Ecosystems (2009) 12: 445–461
DOI: 10.1007/s10021-009-9234-8

ECOSYSTEMS

Studying Fire Mitigation Strategies in Multi-Ownership Landscapes: Balancing the Management of Fire-Dependent Ecosystems and Fire Risk

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Abstract

Public forests are surrounded by land over which agency managers have no control, and whose owners expect the public forest to be a ''good neighbor.'' Fire risk abatement on multi-owner landscapes containing flammable but fire-dependent ecosystems epitomizes the complexities of managing public lands. We report a case study that applies a landscape disturbance and succession model (LANDIS) to evaluate the relative effectiveness of four alternative fire mitigation strategies on the Chequamegon-Nicolet National Forest (Wisconsin, USA), where fire-dependent pine and oak systems overlap with a rapidly developing wildland–urban interface (WUI). We incorporated timber management of the current forest plan and fire characteristics (ignition patterns, fire sizes, and fuel-specific fire spread rates) typical for the region under current fire suppression policies, using a combination of previously published fire analyses and interactive expert opinion from the national forest. Of the fire mitigation strategies evaluated, reduction of ignitions caused by debris-burning had the strongest influence on fire risk, followed by the strategic redistribution of risky forest types away from the high ignition rates of the WUI. Other treatments (fire breaks and reducing roadside ignitions) were less effective. Escaped fires, although rare, introduced significant uncertainty in the simulations and are expected to complicate fire management planning. Simulations also show that long-term maintenance of fire-dependent communities (that is, pine and oak) representing the greatest forest fire risk requires active management. Resolving conflict between the survival of

Received 2 September 2008; accepted 20 January 2009; published online 25 February 2009

Electronic supplementary material: The online version of this article (doi:10.1007/s10021-009-9234-8) contains supplementary material, which is available to authorized users.

Author Contributions: B. R. Sturtevant conceived and designed the project, analyzed model output, and led the writing of the manuscript. B. R. Miranda constructed the simulation scenarios, led the acquisition of input data and model calibration, summarized the model output, and wrote sections of the manuscript. H. S. He is a principle designer and programmer of LANDIS 4.0 who specifically contributed the fuel module for the project. J. Yang designed and programmed the fire module of LANDIS 4.0 and helped calibrate the fire regime with prototype models. E. J. Gustafson helped to design the study and contributed to the writing of the manuscript. R. M. Scheller modeled species establishment coecients as a function of soil input data from the study landscape.

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fire-dependent communities that are regionally declining and continued rural development requires strategic planning that accounts for multi-owner activities.

Key words: LANDIS; fire regime; forest management; rural development; wildland–urban interface; forest succession; simulation modeling; fire risk mitigation.

Introduction

Appropriate mitigation of fire risk is both scientifically and politically controversial (Dellasala and others 2004). The cumulative effects of fire and forest management over the last century have exacerbated fire risk in some regions (Allen and others 2002; Hessburg and others 2005) and threatened fire-dependent systems in many others (Landers and others 1995; Radeloff and others 2000). The issue is further complicated by the recent encroachment of human homes into fire-prone ecosystems that increases fire ignitions (Cortner and others 1990; Lee and others 2006; Sturtevant and Cleland 2007) and increases demands on fire suppression agencies to protect lives and property (Cortner and others 1990; Snyder 1999). Consequently, the balance between forest management, human rural development, and fire risk remains an issue of major concern to natural resource agencies (Dombeck and others 2004).

Fire mitigation is especially problematic for managers of large public forests. Public forests are surrounded by land over which agency managers have no control, and whose owners expect the public forest to be a ''good neighbor.'' It is no small task to manage a forest to produce forest products, conserve biodiversity, maintain ecosystem services, provide recreational opportunities and pristine environments, and mitigate fire risk so that the neighbors' houses do not burn. The magnitude of this management task requires decision support tools that account for complex interactions among management actions, natural ecological processes, and anthropogenic drivers to evaluate management alternatives in terms of fire risk and ecological effects in forested ecosystems.

Landscape disturbance and succession models provide a framework to account for complex interactions among spatial ecological and disturbance processes (Keane and others 2004; Scheller and Mladenoff 2007). In a management context, they provide an objective means to compare alternative management strategies (Zollner and others 2008). The predictions of these models can be used to evaluate research hypotheses and answer management questions, such as the relative risk that fires will spread into sensitive or inhabited parts of a landscape. Because fire risk is as much dependent on landscape factors as site factors, a spatial approach is essential (Loehle 2004; Gonzalez and others 2005). The LANDIS model (Mladenoff 2004) is particularly suited to such applications because it is spatial; it independently models multiple ecological and anthropogenic processes; interactions of these processes are an emergent property of the simulations; it predicts several important characteristics related to the ecological functioning of forested landscapes over long time periods; and it can produce comparable predictions for alternative scenarios.

In this article, we investigated the question of the balance between forest management objectives and the protection of human lives and property in multi-owner landscapes. We used LANDIS to simulate human ignition patterns and changing forest and fuel patterns resulting from succession and forest management that combine to produce an anthropogenic fire regime. In collaboration with the Chequamegon-Nicolet National Forest (CNNF), we designed and evaluated the relative effectiveness of four alternative fire and fuel mitigation strategies in reducing fire risk while maintaining ecological goals outlined in their current strategic forest plan. Our results highlight both general and site-specific insights into the application of landscape models to provide solutions to conflicting human values in multi-purpose and mixed-ownership landscapes.

