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CONSERVATION ISSUES

Wilderness Conservation in an Era of Global Warming and Invasive Species: a Case Study from Minnesota's Boundary Waters Canoe Area Wilderness

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ABSTRACT: Climate warming is predicted to cause boreal forests in the Boundary Waters Canoe Area Wilderness (BWCAW), Minnesota, to shift to savanna and/or temperate forest in the next century. Invasive earthworms, exotic tree pests, and deer overabundance will magnify the impacts of warmer temperatures. Seldom do we assess potential threats to ecosystem and wilderness integrity in a systematic way and develop policy and management strategies ahead of time to mitigate the situation. Debates on several issues involving wilderness users, managers, and scientists need to be resolved for the BWCAW. These include whether, when, and how to: (1) use fire; (2) restore tree species to wilderness areas lost through human actions (e.g., logging of white pine (*Pinus strobus* L.) that occurred before wilderness designation and potential loss of ash species from the introduced pest emerald ash borer (*Agrilus planipennis* Fairmaire)); (3) manage the potential overabundance of deer that threaten reproduction of some tree species; (4) facilitate (or prevent) migration of new tree species currently native south of the wilderness; (5) employ local (within wilderness) or regional assisted migration for species that cannot migrate fast enough on their own to keep up with climate change; and (6) manage invasive species. Some of these activities would not be allowed under the wilderness laws of 1964 and 1978, and may be difficult to enact or limited in effectiveness. Major change in forests of the BWCAW is a certainty, and facilitation of a 'graceful transition' to native species rather than exotic species is desirable.

Index terms: assisted migration, boreal forest, climate change, savanna, wilderness management

INTRODUCTION

Global change poses difficult problems for management of wilderness areas. Wilderness areas play several roles, including spiritual retreats, reference ecosystems for comparison with surrounding lands managed for commercial production, and refuges for biodiversity. Large size, lack of fragmentation, and strict protection from direct human action in wilderness areas does not guarantee future sustainability of these human and biological resources. For forested wilderness areas in North America, there are a number of threats including climate change, invasive tree diseases and pests, invasive plant species, and increasing numbers of deer. This onslaught of ecological changes is capable of removing foundation tree species and causing ecosystem change on a vast scale. These threats generally cannot be kept at bay by ownership boundaries, level of protection, or size of area, and were not anticipated when the Wilderness Act of 1964 was signed into law.

The two million ha Quetico-Superior Ecosystem, located in central North America in the United States and Canada, provides an ideal case study of the problems faced by wilderness areas in a changing climate. This forest ecosystem is among the most endangered in the world for two reasons; first, it is located in a mid-continental, moderately high latitude region where the predicted magnitude of climate change will be more than the global mean (Christensen et al. 2007), and second, the forest vegetation is more sensitive to a changing climate than most because it lies close to the prairie biome. Several premiere wilderness areas and natural areas lie within this ecosystem. The Boundary Waters Canoe Area Wilderness (BWCAW) is a 400,000 ha unit of the national wilderness preservation system established by the Wilderness Act of 1964 and later enhanced by the Boundary Waters Wilderness Act of 1978. It is the only canoe wilderness, the most heavily visited wilderness in the United States wilderness preservation system, the largest wilderness in the northeastern quadrant of the U.S., and contains the only extensive tracts of unlogged lowland boreal forest in the U.S. outside of Alaska (Frelich 1995; Heinselman 1996). The BWCAW shares the international boundary with Quetico Provincial Park, Ontario, Canada, and together the two units comprise a contiguous wilderness area of more than one million ha.

The purpose of this paper is to review threats to the boreal forest of the Quetico-Superior Ecosystem, using the BWCAW as a focal point, and to discuss potential mitigation measures, directions for management, and related policy issues. A number of lessons derived from the BWCAW may apply elsewhere, since many wilderness areas will face similar issues.

DRIVERS OF CHANGE IN BWCAW BOREAL FORESTS

Fire – too little or too much?

Forests of jack pine (*Pinus banksiana* Lamb.) mixed with black spruce (*Picea mariana* (Mill) B.S.P.), quaking aspen (*Populus tremuloides* Michx.), and paper birch (*Betula papyrifera* Marsh.) were a mainstay of the pre-European settlement, upland, southern boreal forests of the Quetico-Superior Ecosystem, and were regenerated by severe crown fires with rotation periods of 50-100 years (Heinselman 1996). These two conifers are adapted to fire via serotinous cones, while *Populus tremuloides* and *Betula papyrifera* reproduce after fires by root sprouting, stump sprouting, or long distance seed transport. A second major forest type, white pine (*Pinus strobus* L.) and red pine (*Pinus resinosa* Ait.), dominated almost 40% of the townships in northeastern Minnesota in the presettlement era (Friedman and Reich 2005). These species do not have serotinous cones, but are well adapted to surface fires with thick bark and foliage held above the reach of scorching heat. For all these species, fires are a double edged sword; it is necessary for regeneration, but if it occurs too often, young trees will be killed before they reach the age of reproduction, and if it does not occur often enough, then the old trees will die without leaving behind reproduction to continue the forest (Heinselman 1996; Weyenberg et al. 2004). A number of fire sensitive tree species are present that are confined to lakeshore and wetland refuges from fire; the most common include balsam fir (*Abies balsamea* (L.) Mill.), white spruce (*Picea glauca* (Moench) Voss), northern white cedar (*Thuja occidentalis* L.), red maple (*Acer rubrum* L.), and black ash (*Fraxinus nigra* Marsh.) (Table 1).

