, warmer winters could allow mountain pine beetle (*Dendroctonus ponderosae*) to establish in Minnesota (Logan, 2007). Exotic, invasive insect pests, plants, and earthworms that hinder establishment and growth of native tree seedlings are expected to spread faster in a warmer climate (Logan et al., 2003; Bohlen et al., 2004). Rising white-tailed deer (*Odocoileus virginianus*) populations in northern Minnesota will also impact regeneration of several dominant tree species (e.g., *Thuja occidentalis, Pinus strobus, Betula alleghaniensis, Q. rubra*) (Côté et al., 2004).

Tree species capable of growing in climates analogous to those projected for Minnesota include elms (*Ulmus americana, Ulmus thomasii, Ulmus rubra*), hackberry (*Celtis occidentalis*), American basswood (*Tilia americana*), bur oak (*Q. macrocarpa*) and white oak (*Q. alba*). Because of ecotypic differentiation across tree ranges, how local populations of these species will adapt is unclear (Davis

Table 1b
Predicted minimum and maximum average annual precipitation (mm/day) for landscape regions in Minnesota, for 1970–1999, 2030–2039, and 2060–2069, based on ensemble modeling (see text for details).

Landscape region	Average annual precipitation (mm/day)					
	1970–1999		2030–2039		2060–2069	
	Min	Max	Min	Max	Min	Max
Agassiz Lake Plain	1.4	1.7	1.4	1.7	1.5	1.8
Boreal Peatlands	1.6	1.9	1.6	1.9	1.7	2.0
Central Lakes	1.6	2.0	1.7	2.1	1.7	2.1
Hardwood Hills	1.6	2.3	1.7	2.4	1.7	2.4
Mississippi Blufflands	2.1	2.4	2.2	2.5	2.2	2.5
Northern Superior Uplands	1.8	2.1	1.9	2.2	1.9	2.2
Southwest Prairie	1.6	2.1	1.7	2.2	1.7	2.2
Western Superior Uplands	1.9	2.2	2.0	2.3	2.0	2.3

Table 2a
Predicted minimum and maximum average summer (June–August) temperatures (°C) for landscape regions in Minnesota, for 1950–1999, 2030–2039, and 2060–2069, based on ensemble modeling (see text for details).

Landscape region	Average summer temperature (°C)					
	1970–1999		2030–2039		2060–2069	
	Min	Max	Min	Max	Min	Max
Agassiz Lake Plain	18.5	21.5	20.2	23.2	21.8	25.0
Boreal Peatlands	17.5	18.5	19.2	20.1	20.8	21.9
Central Lakes	17.0	19.5	18.7	21.2	20.4	23.0
Hardwood Hills	19.5	21.5	21.2	23.2	23.0	25.0
Mississippi Blufflands	20.0	21.5	21.7	23.2	23.5	25.0
Northern Superior Uplands	14.0	17.5	15.6	19.1	17.3	20.9
Southwest Prairie	20.5	21.5	22.2	23.2	24.0	25.1
Western Superior Uplands	20.0	21.5	21.7	23.2	21.0	24.0

et al., 2005), and migration is unlikely to keep pace with the rate of climate change. In existing woodlands, fire and drought-intolerant tree species will likely die and be unable to reproduce, thus leaving vacant niches for grassland species and fire-resistant woody species (e.g. *Q. macrocarpa*). Sheltered areas with mesic soils may continue to support woodland "islands" or savanna vegetation.

3.3. Prairies

Although many of Minnesota's existing grasslands may persist, a gradual shift in composition to drier species (e.g. mesic prairie to dry prairie; dry oak savanna to prairie) will likely occur in response to higher temperatures and ET. Diverse prairies with high environmental heterogeneity are likely to transition smoothly: existing mesic species will decline in abundance, as dry-tolerant species increase. While all prairie communities may experience declines in mesic and wet species, isolated, homogeneous natural areas and low-diversity mesic-wet mesic prairies may be most susceptible to biodiversity losses, opening niches for invasion of exotic species. Wet prairies are likely to experience significant drying. Losses of this distinctive vegetation type may be particularly pronounced in the Southwest Prairie region, where the protected natural areas tend to be very small, fairly homogeneous, and very isolated within the agricultural landscape matrix. Rare wet-prairie species, such as the federally threatened western prairie fringed orchid (*Platanthera praeclara*), are especially vulnerable to extinction, as the last remnants of their habitat are lost.