Methods

Case Study Overview

Much of northern Wisconsin is dominated by fire-resistant northern hardwood forests (that is, sugar maple, *Acer saccharum*; American basswood, *Tilia Americana*; yellow birch, *Betula alleghaniensis*). Yet there are significant areas of pine and oak forests (that is, jack pine, *Pinus banksiana*; red pine, *P. resinosa*; red oak, *Quercus rubra;* pin oak, *Q. ellipsoidalis*) associated with sandy glacial landforms that are prone to high intensity fires and dependent on frequent fire for long-term persistence (Radeloff and others 2000). Because humans are the primary cause of fire in the Lake States (Cardille and

Ventura 2001), the greatest risk of fire ignitions occurs where fire-prone ecosystems overlap the wildland–urban interface (WUI) (Haight and others 2004), defined as ‘‘the area where houses meet or intermingle with undeveloped wildland vegetation,’’ (Radeloff and others 2005, p. 800). Yet fire-dependent ecosystems are also currently in decline in Wisconsin due in part to strict fire suppression policies (Radeloff and others 2000). We assisted the CNNF to develop strategic fire and fuel mitigation plans in a portion of their forest where abundant private land ownership overlap with fire-dependent landscape ecosystems.

The 780 km^2 study area is defined by the outer boundary of the Lakewood subdistrict of the CNNF, located in northeastern Wisconsin (Figure 1). Seventy-four percent of the land area is owned by the CNNF, and the remainder is privately owned. The study area contains three unincorporated towns, and the majority of private land contains low density housing (Median = 4.08 houses per km^2). Land cover is dominated by forest (81%), with

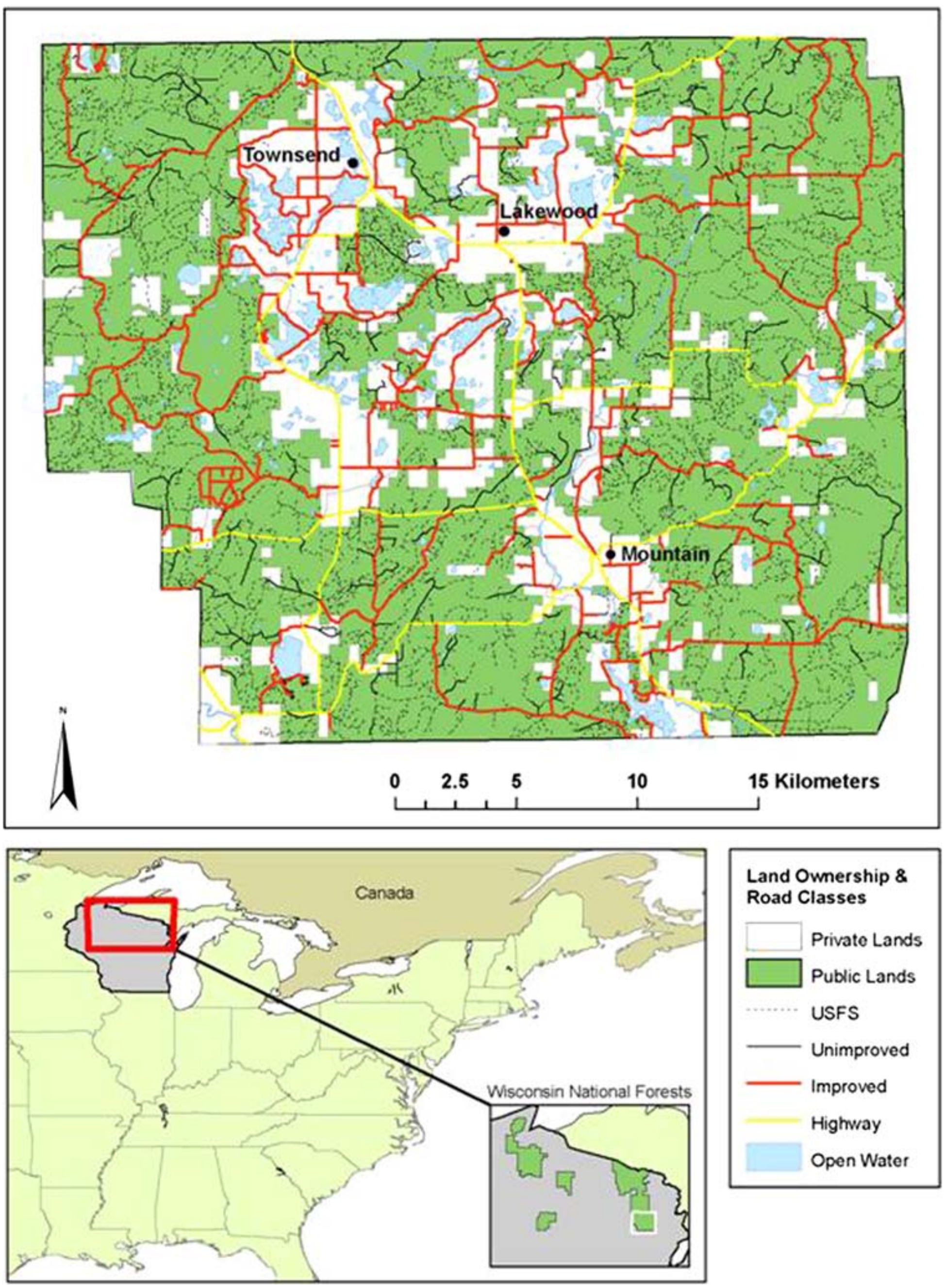

Figure 1. Lakewood study in the Chequamegon-Nicolet National Forest of Wisconsin, USA, showing public and private land ownership and the extensive road network.

some agricultural and hay fields (4.5%) and open wetlands (12.5%). Forested ecosystems in the study area are strongly influenced by glacial landforms that create a sharp soil moisture gradient from west (mesic and nutrient-rich) to east (xeric and nutrient-poor). An extensive unimproved road network is maintained to provide access for both harvest and fire suppression activities, linked by improved county and state roads (Figure 1).