In the past century, the interval between fires lengthened markedly from 50-100 years during Heinselman's 1600-1900 study period, to > 700 years since 1910 (Heinselman 1996). This lengthening of the fire cycle is thought to be caused by a warming climate at the end of the Little

Table 1. Tree species native to the BWCAW grouped by response to a warm/wet climate scenario. DED= Dutch elm disease, MPB = mountain pine beetle, ALB = Asian long-horned beetle, EAB = Emerald ash borer, SOD = sudden oak death, HWA = hemlock woolly adelgid, BWA = balsam woolly adelgid, ELB = eastern larch beetle.

Species and group	Potential problems
Group 1—species likely to largely disappear with a warmer climate	
Balsam fir (*Abies balsamea* (L.) Mill.)	BWA, heat, drought
Black spruce (*Picea mariana* (Mill) B.S.P.)	Heat, drought
White spruce (*Picea glauca* (Moench)Voss)	Heat, drought
Jack pine (*Pinus banksiana* Lamb.)	Heat, blowdown/fire combination, lack of fire, MPB
Red pine (*Pinus resinosa* Ait.)	Heat, drought, blowdown/fire combination, lack of fire, MPB
Balsam poplar (*Populus balsamifera* L.)	ALB, heat, drought
Group 2—abundant species likely to remain (possibly with reduced abundance, marked by asterisk) with a warmer climate	
*Paper birch (*Betula papyrifera* Marsh.)	ALB, soil warming,
*Quaking aspen (*Populus tremuloides* Michx.)	ALB, heat, drought
*Big-tooth aspen (*Populus grandidentata* Michx.)	ALB, heat, drought
Black ash (*Fraxinus nigra* Marsh.)	EAB
*Tamarack (*Larix laricina* (DuRoi)K.Koch.)	ELB, heat, drought
Northern white cedar (*Thuja occidentalis* L.)	Deer
Eastern white pine (*Pinus strobus* L.)	Deer, blowdown/fire
Group 3—species at low abundance likely to increase with a warmer climate	
American basswood (*Tilia americana* L.)	
Northern red oak (*Quercus rubra* L).	Deer, SOD
Bur oak (*Quercus macrocarpa* Michx.)	
Northern pin oak (*Q. ellipsoidalis* E.J.Hill)	Deer, SOD
Green ash (*Fraxinus pennsylvanica* Marsh.)	EAB
American elm (*Ulmus americana* L.)	DED, ALB
Red maple (*Acer rubrum* L.)	ALB
Silver maple (*Acer saccharinum* L.)	ALB
Yellow birch (*Betula alleghaniensis*	Deer, ALB, mismatched soils
White oak (*Quercus alba* L.)	

continued

Table 1. Tree species native to the BWCAW grouped by response to a warm/wet climate scenario. DED= Dutch elm disease, MPB = mountain pine beetle, ALB = Asian long-horned beetle, EAB = Emerald ash borer, SOD = sudden oak death, HWA = hemlock woolly adelgid, BWA = balsam woolly adelgid, ELB = eastern larch beetle.

Species and group	Potential problems
Group 4--species likely to migrate in with a warmer climate	
Sugar maple (*Acer saccharum* Marsh.)	Drought, earthworm invasion, fire,
Black cherry (*Prunus serotina* Ehrh.)	Drought, mismatched soils
Cottonwood (*Populus deltoides* Bartr. Ex Marsh.)	
Boxelder (*Acer negundo* L.)	ALB
Black willow (*Salix nigra* Marsh.	ALB

Ice Age (allowing more humid air masses from the Gulf of Mexico to penetrate further north), fragmentation of the landscape to the south of the BWCAW (interrupting the flow of fire across the landscape), and fire suppression (Johnson 1992; Bergeron and Archambault 1993; Heinselman 1996). During this long period without chronic stand-clearing disturbances, late-successional species that formerly occupied a small proportion of the BWCAW landscape increasingly became the forest dominants (Frelich and Reich 1995). It is clear that a major reintroduction of fire will be necessary, or *Pinus* dominated forests will decline over time and completely disappear within 150 years (Heinselman 1996; Scheller et al. 2005). The disappearance of early-successional *Pinus* forests has also been accelerated by the 'Big Blowdown' of 1999, a derecho that leveled about one-fourth of the forests within the BWCAW, which preferentially removed early successional species from the forest canopy (Rich et al. 2007) and placed the canopy stored seedbank of *Pinus banksiana* near the forest floor, where cones are likely to be consumed by subsequent fires. Such blow downs are predicted to increase with a warmer climate (Trapp et al. 2007).