Losses of today's prairies could potentially be offset, because grasslands have the greatest potential for expansion in Minnesota with oncoming climate change. Many wetlands and wetland perimeters will become suitable for upland prairie species, and the prairie-forest border will likely shift northward as anticipated decreased soil moisture and increased fire frequency favors grassland vegetation over woodland vegetation (Davis et al., 1998). The ability of prairie vegetation to expand into drying wetlands and receding forests will depend on whether a sufficient number of appropriate seeds can disperse into and effectively colonize these niches as they are vacated. Thus, protected natural areas that contain both woodland and prairie in close proximity are more likely to make this transition with minimal facilitation.

Unfortunately, the highly fragmented nature of Minnesota's protected areas, as well as the abundance of invasive species in the landscape, will limit the ability of prairie species to colonize newly-opened niches. Prairie species have limited long-range dispersal abilities (Kiviniemi and Eriksson, 1999; Bischoff, 2002; Soons et al., 2005), making them unlikely to effectively colonize isolated wetlands located in agricultural fields, urban areas, or highly degraded sites, or extensive areas of present-day forest which may fail to regenerate after large disturbances (e.g. windstorms, fire and insect outbreaks). Even when connected via corridors, grassland expansion into these vacant niches is unlikely to keep pace with the rate of forest die-out (van Dorp et al., 1997;

Table 2b
Predicted minimum and maximum average summer (June–August) precipitation (mm/day) for landscape regions in Minnesota, for 1970–1999, 2030–2039, and 2060–2069, based on ensemble modeling (see text for details).

Landscape region	Average summer precipitation (mm/day)					
	1970–1999		2030–2039		2060–2069	
	Min	Max	Min	Max	Min	Max
Agassiz Lake Plain	2.4	3.0	2.4	3.0	2.4	2.9
Boreal Peatlands	2.9	3.1	2.9	3.1	2.9	3.1
Central Lakes	3.0	3.5	3.0	3.5	2.9	3.4
Hardwood Hills	2.9	3.6	3.0	3.7	2.8	3.5
Mississippi Blufflands	3.5	3.7	3.6	3.8	3.4	3.5
Northern Superior Uplands	3.0	3.3	3.0	3.3	3.0	3.3
Southwest Prairie	2.7	3.6	2.8	3.7	2.6	3.5
Western Superior Uplands	3.3	3.6	3.4	3.6	3.2	3.5

Table 3
Each landscape region's primary ecosystems and extent of protected areas is summarized along with the most significant ecosystem impacts predicted to occur as a result of global climate change, and several key adaptation strategies that may be important for climate change adaptation during the next 50–60 years.