LANDIS 4.0

LANDIS is a spatially explicit landscape model designed to simulate forest landscape change over large spatial and temporal scales (Mladenoff 2004). LANDIS simulates forest dynamics at the tree species level using species vital attributes such as shade tolerance, fire tolerance, seed dispersal, ability to sprout vegetatively, and longevity. Processes simulated in LANDIS 4.0 include succession, seed dispersal, multiple natural disturbances including fire, timber harvest, and fuel management (He and others 2005). Independent disturbance modules can be added and/or modified as needed to address specific questions (He and others 2002b). The model operates on a raster (grid) map, where each cell (0.09 ha) contains information on the presence/absence of tree species and their 10-year age cohorts (species-age list), but no information about the density or size of individual stems.

The fire module of LANDIS 4.0 provides several options to customize a fire regime to fit a particular question (Yang and others 2008). We used a hierarchical fire frequency model (Yang and others 2004) to simulate the distribution of fire initiations according to the above assumptions. In a given time step, the number of ignitions is generated from a Poisson distribution with parameters defined spatially by a fire regime map, defined below. For each ignition attempt, the model compares a random number to the fire probability corresponding with the fuel type for the cell. For each successful fire initiation, the model selects a wind direction and intensity class from a user defined distribution. It then calculates a cost surface representing the minimum time travel (Finney 2002) required to reach each cell in a large neighborhood based on the ignition point, the wind speed and direction relative to the ignition point, and relative rates of spread for cells based on fuel their fuel type (Yang and others 2008). The actual burn perimeter for an event is determined by selecting a fire duration from a lognormal distribution defined by μ & σ^2 parameters and burning only those cells with a time travel less than or equal to that duration (Yang and others 2008). This method allows the fire regime to change in response to changing fuel conditions (Pennanen and Kuuluvainen 2002; Didion and others 2007).

Base Scenario

In collaboration with CNNF managers, we developed a base scenario in LANDIS that represented current disturbance, succession, and forest management activities for the study area (Gustafson and others 2006). The base scenario represents (1) succession drivers (that is, soil texture) and patterns consistent with the experience of local silviculturalists, (2) harvest patterns and prescriptions defined by the current CNNF forest plan (http://www.fs.fed.us/r9/cnnf/natres/final_forest_plan/index.html), (3) a spatial distribution of fire ignitions affected by the current distribution of residential development and road networks, and (4) realistic burn patterns affected by spatial configurations of fuels and both natural and man-made fire breaks. Fire ‘‘ignitions’’ are limited to those fire starts with sizes detectable at the resolution of our raster maps (that is, fire sizes greater than or equal to 75% of one grid cell (that is, 0.0675 ha)).

LANDIS requires ‘‘land type’’ maps that represent the spatially homogeneous growing environment for tree species and fire disturbance regimes within a landscape. We used a fine-scaled landscape ecosystem classification map for northern Wisconsin to define upland forest and lowland (combined open wetland and lowland conifer) land types. The ecosystem classification reflects the biogeography of fire-prone versus fireresistant forest ommunities known to influence modern fire regimes (Sturtevant and Cleland 2007). Two additional land types (open fields and lowland hardwoods) were defined by WISCLAND (http://www.dnr.state.wi.us/maps/gis/datalandcover.html#data) classified Thematic Mapper imagery. We adapted the procedure of Scheller and others (2005) to estimate land type-specific species establishment coefficients (SEC), defined as the probability of species establishment given adequate light, using LINKAGES (Post and Pastor 1996) and based on land type variability in soil moisture (determined by soil texture). SEC values and resulting succession patterns were reviewed by CNNF silviculturalists, who recommended three adjustments to better fit their local experience (Appendix I).

To create an initial conditions map, we used plot-level Combined Data Systems (CDS) data collected by the CNNF to stratify random assignment of tree species cohorts to approximate the range, landscape abundance, and spatial pattern of tree species composition and age structure found in the current Lakewood landscape. CDS data contains stand polygons, stand-scale attributes, and forest plots within a subset of stands. All cells within a stand were assigned the forest type–land type–age class of that stand, and the cohort presence/absence list of individual cells was assigned using the cohort list found on a randomly selected representative CDS plot with the same forest type–land type–age class. For private lands, we used quarter-quarter [that is, one sixteenth of a square mile section (16 ha)] boundaries of the Public Land Survey System to define stands to approximate the resolution of land management on private lands (Gustafson and Loehle 2006). We then assigned a dominant forest type and land type to each patch of forested cells based on WISCLAND classified satellite imagery and land-type polygons, respectively, and randomly assigned representative plots with these attributes.