Even more recently, large-scale fire has returned with the Cavity Lake Fire of 2006 (13,000 ha) and the Ham Lake Fire of 2007 (29,000 ha). It is too early to tell whether this heralds a reversal of the low fire frequencies of the 20th century. Although the warming at the end of the Little Ice Age favored reduced fire frequencies, as warming proceeds, greater evaporation may come to predominate over the effects of moist air masses and lead to an increase in fire frequency. More fires like those of 2006 and 2007 are likely to occur, and with higher blowdown frequencies and the predominance of older forests, these storms and fires will probably hasten the demise of *Pinus* forests.

Global warming

The BWCAW, and northern Minnesota in general, have a large number of tree species at the edge of their ranges. All of the boreal tree species in the BWCAW are within 300-500 km of the southwestern edge of their ranges. Moreover, for Quetico-Superior forests, the biome boundary with the tallgrass prairie is only 200-350 km to the west. The best available predictions are for increases in summer temperatures of 3-7^{o} C by the end of the 21st century (Christensen et al. 2007). Rainfall is likely to remain about the same as at present but with increasing variability, creating a warmer and drier climate, although there is also some chance that the future climate will be warmer and wetter (Wuebbles and Hayhoe 2004). In addition, variability in texture, depth, and water holding capacity of soil and topographic features in the BWCAW may allow patches of forest to persist in some areas even if a warm/dry scenario develops.

Thus, a warming climate is likely to cause a biome change - most likely from boreal forest to grassland/savanna and possibly from boreal forest to temperate hardwood forest. Whether and how quickly the existing forest converts to either of these more southerly vegetation types depends on the inertia of the system. The paleoecological record indicates that vegetation of northeastern Minnesota is particularly sensitive to climate change, with little inertia. An episode of warm and dry climate 8000 ybp to 5000 ybp (which was not as warm as the predicted climate for the late 21st century) resulted in northeastward movement of species with high abundances of *Quercus* and grasses in areas that have boreal forest today. During the last 3000 years (and reinforced during the last 1000 years by episodes of cool climate such as the Little Ice Age), grasses and *Quercus* declined in the area, and were replaced by the existing boreal forest (Webb et al. 1983). Vegetation near biome boundaries is generally thought to be more sensitive to climate change, and paleohistory shows this is the case for the Quetico-Superior Ecosystem.

Whether transition to savanna or forest occurs, the vegetation of the BWCAW is likely to be in a state of flux for centuries while new species migrate in and develop the relationships among themselves and their environment that will define the future ecosystem. As Heinselman (1996) points out, a warm/dry climate warming scenario would, by 2100, create a climate similar to Iowa that typically supports "tallgrass prairie on the uplands and wet prairie and marsh on poorly drained soils, with scattered oak groves on the uplands and with cottonwood, box elder, willow, elm, and ash along streams". Bur oak (*Quercus macrocarpa* Michx.), northern red oak (*Q. rubra* L.), and northern pin oak (*Q. ellipsoidalis* E.J. Hill) are already present in low numbers on rocky sites throughout the BWCAW, and *Ulmus* and *Fraxinus* are also present, but face other threats discussed below.