Landscape region	Conservation context	Most significant ecosystem impacts anticipated	Key adaptation strategies
Agassiz Lake Plain	This region consisted of extensive prairies with aspen parkland on sandy glacial lake deposits and on heavy clays of the Red River Valley. Although there are extensive protected areas on the lake plain, the river valley is mostly converted to drained, agricultural land	Reduced extent of wet prairies and meadows; shorter hydroperiods in wetlands; increased brackish and alkaline conditions in wetlands; reduced groundwater flow to calcareous fens	Prohibit agricultural drainage improvements in vicinity of protected wetlands; Prohibit groundwater withdrawals in recharge areas of calcareous fens; Restore agricultural lands to expand small reserves using facilitation practices
Boreal Peatlands	Flat, poorly drained landscape dominated by peatland vegetation, including bogs, black spruce and tamarack swamps, and fens. Protected areas include several large Scientific and Natural Areas	Lower water table in peatlands; increase in peat fires; increased shrub growth in bogs; increased tree mortality from drought, disease, insects and disturbances	Prohibit drainage improvements in vicinity of peatlands; Control peat fires
Central Lakes	Second-growth commercial forests of aspen, maple-basswood, and oak, with some jack, red and white pine on complex glacial deposits (including numerous lakes). Region includes large lake plains with extensive peatlands or bogs, tamarack swamps, and sedge meadows. Many sizeable protected areas (state parks, wildlife refuges)	Increase in large-scale tree mortality; loss of boreal forests; expansion of weedy grassland species; influx of exotic submersed aquatics in lakes; lower water table in peatlands; increase in peat fires	Manage forests to reduce water stress; Facilitate transition from forests to grasslands (rather than invasive species) on shallow and sandy soils; Facilitate expansion of oaks on loamy soils; Remove exotic submersed aquatics from lakes
Hardwood Hills	Hardwood forests and oak woodlands and savannas were interspersed with prairies along this 'prairie-forest border' region. This region includes the Minneapolis-St. Paul metropolitan area and most of the non-metropolitan area has been converted to agriculture. Most of the protected areas are small wildlife management areas	Increased tree mortality from drought, pests, disturbances; influx of exotic submersed aquatics in lakes; shorter hydroperiods in wetlands; expansion of weedy grassland species	Manage forests for reduced water stress; Use fire to reduce dominance by weedy grassland species; Monitor changes in community composition to detect species' declines
Mississippi Blufflands	Steep, highly dissected topography once supported hardwood forests on north slopes and oak savannas and prairies on hilltops and south slopes, with riverbottom forests, oak woodlands and prairies in the valleys. Today, small prairie remnants and second growth oak forests are embedded within a predominantly agricultural landscape. A large state forest and National Wildlife Refuge are the most significant protected areas in this region	Increased tree mortality from drought, pests, disturbance; reduced groundwater flow to calcareous fens	Protect potential refugial habitats; manage forests for reduced water stress; Prohibit groundwater withdrawals in recharge areas of calcareous fens
Northern Superior Uplands	Red and white pine forests and boreal forests of jack pine and black spruce, have mostly been replaced by second-growth commercial forests with aspen, spruce and balsam fir mixtures. Glacially scoured bedrock terrain, often rugged and with numerous lakes. Protected areas include BWCA Wilderness, Voyageur's National Park, Superior National Forest	Increase in large-scale tree-mortality; reduced regeneration from increased deer herbivory; loss of boreal forests	Minimize deer herbivory in white cedar and pine forests; Protect potential refugial habitats; Monitor community changes to detect species' declines; Facilitate transition from forests to grasslands (rather than invasive species) on shallow and sandy soils
Southwestern Prairie	Bisected by the Minnesota River valley, this landscape was once a mosaic of tallgrass prairie and emergent wetlands. More than 90% is now drained agricultural land. Many small wildlife management areas comprise most of the protected areas network in this region	Increased exotic invasions in small protected areas; loss of rare wet-prairie species; reduced extent of wet prairies and meadows; shorter hydroperiods in wetlands; brackish and alkaline conditions increase in wetlands; reduced groundwater flow to calcareous fens	Restore agricultural lands to expand small reserves using facilitation practices; Intensify invasive species removal; Prohibit agricultural drainage improvements in vicinity of protected wetlands; Prohibit groundwater withdrawals in recharge areas of calcareous fens
Western Superior Uplands	Second-growth commercial oak woodlands and hardwood forests on non-calcareous glacial tills, ranging from clayey to sandy. Protected areas with high-quality vegetation are of minor extent, although several large state parks and wildlife areas are in this region	Increased tree mortality from drought, pests, disturbances; shorter hydroperiods in wetlands, influx of exotic submersed aquatics in lake.	Facilitate transition from forests to grasslands (rather than invasive species) on shallow and sandy soils; Facilitate expansion of oaks on loamy soils; Manage forests for reduced water stress: Prohibit drainage improvements in vicinity of protected wetlands; Intensify invasive species removal

Soons et al., 2005); the sheer volume of seeds required to vegetate such a large area makes unassisted transition of boreal forests to high-quality prairie highly improbable. Instead, weedy species are more likely to colonize and spread in drying wetlands and dying forests, because of their superior dispersal and competitive abilities, and their relatively broad environmental tolerances (Lockwood et al., 2005). Without management, these ecosystems will become communities of exotic species—not native prairies.