The CNNF management plan includes harvest prescriptions specific to spatially delineated Management Areas. Prescriptions were implemented using the LANDIS harvest module (Gustafson and others 2000). We used the methods of previously published modeling studies conducted on the CNNF (Gustafson and others 2004; Zollner and others 2005), modified to fit the local conditions of the Lakewood area based on CNNF recommendations. Specific changes included aspen rotation treatments that assumed current aspen stands will be managed for aspen indefinitely; oak shelterwood treatments that assumed silviculturists will be successful in establishing oak but allows natural regeneration by other species, and conifer plantation treatments that exclude all regeneration other than the planted species. All other prescriptions assumed natural regeneration and included selection harvests for uneven-aged northern hardwoods, clear-cutting treatments for early successional species, and shelterwood harvests encouraging establishment of balsam fir (*Abies balsamea*) or white pine. We assumed that the proportion of private lands under management is similar to the state-wide average of 54% (J. Lampereur, CNNF, personal communication), and that management activities on managed private lands are similar to those found in adjacent federal lands.

We parameterized the LANDIS fuel module (He and others 2004) so that forest types corresponded to BEHAVE fuel models (Andrews 1986) based on the experience of CNNF fire management officers (J. Grant and J. Saunders, personal communication). Resulting fuel types affected spread rates, fire initiation probabilities, and fire severity class (Table 1). Land type and housing density-specific fire ignition rates, mean fire sizes, and fire rotations were estimated from a 16-year fire database for northern Wisconsin (Sturtevant and Cleland 2007) (Table 2). A housing density threshold of 2.09 homes/km^2 was used to separate high and low density housing based on recent analysis of fire risk factors in the region (Sturtevant and Cleland 2007) (Table 2). Roads were represented as 30 m wide (that is, one cell-width) semi-permeable barriers to fire spread, where fires could cross roads at randomly placed crossing points (cells) that varied in their linear density according to the road class (Table 3; Alan Harrison, CNNF, personal communication). Road-related fire starts were added to the cells bordering the road, so that the combination of roads, land types, and housing density spatially defined the fire regime (that is, fire regime map; Figure 2B).

Wind statistics from a local weather station were used to define probabilities for different wind

Table 1. Crosswalk Between BEHAVE and LANDIS Fuel Types and Associated Parameters

BEHAVE Fuel model	Vegetation type	LANDIS Fuel class	Ignition Probability	Spread rate (m/min) Min	Spread rate (m/min) Max
NA	Water	0	0	0	0
8	Deciduous (except oak)	1	0.5	0.1	1.1
9	Oaks and pine[1]	2	1	0.25	4.3
11	Recent harvest	2	1	0.25	4.3
10	Old jack pine (≥50 years)	3	1	0.4	6.1
4	Young pine, spruce & fir	4	1	1.39	89.7
1	Grasses and wetlands	5	1	1.46	99.5

Data from Andrews 1986; He and others 2005.
Listed parameters include ignition probability and ranges in spread rate from moderate (minimum) to extreme (maximum) fire weather (that is, windspeeds).
[1]Exception is old jack pine, where BEHAVE fuel model 10 is applied.

Table 2. Fire Regime Attributes Estimated from the Wisconsin Fire Database

Landtype	Housing density class	Mean fire size (ha)	Ignition rate (#/km^2/decade)	Burn rate (ha/km^2/decade)	Fire rotation (years)	Probability of crown fire
FR1	High	1.32	0.26	0.34	2914	0.10
	Low	7.06	0.06	0.38	2598	0.10
FR2	High	1.00	0.18	0.18	5497	0.05
	Low	1.48	0.06	0.09	10566	0.05
FR3	High	0.77	0.13	0.10	10025	0.01
	Low	1.46	0.03	0.05	20579	0.01
FR4	High	0.87	0.07	0.06	16402	0
	Low	1.58	0.02	0.04	25971	0
Marsh	High	2.10	0.06	0.12	8608	NA
	Low	3.86	0.02	0.09	11598	NA
Open	High	1.26	0.17	0.21	4727	NA
	Low	2.34	0.11	0.26	3792	NA
Swamp	High	0.49	0.05	0.02	42098	0
	Low	0.90	0.02	0.02	54013	0
Entire landscape[1]	Small	1.00	0.074	0.075	13388	0.009
	Total	1.54	0.075	0.115	8659	0.009

Regime attributes are assigned to the fire regime map (Figure 2B). Low and high housing density classes refer to housing densities less than and greater than 2.09 homes/km^2, respectively (Sturtevant and Cleland 2007). Probability of crown fire is based on expert opinion (J. Saunders, personal communication).
[1]Fire regime attributes averaged across the study landscape. ''Small'' refers to attributes calculated for fires less than 20 ha in size, whereas ''Total'' refers to attributes estimated when ''escaped fires'' (>20 ha) are added to the small fire records.

Table 3. Road Type-Specific Likelihood of Fire Breach

Road class	Description	Proportion fire crossing points
Highway	Nondivided paved roads with broad shoulders	0.02
Improved	Smaller paved roads	0.05
Unimproved	Unpaved roads	0.20
Forest Service	Unpaved roads for harvest and recreational access	0.40

Simulated as type-specific proportion of road length containing randomly-placed fire crossing points by road type. In the FIREBREAK scenario, the addition of a fire break adjacent to a road changes its class the next highest level.

directions and four classes of wind speeds representing moderate (>8 km/h) to extreme fire weather conditions for the region. Wind data were limited to April and May dates, representing the primary wildfire season in the upper Midwest that corresponds with the driest understory conditions following snowmelt but prior to leaf out (Cardille and Ventura 2001). Spread rates were estimated for all fuel types in each wind speed class using Farsite (Finney 2004; Table 1). We then calibrated fire durations and ignition rates to approximate the fire rotation periods and fire sizes estimated from the fire database under contemporary fuel conditions. Fire suppression has affected the fire size distribution and required fitting two different fire size distributions (that is, small fires that were quickly contained and large fires that likely escaped containment). We defined ''escaped'' fires as fires greater than 20 ha (50 ac.) based on the experience of local fire management officers (J. Grant, CNNF, personal communication). Escaped fires occurred rarely (less than 1% of all fire occurrences) and were assumed to occur only during very high or extreme fire weather conditions (J. Grant, CNNF, personal communication). We also assumed that fires burning in deciduous non-oak fuels can always be contained. Further details on the methods used to parameterize the fire and fuel modules can be found in Appendix II.