A warm/wet scenario would allow for many possibilities for future forests, which is best summarized by dividing tree species into four groups (Table 1). Group 1 includes boreal species with the southern margin of their range in northern or central Minnesota. This group includes *Picea mariana*, *P. glauca*, *Abies balsamea*, *Pinus banksiana*, *P. resinosa*, and balsam poplar (*Populus balsamifera* L.) (Heinselman 1996; Prasad et al. 2007). These species can be expected to decline greatly in abundance or to disappear, depending on the magnitude of warming, based strictly on climate-distribution relations, with premature death of mature trees and lack of regeneration ability to compete with species adapted to warmer conditions probably the actual mechanisms involved. Group 2 includes species present in high numbers in the Quetico-Superior that have ranges extending further south or that can grow on warmer, drier landscape positions than species in Group 1. These species are predicted to remain, possibly in reduced numbers, and the group includes tamarack (*Larix laricina* (DuRoi)K.Koch.), *Betula papyrifera*, *Populus tremuloides*, bigtooth aspen (*Populus grandidentata* Michx.), *Fraxinus nigra*, *Thuja occidentalis*, and *Pinus strobus*. Group 3 includes species present at low numbers in the Quetico-Superior and elsewhere in the southern boreal forest, but which are limited in terms of northern distribution by the present climate, such as *Acer rubrum*, *Quercus macrocarpa*, *Q. rubra*, *Q. ellipsoidalis*, yellow birch (*Betula alleghaniensis* Britton), green ash (*Fraxinus pennsylvanica* Marsh.), and American basswood (*Tilia americana* L.). Group 3 species currently dominate small patches that can be expected to expand across the landscape under a warm/wet scenario. Group 4 includes species whose northern range limit is south of the BWCAW but that may migrate in. There are many possibilities, but the most likely species that are closest include cottonwood (*Populus deltoides* Bartr. Ex. Marsh.), box elder (*Acer negundo* L.), black willow (*Salix nigra* Marsh.), sugar maple (*Acer saccharum* Marsh.), white oak *Quercus alba* L.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and black cherry (*Prunus serotina* Ehrh.) (Walker et al. 2002; Prasad et al. 2007). Recent experiments in Ontario indicate that *Acer saccharum* would have no problems other than seed source limitation to invade the southern boreal forest (Kellman 2004). A review of predicted future range maps shows that under a warmer, wetter climate, vegetation similar to that in the region from Upper Michigan to Pennsylvania is likely to develop, although the shallow rocky soils in parts of the BWCAW may limit the success of some of those species (Table 1).

Invasive species

There are no native earthworms in the northern temperate or boreal forests, including the BWCAW (Tiunov et al 2006). European earthworms are invading at this time and are readily able to penetrate the depths of the wilderness since they are used as live fishing bait, and the region has many popular fishing lakes. Earthworms are fundamental ecosystem engineers that change soil structure, seedbeds, nutrient cycles, and the hydrologic cycle. In this region, the invasive earthworm *Lumbricus rubellus* Hoffmeister, is capable of consuming the forest floor duff layer in all forest types except *Picea*, *Pinus banksiana*, and *P. resinosa*, and the nightcrawler (*L. terrestris* L.) maintains the litter-free conditions indefinitely, making the soil susceptible to erosion (Hale et al. 2005). Earthworms are particularly abundant in Ca-rich forests dominated by *Acer* and *Tilia* (Reich et al. 2005), so it is not clear how intensely they will affect the BWCAW forests as they invade. In *Acer*-dominated forests, earthworms increase the bulk density of the soil A horizon, and reduce availability of the key nutrients N and P, leading to declines in tree growth rate (Hale et al. 2005). They also open the door for invasive plant species from Europe that coevolved with earthworms, including garlic mustard (*Alliaria petiolata* (M. Bieb.) Cavara and Grande) and common buckthorn (*Rhamnus cathartica* L.), and by reducing seedling density also increase the deer:plant ratio and magnify the impact of deer grazing on tree reproduction (Frelich et al. 2006; Heneghan et al. 2006).

Invasive tree diseases and pests

Several introduced insect pests and diseases will likely have major impact on temperate and boreal North American tree species over the next several decades. The emerald ash borer (*Agrilus planipennis* Fairmaire) is a native of Asia and has the capability to cause nearly100% mortality of native ash species over large regions (MacFarlane and Meyer 2005). *Fraxinus nigra* is abundant within forested wetlands in much of the southern boreal zone, and is considered an important tree for the function of boreal wetlands in eastern North America (Tardiff and Bergeron 1999). The BWCAW is in the high susceptibility zone for Asian longhorned beetle (*Anoplophora glabripennis* Cano), which can destroy tree species in the genera *Acer* and *Populus* (Nature Conservancy 2008). Hemlock woolly adelgid (*Adelges tsugae* Annand) is a needle sucking insect from Asia that causes close to 100% mortality of *Tsuga canadensis* (Stadler et al. 2005). It has already caused widespread devastation of forests in the eastern United States and although *Tsuga canadensis* is currently absent, the BWCAW is predicted to become climatically optimal for hemlock under some global warming scenarios. Thus, the adelgid may prevent *Tsuga*'s future migration into the BWCAW. Balsam woolly adelgid (*Adelges piceae* Ratzeburg) is capable of devastating *Abies balsamifera*, and is limited by cold winters, but has invaded the southern portion of Maine in recent years due to mild winters (Maine Forest Service 2008). This recent invasion is of concern for the BWCAW because winters in northern Minnesota are projected to become as mild as Maine within several decades. Sudden oak death (*Phytopthora ramorum* S. Werres) is a foliar and trunk canker disease from Asia first introduced in California several years ago. Tests indicate that *Quercus rubra* and *Q. ellisoidalis* are susceptible (U.S. Department of Agriculture, Forest Service 2002; Table 1).