4. Adaptation options

To address the most significant impacts anticipated for each landscape region, we describe adaptation actions intended to resist climate change, promote resilience to change, or facilitate change (Table 3). As part of a scenario planning process, regional participants would build a set of scenarios that link alternative futures to logical sets of these actions, in a way that is consistent with the reality of both the ecological and socioeconomics of the region (Peterson et al., 2003; Brooke, 2008).

4.1. Resistance strategies

As Millar et al. (2007) noted, resisting climate change is akin to paddling upstream. Resistance actions, i.e., those that oppose changes associated with a shifting climate, will be most useful for overcoming small magnitudes of climate change and, under greater climate change, to save native species for the short term—perhaps a few decades—until other adaptation options are found. Strategies might include increasing water supply, reducing herbivory and invasive species abundance, and fighting insect and disease outbreaks that can overwhelm native plant communities under stress. In some cases, disturbance frequency can be manipulated to help certain plant communities persist as relicts.

Management actions that promote regeneration may increase persistence of existing plant communities by decades or more. Reducing the impacts of woody plant herbivory by white-tailed deer should be considered a key resistance strategy in forested systems. Deer reduce establishment, growth, and, therefore, seed production of many woody and herbaceous species in forests (Ruhren and Handel, 2003; Côté et al., 2004) and prairies (Spotswood et al., 2002). Strategically-located deer exclosures and intensive hunting zones may be critical for certain rare plant species and communities (for example Canadian yew (*Taxus canadensis*) and white cedar forests), thus preserving them until other strategies such as assisted migration can take place.

To maintain the current composition of native communities, intensive vegetation management will be required as rates of invasion increase with species from southern regions migrating northward in response to warmer climates. Thus, resistance strategies could logically include broadening our scope of potential "invaders" and removing incoming migrants as they arrive. For example, removing encroaching non-calciphytic vegetation in fens will be required to maintain species composition as groundwater recharge declines. Species with the capacity for rapid response to climate change will be perceived as management problems and potentially possess traits normally considered invasive. Increased surveillance of already-present diseases, insect pests and exotic plants will also be required, with increase in efforts towards control or eradication. Control of exotic submersed aquatic vegetation will likely be an increasing management concern in lakes; longer ice-free conditions and warmer conditions will increase productivity of extant species and spread of invasive exotics species from the south (Grace and Tilly, 1976; Haag, 1983; Anderson et al., 1996; Magnuson et al., 1997). Statewide surveillance and management programs should anticipate that biological inertia will vary among ecosystems; some, especially forests, could resist invasion by southern and invasive species for decades or more than a century (Von Holle et al., 2003), whereas others will have only short lags in response to climate change.

Management that mitigates drought stress may also be necessary to prolong the lifespan of existing plant communities. For example, agricultural and urban drainage projects need to be more-critically evaluated to prevent lowering the water tables of remaining wetlands, and existing drainage systems may need to be modified so wetlands and wet prairies have improved water supply. In terrestrial ecosystems, well-watered vegetation can resist the effects of heat and, most importantly, manufacture secondary defensive compounds that help resist insects and disease that attack plants under stress. Thinned forest stands will be more resistant to drought because of reduced ecosystem demand for water, and the remaining trees will face less competition for water (Millar et al., 2007).

Fire management can be used to help certain plant communities persist as relicts for a time in a warming climate. For example, fire control could allow mesic forests of maple and oak to persist in climates somewhat warmer and drier than those historically occupied. Due to Minnesota's location on the prairie-forest border, it is expected that fires will lead to rapid conversion of forests to grassland vegetation types in a warming climate. On the other hand, use of frequent fire could help keep out invasive species in prairies (Pauly, 1997).

4.2. Resilience strategies

Adaptation options that maintain or restore an ecosystem's resilience are widely recommended responses to climate change, although how to promote gradual change while aiming for post-disturbance recovery to a prior condition may be difficult to reconcile "on-the-ground" (Dale et al., 2001; Price and Neville, 2003; Spittlehouse and Stewart, 2003; Millar et al., 2007). Managing ecosystems so disturbances do not trigger a shift to a stable state of a few invasive species is clearly critical, given anticipated lags in adaptation or migration of many plant species. An abrupt shift to an invasives-dominated state can arise following a disturbance when a latent seedbank of invasives is present, when stressors favor establishment of the invaders over indigenous species, or when the disturbance itself undermines the capacity of the indigenous community to regenerate. High proportions of the protected areas network in the western and southern parts of Minnesota are likely to be especially vulnerable to climate change impacts because they receive high propagule loads of invasive species or are surrounded by agricultural land.