Alternative Fire Mitigation Strategies

Four alternative strategies were designed in collaboration with CNNF personnel to reduce fire risk in the Lakewood area:

1. FIREBREAK—Placement of permanent firebreaks within fire-prone land types. Permanent firebreaks (101 km) were established within fire-prone land types, placed along logical paths that took advantage of the existing road network. Fire breaks were parameterized by increasing the class of the road to the next level,

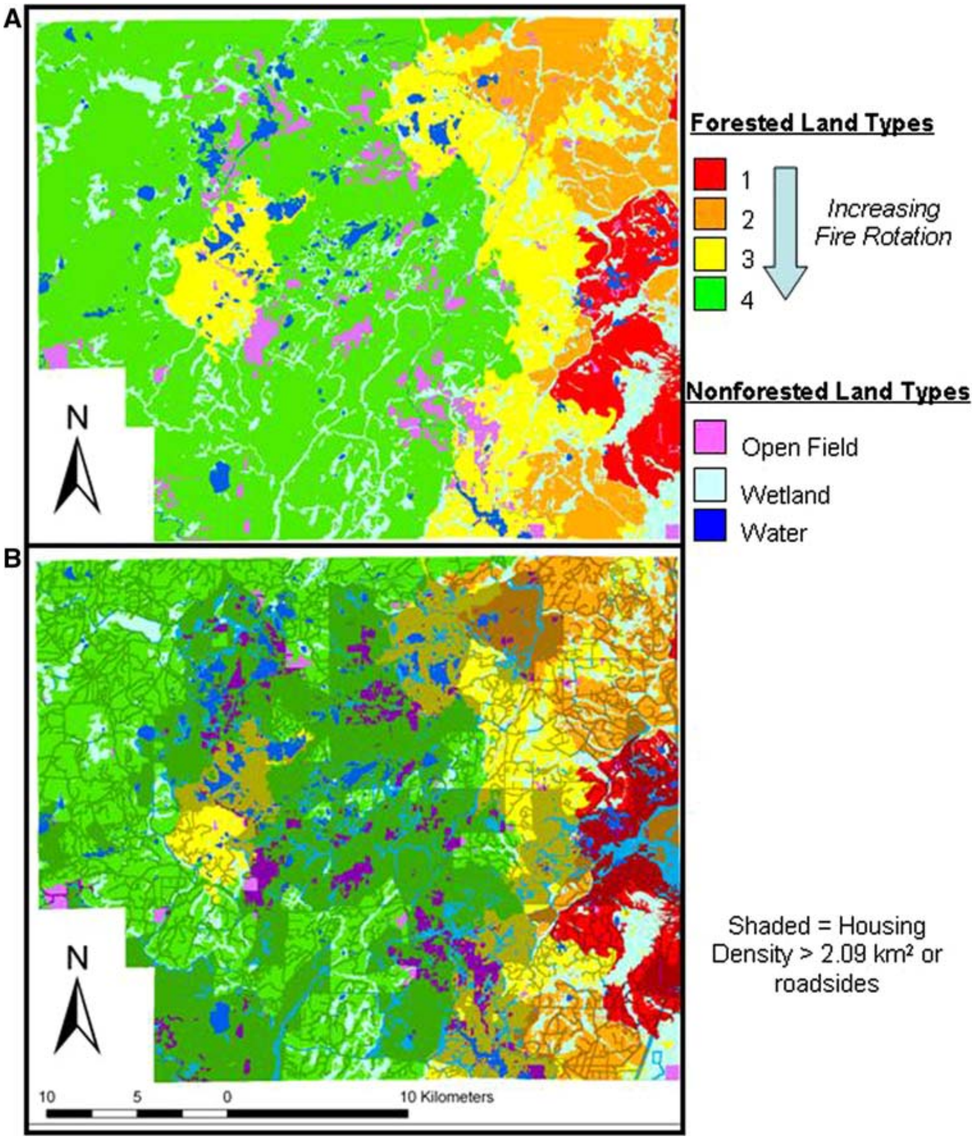

Figure 2. Fire regime map based on the overlap between **A** landforms affecting soil moisture and therefore ecosystem development and **B** human development (that is, open lands, housing density, and roads). Previous research (Sturtevant and Cleland 2007) found the combination of these biophysical and human factors best explained fire occurrence and fire size in northern Wisconsin.

reducing their probability of fire breach accordingly (See Table 3 for road class description). Fire breaks alone were assigned the lowest road class, and ''road'' ignition rates were added to their borders.