Insects native to Minnesota and other parts of North America can also become invasive in a warmer climate. The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) has a good chance of making its way to Minnesota from British Columbia, where it has killed 12 million ha of lodgepole pine (*Pinus contorta* Dougl. Ex Loud.) in recent years (Kurz et al. 2008). With warmer winters, the beetle population may move across the southern margin of the boreal forest, and is capable of killing *Pinus banksiana* (a close relative of *P. contorta*) and possibly *P. resinosa* and *P. strobus* (Logan 2007). The eastern larch beetle (*Dendroctonus simplex*

LeConte) is a native to Minnesota that has experienced rapid population growth in recent years with mild winters, and has caused significant mortality in Minnesota *Larix* stands.

Deer Browsing

Currently, grazing by white-tailed deer (*Odocoileus virginianus* Zimmermann) is not a major problem for tree regeneration in the BWCAW, which has a density of 0.8-1.2 deer per km^2 (Lenarz 2005), and prior to European settlement in the late 1800s, deer were virtually absent in the region. Regeneration of species such as *Thuja occidentalis* is abundant, a situation rarely seen 100 km further south where deer populations range from 6-7 per km^2 (Lenarz 2005). The deer population in the BWCAW is limited by deep snow and number of severely cold days each winter. Areas south of the BWCAW and much of the eastern U.S. report widespread problems with regeneration of *Thuja occidentalis*, *Pinus strobus*, *Quercus rubra*, and *Betula alleghaniensis* due to deer grazing (Cornett et al. 2000; Cotè et al. 2004; Table 1); and the BWCAW may experience winter climate conditions similar to those areas within a few decades. A warmer climate will allow a higher deer population in the BWCAW, but it is uncertain how much higher. The BWCAW has a large population of gray wolves (*Canis lupus*), and it lacks the upland checkerboard of edge habitat that logging has created over most of the landscape, two factors that may work to limit the deer population to lower levels than experienced elsewhere. The next few decades in the BWCAW will be a good test of the hypothesis that high deer populations are facilitated by human-caused landscape fragmentation (Alverson et al. 1988).

IMPACT SCENARIOS

The possibility of a major dieback of BWCAW forests during global warming exists. Serial correlations in weather patterns (i.e., the tendency to have several years in a row of extreme weather) show that a few years of extreme conditions could cause major forest change well before the mean temperature reaches a level that would induce change (Cohen and Pastor 1991). In addition, rapid change is more likely for regions such as Minnesota, where drought frequency is high so that a constant supply of water will not mitigate the impacts of a warmer climate on trees. Recent diebacks and growth declines in boreal trees over large areas of boreal forest in Alaska and Canada, and the possibility of synergistic responses by forest pests and the likelihood of increased frequency of large blowdowns in a warmer climate, make major diebacks likely (Barber et al 2000; Logan et al. 2003; Hu et al. 2004).

The following scenarios are intended to bracket the range of possibilities for the future of BWCAW forests by the late 21st century. Land managers will face the task of narrowing and refining the potential scenarios under consideration as new information on climate trends, better climate models, degree to which climate mitigation may become effective, and response of the existing forests become evident over the next few decades.

Scenario 1. Very warm and dry, IPCC (Intergovernmental Panel on Climate Change) high emission scenario (Christensen et al 2007) with a large decrease in growing season precipitation to evaporation ratio. The expected outcome for the vegetation would be transition from boreal forest to *Quercus* savanna. The BWCAW could become the largest savanna wilderness in the eastern U.S. and provide a landscape-scale restoration of an ecosystem that was decimated during the 20th century (Nuzzo 1986). The challenge for managers would be to facilitate a 'graceful transition' to savanna, during which assisted migration may be necessary to help a large suite of native savanna species enter the wilderness, and to keep European and Asian invasive species at bay. Triage of existing forests as they died would also be a major challenge (Millar et al. 2007). Large-scale high-severity fires in dying, drought stressed forests would occur, similar to the Cavity Lake and Ham Lake fires of 2006 and 2007, both of which burned parts of the BWCAW. As the savannas (with considerable grass understory) replaced the forest, fires would become more frequent with relatively high rates of spread, but the fire intensity would decrease. Many prairies and savannas interspersed with human settlement are currently managed with natural and prescribed fires, since the firebreaks required and effort necessary to suppress low-intensity grass fires are modest relative to the boreal forest fires that have occurred historically in the BWCAW.

Scenario 2. Warm and dry, IPCC low emission scenario with some decrease in growing season precipitation to evaporation ratio. The expected outcome for vegetation would be a mosaic of savanna on shallow soils and stands of northern hardwoods with some pines on deeper soils and north aspects. Management challenges with regard to fire and invasive species would be similar to the very warm dry scenario, although some moderate to high intensity fires would continue to occur due to continued presence of forests. Assisted migration would be more complicated because it would include the savanna and northern hardwood species groups. Refuge populations of some currently common boreal species may persist in wet areas and on north slopes, and these would become the rare species of the future in Minnesota.