The importance of buffers for reserves is not a new idea, but a response to climate change in fragmented landscape regions needs to more-highly prioritize systematic planning of buffers for protected areas based on maximizing resilience. Buffering protected areas will often necessitate restoration, but the goal may not always need to be revegetation of high-diversity natural communities; in some cases buffer protection can focus on reducing specific impacts. For example, in the vicinity of high-quality wetlands, drainage "improvements" that lower water tables should be curtailed or reversed to minimize problems associated with climate-triggered water stress. Ecosystems in relatively intact landscapes currently may have sufficient resilience but land and water use policies should be conservatively implemented in these regions as well, to avert resilience loss.

In highly converted landscape regions, many reserves may not have adequate environmental heterogeneity for plant and animal populations to escape or recover from increasing episodes of drought and heat expected with climate change. These reserves should be enlarged so they contain more physiographic diversity. Statewide, locations that are cooler and wetter, such as north-facing slopes and depressions, are likely climate refuges. However, we know relatively little about the degree to which topographical features will be able to provide refuges for species because nearly all climate observations are made on sites with low relief. In aquatic ecosystems, refuges will often be tied to specific hydrologic settings. For example, floating bogs, which form as shelves extending into lakes, could potentially serve as refuges because they will be less affected by water level declines than other kinds of peatlands. Relict floating *Sphagnum* bogs (poor fens) are scattered throughout southern Minnesota and even into northern Iowa (Grant and Thorne, 1955).

Vegetation management within reserves will also be crucial for maintaining resilience. In forests, multi-aged and multi-species stands will be more resilient to change because there will be within-stand variability in resistance to wind (within and across species), and more species will be available to fill niches for those lost to drought and insect mortality (Rich et al., 2007). Northern and mesic tree species can be allowed to contract their niche, so that species adapted to warmer and drier conditions can expand. Prescribed fire can be used to allow episodes of natural selection and recruitment among small seedlings as the climate warms. Selection at the seedling stage is very intense in tree species, allowing relatively fast adaptation in terms of generation times (Davis et al., 2005); thus increasing reproduction opportunities during a warming climate could help tree species adapt to climate change. The minimum age of reproduction is a limiting factor as to how much selection and adaptation could occur over the next several decades.

For both prairies and forests, disturbance prescriptions, such as controlled fires and floods, will need to be shifted over time in accordance with new climate realities (Ryan, 1991). For sites that have analog communities, knowledge of these communities may be critical for guiding management prescriptions.

4.3. Facilitation strategies

Shifting from a conservation practice paradigm centered on resistance and resilience to one focused on facilitation and resilience will be necessary to avoid unsustainable land management expectations and, consequently, serious losses in biodiversity when these expectations cannot be met or are no longer effective. Facilitation actions could "mimic, assist, or enable ongoing natural adaptive processes such as species dispersal and migration, population mortality and colonization, changes in species dominances and community composition, and changing disturbance regimes" (Millar et al., 2007). The high level of fragmentation in southern Minnesota and southward into Iowa means that many immigrating colonists may not accomplish range shifts without assistance if they cannot adapt in place. Landscape corridors, often touted as a way to foster range shifts, are unlikely to be an effective strategy for much of Minnesota given the amount of acquisition and restoration required to create corridors through agricultural landscapes and the low probability that many plant species will jump to these corridors and move at a rate that keeps pace with climate change.