2. ZONE—Redistribution of ''risky'' management treatments (that is, those establishing pine or oak) to areas of the forest more isolated from housing developments. Management areas were reconfigured by overlaying a ''WUI protection zone'', defined by a 1 km buffer surrounding existing WUI areas (that is, areas with more than 6.17 homes per km^2). All management prescriptions promoting either pine or oak were reallocated outside of this zone in a way that maintained the same total area of each prescription (for each management area) as the base scenario.
3. DEBRIS—Reducing fire ignitions by 25% by banning local debris-burning practices. Fire starts caused by debris-burning practices were eliminated from the Wisconsin fire database and the fire regimes (ignition rates and fire rotations) were adjusted accordingly.
4. ROAD—Reducing fire ignition rates along roads through roadside vegetation management on federal lands. The elevated fire ignition rates along roadsides were reduced to background ignition rates where roads overlapped with National Forest lands.

The simulation experiment was designed as a full 4^2 factorial with three replicates of each combination. Three replicates were selected as an appropriate balance between statistical power and ecological insight from the results. Simulations were run for 250 years. Response variables were the cumulative area burned both inside and outside WUI areas (housing densities >6.17 houses per km^2 (Radeloff and others 2005)) during the 250-year time period. MANOVA was used to evaluate the null global hypothesis that neither treatments nor their interactions had significant effects on the response variables, although our emphasis in interpretation was on resulting trends rather than significance per se. Standard diagnostics were applied to results to detect for outliers and other observations with high leverage that may have affected the results. We evaluated whether treatments had unintended consequences on ecological goals by comparing ecological indicators with targets outlined in the CNNF forest plan. Spatial maps of fire risk were estimated as the cell-scale probability of burning during 100 replicate simulations.

Sensitivity Analyses

Many dimensions of sensitivity have been previously addressed for LANDIS (He and others 2002a; Wimberly 2004; Xu and others 2005). We evaluated the sensitivity of our results to key assumptions for which empirical information was limited by repeating the full experiment to make the following comparisons:

1. Adjusted SEC versus original output from the LINKAGES model (see Appendix I).
2. Road class-specific permeability assumptions (Table 3) versus two logical extremes: (a) roads do not affect fire spread and (b) all roads act as complete barriers to fire spread.
3. Probability of crowning (that is, ground fires become crown fires) in conifer types is a function of land type versus the extreme case that conifer forest types always crown.
4. Assumption that 54% of private lands are actively managed versus two logical extremes: (a) all private lands are managed and (b) no private lands are managed.
5. Wetlands always burn like grasslands versus wetland types never burn.

Results

Base Scenario

Simulated fire shapes and ignition patterns approximated the modern fire size distribution of northern Wisconsin (Appendix II) and were consistent with the experience of local fire management officers (J. Grant, CNNF, personal communication). Fire probability maps indicate a highly heterogeneous fire risk across the landscape due the combined effects of landform, the distribution of open cover types (that is, fields and wetlands) that burn frequently relative to deciduous forests, rural development, and forest composition (Figure 3A).

Changes in forest composition in response to simulated harvest and succession processes of the base scenario were most striking for deciduous species (Figure 4A). Northern hardwoods nearly doubled their landscape-scale dominance, primarily at the expense of aspen and birch forest types. Oak also declined to about half of its initial dominance. Changes in pine dominance depended on species—red pine declined, jack pine remained constant, and white pine increased during the simulation period, with a net loss of pine dominance by the end of the simulation. Persistence of jack and red pine was due almost exclusively to simulated plantation practices. Comparison of the forest composition at simulation year 100 with the ecological goals of the CNNF indicates that the forest managers may have difficulty in increasing pines and maintaining aspen and oak at current levels given fire suppression practices and the current management plan (Table 4). Such regeneration challenges are consistent with the experience of CNNF silviculturalists (M. Theisen, J. Lampereur, personal communication). The base scenario therefore appears to realistically simulate the fire and vegetation dynamics in response to current management practices. Despite large changes in forest composition, landscape-scale fuels change only slightly during the course of the simulation because the majority of change is between non-oak deciduous species modeled as the same fuel type (Figure 4A). Most fuel type conversion occurred in the eastern half of study area on drier land types where oak and pine types were initially more common.

Main Experiment

MANOVA results indicate that eliminating debris fires as an ignition source (DEBRIS treatment) had the greatest influence on the area burned ($M = 0.21$, $F = 78.64$, $P < 0.0001$). This response was consistent both within and outside WUI areas, decreasing the cumulative area burned relative to the base scenario by 35% (Figure 5). The ZONE treatment had the next largest influence on area burned ($M = 0.84$, $F = 3.88$, $P = 0.029$), although the magnitude of change was small relative to the DEBRIS treatment. The ZONE treatment decreased the area burned inside the WUI by 16%, but slightly increased the area burned outside the WUI (Figure 5). The ROAD treatment caused a counter-intuitive increase in area burned inside the WUI,