Scenario 3. Very warm and wet - IPCC high emission scenario with precipitation to evaporation ratio remaining similar to today. The expected outcome for the vegetation would be a mixture of central and northern hardwoods. Some savannas may appear on shallow rocky soils, because more divergence in vegetation types across soil depth and texture gradients is expected in a warmer climate (Cohen and Pastor 1991). Triage during death of existing forests would be required, including a period of high-severity fires as existing forests die. Assisted migration would become a complex issue, since species of trees and understory plants from far away would have no way of reaching the area for centuries with only natural migration. A different set of invasive species could invade during the transition period than for scenario 1. Once forests were established, large-scale windfall from derechos and tornadoes, and associated fire danger, would be a common occurrence. The exercise in blowdown fire hazard management through salvage outside the wilderness and prescribed burns within the wilderness that happened after a large-scale 1999 derecho leveled > 100,000 ha of forest in and around the BWCAW would become commonplace. A number of tree diseases and pests common further south could invade the BWCAW. Questions about reintroduction of disease-resistant species of trees, and treatment of trees in the wilderness, would be important, because *Fraxinus*, *Tsuga*, and *Ulmus* would be members of the forest.

Scenario 4. Warm and wet - IPCC low emissions scenario with precipitation to evaporation ratio similar to today. This scenario might allow for adaptation of some existing tree species to the future climate and formation of a northern hardwood and boreal mixture. Triage of dying forests would be necessary, but existing forests would die over a longer period of time, and replacement would be more gradual. *Pinus strobus*, *Thuja occidentalis*, *Betula alleghaniensis*, *Acer rubrum*, *Quercus rubra*, *Quercus macrocarpa*, and *Tilia americana* are already present and could expand, and the forest may retain a few boreal characteristics, such as *Picea mariana* bogs and some groves of *Pinus resinosa*. Use of prescribed and natural fire could allow species such as *Pinus banksiana*, *Betula papyrifera*, *Populus tremuloides*, and *Picea mariana* to undergo natural selection and adapt to the new climate on poorer soils. Expanded seed zones, especially to the south, would facilitate adaptation by existing tree species by introduction of genetic stock adapted to a slightly warmer climate. Reintroduction of disease and pest-resistant *Ulmus* and *Fraximus* would be an issue to resolve. Assisted migration would be relatively low in importance, but perhaps *Quercus alba*, *Tsuga canadensis*, and *Prunus serotina* could move into the area. Refuges for boreal species would remain in many places (e.g., north slopes), but local assisted migration may be necessary to help species find those refuges.

Impacts on tree diversity.

For warm/dry global warming scenarios, all existing tree species would be negatively impacted except the three *Quercus* species. For warm/wet scenarios, six of 22 tree species native to the BWCAW are predicted to be greatly reduced in abundance by warming alone (*Abies balsamifera*, *Picea mariana*, *P. glauca*, *Pinus banksiana*, *P. resinosa*, and *Populus balsamifera*), four additional species may have substantial decreases in abundance (*Populus tremuloides*, *P. grandidentata*, *Betula papyrifera*, and *Larix laricina*), four additional species may be negatively impacted by increasing deer (*Pinus strobus*, *Betula alleghaniensis*, *Thuja occidentalis*, and *Quercus rubra*), six potentially impacted by exotic tree pests (*Acer rubrum*, *Populus balsamifera*, *P. grandidentata*, *P. tremuloides*, *Fraxinus nigra*, and *F. pennsylvanica*), and two potentially impacted by exotic disease (*Quercus rubra* and *Q. ellipsoidalis*; Table 1). *Ulmus americana* is a native species that is functionally extinct due to the spread of Dutch elm disease over the last 20 years, although a few individuals remain, and should be able to expand under a warmer climate. This leaves two species with only minor impacts expected under a worst case warm/wet scenario: *Tilia americana* and *Quercus macrocarpa*, although there is hope that Sudden oak death and Asian long-horned beetle will be kept at bay, leaving *Populus tremuloides*, *P. grandidentata*, *Acer rubrum*, *Quercus rubra*, and *Q. ellipsoidalis* among the species that would be present. With good deer management, four additional species would be gained, and seven more species could migrate in. Thus, with an optimistic scenario, 18 tree species could exist in the BWCAW in the future, although whether these would be in scattered groves on moister sites or patches of contiguous forests would depend on how wet the future climate is.