Assisted colonization (also called assisted migration) has become a contentious conservation issue because of ecological uncertainty and perceived risks (McLachlan et al., 2007). However, both risks and uncertainty are likely to be low when facilitating gradual shifts of common species (Hunter, 2007, in part). Making relatively minor changes to ecosystem restoration practice should be one straightforward way to facilitate transitions for these species. To avoid creating relict communities at the onset of restorations, seeds rather than plants should be relied on for revegetation (Young, 2007). Germination and seedling establishment are often the most sensitive life stages to environmental cues, so seeding allows prevailing conditions to filter species composition. Seeding prairie restorations (but not forests and wetlands) in Minnesota is already the norm and is supported by a well-developed network of native seed producers and restoration nurseries. Seed mixes for climate change facilitation need to have broader seed zones than are currently recommended (which can be as restrictive as setting zones to be within 30 km of projects). Drawing propagules from sources in the geographic direction of projected climate shifts and including many propagule sources to maximize genetic diversity will help ensure greater adaptability to a variable climate (Millar et al., 2007). Mixes should include some species from climates expected in the near future (sensu "ecological blueprint concept", Frelich and Puettmann, 1999).

Restorations for wildlife habitat, legally-required mitigation, and expanding protected areas should provide significant facilitation opportunities for common species in Minnesota, without relying on remnant/relict natural ecosystems to serve as recipient sites. However, following large-scale forest mortality, natural communities may require species augmentation, if regeneration of the prior community fails. Overseeding these sites with mixes including species from adjacent, warmer locales may be an effective adaptation action that will reduce the likelihood that invasive species will dominate in these protected areas.

Facilitating climate transitions will undoubtedly be a less certain practice for uncommon species or even subdominant species (such as forest understory forbs) that may have specific habitat requirements, poor dispersal and regeneration capacity, or few and small populations. The biology of these species is often poorly understood and propagation practices undeveloped. Nonetheless, assisted colonizations will likely need to be attempted; species with small ranges/distributions generally face greater risk of extinction as a result of climate change (Schwartz et al., 2006). A system for monitoring candidates for assisted colonization is particularly important for species with narrow ranges that could experience fundamental habitat changes because of climate change, e.g., those restricted to calcareous fens, ombrotrophic bogs, and at the "trailing edge" of freshwater habitats in Minnesota. Species of special conservation importance from these wetlands may need to be translocated to less impacted sites when chemical changes (i.e., calcium, acidity, alkalinity) become unsuitable. Monitoring "trailing edge" populations of all rare/threatened species (e.g., *Lespedeza leptostachya, P. praeclara*) needs to be a conservation priority so if populations begin to decline, plans for assisted colonization can be implemented for these species along with associates, such as specialized pollinators (e.g., hawkmoths for *P. praeclara*, Sheviak and Bowles, 1986) and seed dispersers (e.g., ants for forest spring ephemerals). As with common species, introduced populations of rarer species should attempt to maximize genetic diversity by relying on multiple donor sites. In addition, assisted colonization projects should be conducted in multiple years, bet-hedging against years with unfavorable conditions for establishment.

5. Adopting climate change adaptation conservation practices

In conclusion, there are limitations on the magnitude of climate change for which each of the three strategies discussed in this paper will be helpful. In general, resistance, resilience and facilitation strategies will allow adaptation to small, medium and large magnitudes of expected climate change, respectively. It may be necessary to switch from one strategy to another as the climate continues to warm. Local expertise at the ecoregional scale will be necessary to match the appropriate strategies with the expected responses of the species present given the predicted rate and magnitude of climate change. Local knowledge of the physiography of the landscape also comes into play. For example, on a flat landscape there may be no refuges from a given magnitude of climate change, triggering a facilitation strategy such as assisted migration. On the other hand, a hilly landscape may provide refuges for some species on north slopes with cooler temperatures, and a facilitation strategy may not be triggered until a larger magnitude of climate change occurs.

Coupling monitoring to decision-making, i.e., adaptive management, should be central to scenario plans developed for biodiversity conservation. Explicitly considering the information needed to assess whether strategies are proving effective or need to be shifted should drive a serious commitment to biological monitoring. The uncertainties associated with climate change cannot be surmounted *a priori;* the only rationale approach to adaptation will be based on contemporaneous information. Major institutional development and reform in environmental agencies and organizations will almost universally be needed to ensure reliable data is collected, analyzed and used as part of iterative decision-making. As importantly, planning and monitoring cannot be constrained by political boundaries (e.g., states) – there must be coordination across broad geographic areas, as indicated by current projections of climate analogs. The aggregated challenges posed by climate change to biodiversity conservation will hopefully spur, not stall, meaningful adaptation planning.

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