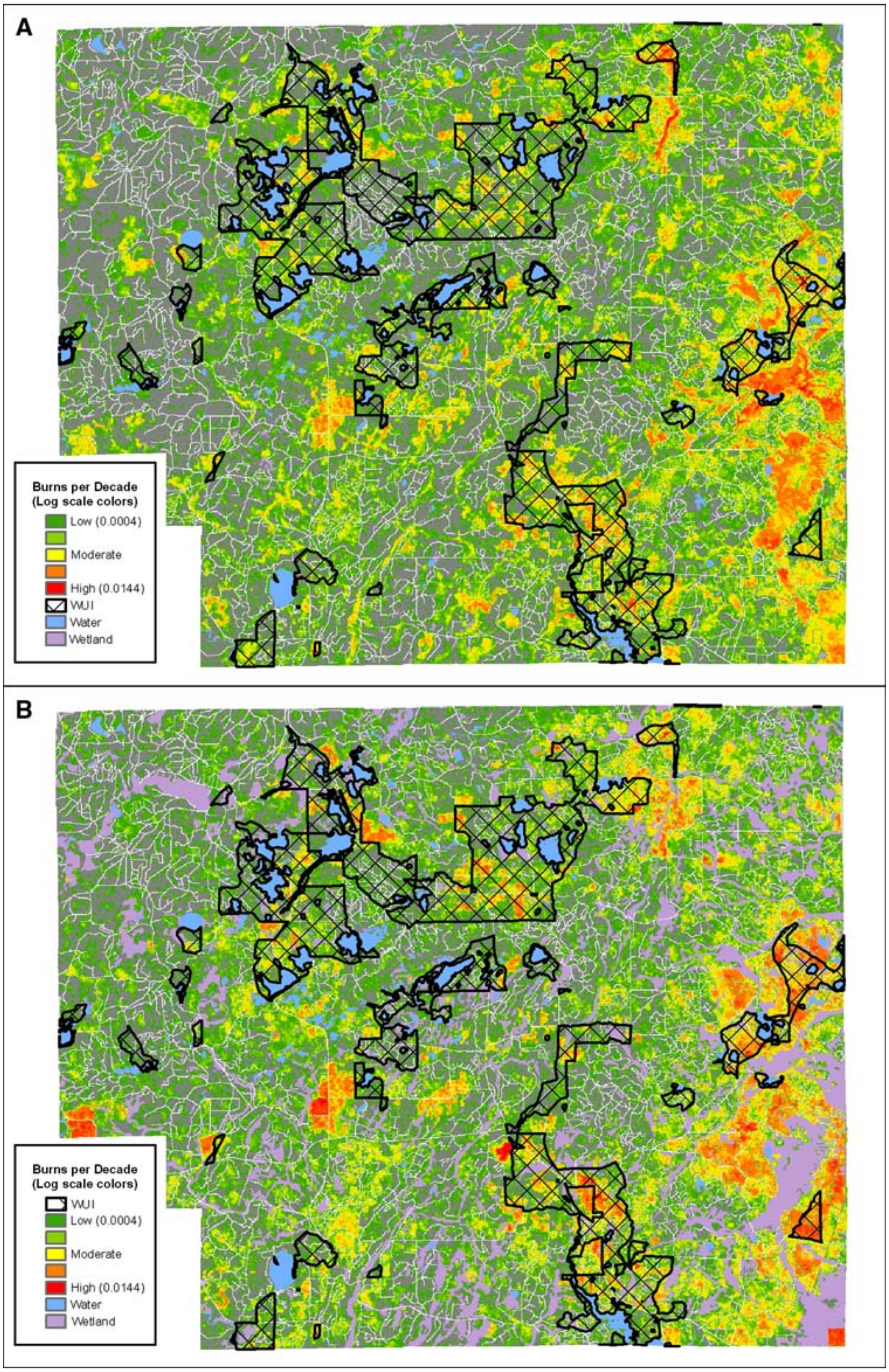

Figure 3. Fire probability maps for the **A** base scenario and **B** an alternative assumption that wetlands never burn, indicating the strong influence of wetland cover types on upland wildfire patterns. Wildland–urban interface areas are outlined in *black*. Fire probability maps were estimated as the number of times a cell burned per decade from 100 replicate simulations of 250 years. *Gray shaded areas* were never burned, and the color palette is based on a log scale.

though both MANOVA and individual ANOVAs indicated the treatment effect was marginal ($M = 0.90$, $F = 2.46$, $P = 0.098$; Table 5). FIREBREAK treatment had virtually no effect ($M = 0.98$, $F = 0.50$, $P = 0.61$). Interaction terms were not significant and therefore removed from the analysis. There was one notable outlier detected that had unusually low area burned. Removal of the outlier slightly weakened the influence of the ZONE treatment but did not change the main results.

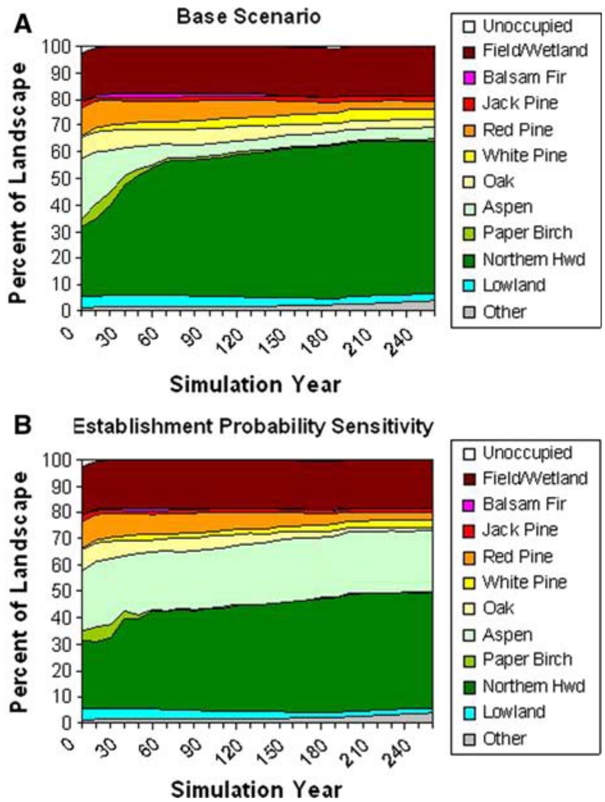

Figure 4. Percent of the study landscape occupied by dominant forest/cover types during the 250 year simulation. Dominant types are rank-ordered according to relative flammability, where *green shades* burn at the slowest rate (LANDIS fuel class 1), *yellow and orange shades* burn at faster rates (LANDIS fuel classes 2, 3 or 4 depending on the age and species of pine), and *pink and red shades* burn at the fastest rates (4 & 5, respectively). **A** Base scenario. **B** Sensitivity scenario based on alternate species establishment coefficients.