MITIGATION MEASURES, MANAGEMENT DIRECTIONS, AND POLICIES

Wilderness law and management issues

Several management issues mentioned in the impact scenarios have not been debated, have no precedents in the BWCAW, or may conflict with wilderness laws governing wilderness management and/or interpretation of the law by the U.S. Forest Service: (1) chemical and biocontrol treatments for exotic tree diseases and pests; (2) reintroductions of native species extirpated by direct human action, or by indirect, unintentional human action including species removed through exotic pests and diseases; (3) establishment of neo-native species (assisted migration, regionally and locally, into and within the BWCAW); (4) triage of forests dying from invasive pests (i.e., sanitation and fire safety); and (5) loss of endangered species now at the southern edge of their range, as well as non-endangered species whose ranges may no longer include the BWCAW (e.g., *Picea mariana* and associate wildlife species).

Two other issues have precedents in the BWCAW. Removal of invasive plant species is already allowed and practiced through a joint effort of Friends of the Boundary Waters Wilderness and Superior National Forest (Friends of the Boundary Waters Wilderness 2006). This effort will need to be increased substantially, and would be greatly facilitated by an invasive species buffer zone implemented outside the wilderness. A second issue with precedent is prescribed fire within the wilderness. A prescribed burning program was instituted in response to fire danger created when a massive derecho leveled a great expanse of forest within the BWCAW in 1999. Whether prescribed fire would be allowed for ecosystem management purposes is unclear at present.

Fire and adaptation to climate

Although trees in the past have responded to warming climates mostly by northward migration, which was facilitated by warmer climates at the northern edge of their range and forced by superior competitive ability of more southerly species along the southern margin of their range, it is also possible for trees to adapt genetically to varying temperatures (Davis and Shaw 2001), as evidenced by the remarkable ecotypic variation among populations of widespread tree species. In terms of generation times (but not on an absolute time scale), trees undergo relatively rapid evolution compared to some other organisms because of the intense selection afforded by the large ratio between the number of seeds shed to those that become adult canopy trees. Therefore, it may be possible to allow trees to adapt to a moderate degree of warming by keeping out southern invaders and insuring that sexual reproduction occurs regularly during warming. Southern populations of widely distributed conifers are likely to grow poorly and exhibit heightened mortality with climate warming, largely due to enhanced heat and drought (Reich and Oleksyn 2008), but survival should be sufficient for some selection to proceed. Whether adaptation would occur fast enough to allow these species to persist in the landscape is unknown and uncertain. It is much less likely and perhaps impossible for trees to adapt to large magnitudes of warming that result in a climate suitable for a different biome.

For the BWCAW, reinstatement of fire (or increased natural ignitions due to increased drought during climate warming) would increase *Pinus* reproduction and, thus, assist their adaptation to warmer temperatures through natural selection as well as prevent takeover by fire sensitive trees in Groups 3 and 4, such as *Acer rubrum*, which already exists in small numbers (Table 1). *Populus* would be helped by reinstatement of fire to a limited extent, because much of its reproduction is vegetative, from root sprouts, which limits opportunities to adapt by natural selection; however, it may maintain its populations for far longer on the landscape if disturbance is frequent rather than infrequent. Before undertaking any fire reinstatement program, there are three issues to resolve. First, the debate among scientists and managers over whether to help the existing species adapt, versus allowing or facilitating the movement of new species into the area needs to be resolved. Second, regardless of how this debate is resolved, policies would need to be in place to allow the management strategy to take place. Third, at this point there is a wildland fire-use policy in place which allows natural ignitions to burn under certain conditions, but it is uncertain whether this policy will allow fire to return to its natural role in the BWCAW due to the impacts of decades of fire exclusion, the landscape context in which the wilderness sits, and climate change. If climate becomes warmer and functionally drier, fires could play a larger role in the 21st than the 20th century without prescribed burning.

Response to tree pandemics

As previously mentioned, a number of BWCAW tree species could be impacted by pandemics. Should we reintroduce tree species after a pandemic goes through, and should we use the native variety or a new variety with resistance developed through selection or other ways of modifying the genome? Is it more natural to watch how the remaining species respond when one species is removed because of a pest we introduced, or is it more natural to restore the species to the wilderness, even if it has been bred to be resistant? Although it seems that a distinction could be made between species that may go extinct due to an introduced pest or disease (where some might argue that they should probably be restored if possible) and those species reduced to low levels that may be able to respond by natural selection (restoration can perhaps occur by natural processes), there has not been sufficient discussion of these questions nor establishment of policies to deal with the consequences of pandemics.

Another question is whether to treat exemplary stands chemically when a pandemic arrives. This has been done for a few groves of *Tsuga canadensis* in Shenandoah and Great Smoky Mountain National Parks, where hemlock woolly adelgid is rapidly extirpating the species. Soil treatments with the systemic insecticide, Imidacloprid, are highly effective in eliminating the adelgid for about two years (Cowles et al. 2006). For the BWCAW, this situation may arise for *Fraxinus nigra* if the rapidly expanding emerald ash borer arrives in the next few decades. Will we choose a representative or exemplary set of ash stands in the BWCAW to treat and preserve a few 'postage stamps' of this forest type? One could argue for this for esthetic reasons, preservation of germplasm, the scientific information contained in tree rings, the ecological relationships among tree species, and the relationship of the species to habitat factors.

Unlike previous conservation problems (such as logging and conversion of land to other uses) that were remedied by wilderness protection, just the opposite may occur with this new set of threats to the ecosystem; it will be more difficult to use traditional disease and insect management techniques, such as sanitation and removal of susceptible species to create breaks in transmission, within the wilderness than outside of it. The wilderness may end up with fewer native tree species (i.e., be less natural) than the surrounding forest, an unintended consequence of wilderness laws implemented during times when we as a society believed that natural areas of sufficient size were capable of maintaining themselves.

CONCLUSIONS

If climate change mitigation is successful, and a global warming scenario of modest magnitude develops, a sound overall strategy to preserve species diversity in the BWCAW would include several elements. First, it may be critical to allow a sufficient number of wilderness fires to burn, possibly supplemented by prescribed fires if needed, to allow maintenance of conifer populations and abundant sexual reproduction to provide the opportunity of adaptation by natural selection by the native tree species. Second, a deer management strategy should be employed that keeps the herd size in check. Third, an all-out effort should be made to keep exotic pests and diseases from reaching the BWCAW (or at least delay the timing of their arrival). It may be wise to restore certain species to the wilderness if exotic pests and diseases threaten extinction, as well as *Pinus strobus* in parts of the wilderness where it was removed by logging prior to establishment of the wilderness. Some local assisted migration within the BWCAW may help native species find refuges on north slopes or in wetlands where the drying impacts of a warmer climate are less severe. Some long distance assisted migration might also be warranted to bring in new species to replace those that cannot be sustained. Each of these elements has costs and benefits, as well as uncertainties regarding outcomes - hence, much debate will be required to reach a consensus on which are worth doing.

If climate change mitigation is not successful, and a large magnitude of change becomes inevitable, the choices are starker. Letting nature take its course would likely lead to a scrubby, species-poor landscape. If maintaining a diverse, tree-dominated landscape is a priority, then large-scale regional assisted migration of new species into the BWCAW will be required, to allow the wilderness to make a 'graceful' change to neo-native species, and to insure that European buckthorn and other exotic plants do not take over the ecosystem.

At the current time, wilderness management policies and perhaps the wilderness law itself, do not allow these management actions. The wilderness act of 1964 and the BWCAW wilderness act of 1978 did not recognize the types of threats discussed in this paper - at the time these laws were passed, it was widely believed that natural processes and species would remain intact within wilderness areas. Both acts mention that wilderness areas should maintain 'natural values', but that term itself was not defined. The intent was surely not to observe how natural systems deal with loss of species caused by humans.

There is a distinction between manipulation of the wilderness for spurious reasons (e.g., as the vegetation of a city park is manipulated to create a desired look) and restoration of processes (i.e., fire) and species (e.g., *Pinus strobus* and perhaps *Fraxinus nigra* in the future) that have been eliminated through human action and that scientists believe would be there in the absence of human intervention. The late preeminent BWCAW ecologist Heinselman (1996) also made this distinction, and allowed that although natural processes should predominate, "species known to be missing from the system through recent human impacts and thought to be still adapted to the environment", should be restored. Rapid climate change makes manipulation considerations much more complex, as we will be forced to decide whether to manage for what was present when wilderness status was enacted or when European settlers reached the BWCAW or for what might be the successful dominant vegetation under the altered climate if other anthropogenic constraints (fragmentation, exotic species, etc.) did not exist.

Although the current human generation is likely to witness the end of the existing forest types in the BWCAW (and indeed the last remnants of the pre-European settlement forest throughout eastern North America), the ecosystem will respond, possibly assisted by management and research. New southern species will spread into the area and new competitive relationships will allow development of new communities. Invasive plant species will acquire control mechanisms and native species will become better competitors through natural selection. Invasive diseases will come into balance through natural selection of the host tree species and as less virulent strains more successfully spread across the landscape. An altered disturbance regime (more windstorms and either less or more fire) will mold future forest dynamics. A new nutrient cycling system will come into being influenced by earthworms. However, all of these ecosystem modifications will take centuries if not millennia. Even if prescribed fire, assisted migration and introduction of trees species resistant to exotic diseases occurred within the wilderness, natural selection, ecological sorting, and other natural forces will still have a chance to operate, and wilderness areas like the BWCAW will continue to play a role of primary importance as potential reservoirs of biodiversity and as references and controls to be compared to the rest of the planet where extraction of resources controls ecosystem function (Frelich et al. 2005).

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