Simulated mitigation treatments had little influence on either landscape-scale forest composition or the ecological goals of the CNNF. With the exception of the ZONE treatment, management area percentages of forest types differed less then 1% from the base scenario. The ZONE treatment had slightly more influence on forest composition, including a 10% increase in jack pine in management area 1B and other minor differences in the remaining forest types, all less than 5% relative to the base scenario.

Sensitivity Analyses

Individual fire mitigation treatments had differing sensitivities to alternate model assumptions (Table 5). DEBRIS treatment effects were robust to all assumptions, showing consistency in both the magnitude and direction of effects on area burned across all assumptions. ZONE treatment effects varied from none to strong depending on our assumptions, although the direction of the treatment effect remained generally consistent. ROAD and FIREBREAK treatments each had comparably low effects on area burned, and the direction of change varied with each assumption. With few exceptions, we interpret the variable response of ROAD and FIREBREAK treatments as a consequence of their inherent variability of treatment effectiveness rather than sensitivity to our assumptions per se.

Adjustments to species establishment coefficients (SEC) and different assumptions regarding forest management activities on private land affected forest composition and consequently the abundance and distribution of different fuel types. The base scenario drastically reduced the probability of establishment of aspen (due to competition establishment by other species) and decreased the probability of establishment of nutrient-demanding northern hardwood species such as sugar maple on more xeric land types based on local expert opinion (see Appendix). Without these adjustments to SEC, aspen dominated a much higher proportion of the landscape by rapidly seeding into newly harvested stands (Figure 4B). Fire-resistant fuel types associated with northern hardwoods and aspen also displaced some of the more flammable oak and pine fuel types. As a consequence, the original SEC estimates virtually eliminated the ZONE treatment effect within the WUI (Table 5). Forest composition relative to the ecological goals of the CNNF was also strongly affected—northern hardwoods were much closer to management area targets (most within 5%), but aspen exceeded target levels up to 22%. The remaining types were negatively affected. The degree to which private lands were managed also influenced landscape fuel composition; more harvesting favored oak and pine, whereas less harvesting favored northern hardwoods. However differences in composition relative to the base scenario were slight (that is, 1–2%) because the majority of the private land base was located on the most mesic land type (that is, FR4, Figures 1, 2A) where northern hardwoods already predominate. The ZONE treatment was therefore less sensitive to forest management assumptions on private lands (Table 5).

Our conifer fuel assumption changed the relative influence of pine forest types on fire risk. The ZONE treatment had a much stronger influence on the area burned when all conifers were assumed to burn as crown fires, particularly inside the WUI. This change also increased the relative importance of the FIREBREAK treatment, although in this case

Table 4. Chequamegon-Nicolet National Forest Ecological Targets Within the Lakewood Area

Management area	Northern hardwoods	Aspen	Paper birch	Oak	White & red pine	Jack pine	Balsam fir
Ecological goals							
1B	10	37	3	5	24	13	1
1C	28	40	5	10	10	1	1
2A	57	20	2	5	12	1	1
2B	77	10	1	3	5	1	1
2C	36	25	2	8	24	1	1
3C	22	27	4	21	15	3	1
4B	12	7	3	10	51	6	1
Initial conditions							
1B	−1	−3	−1	1	−14	3	0
1C	−1	1	0	2	−2	0	−1
2A	−13	12	0	1	−4	0	−1
2B	−10	12	0	2	−2	−1	−1
2C	−6	4	1	2	−3	0	−1
3C	−3	−1	1	0	1	0	0
4B	3	16	0	−2	−24	4	0
Base experiment—year 100							
1B	19	−23	−1	−2	−7	15	−1
1C	38	−26	−4	−4	−4	0	−1
2A	24	−17	−1	−2	−4	0	0
2B	19	−9	−1	−3	−5	−1	−1
2C	28	−18	−1	−4	−5	0	−1
3C	18	−14	−1	−2	1	0	0
4B	21	−3	3	3	−20	0	0

Ecological targets are in percent of land base within each forest type for each management area. Initial conditions numbers represent the current percent departure from the target goals; base scenario represents the percent departure from the target goals by simulation year 100, averaged across three replicates.

placement of permanent fire breaks increased fire risk within the WUI while decreasing fire risk outside the WUI (Table 5). Assumptions about permeability of roads to fires as well as whether wetlands do or do not burn primarily affect the connectivity of the landscape to fire. Changing these assumptions had a complex influence on the experiment, resulting in reduced influence of the ZONE treatment but producing significant interactions between treatments (Table 5). Fuel, road, and wetland assumptions had little influence on forest composition or the ecological goals of the CNNF.

Discussion

Landscape Fire Mitigation Strategies

Banning debris burns had the greatest influence on the landscape area burned over a 250-year period, both inside and outside of the WUI. Debris burns accounted for roughly 25% of the total fire ignitions in the northern Wisconsin fire database, and our simulations indicate that banning debris burns resulted in 35% less area burned in the study area. This treatment effect was robust to primary uncertainties of our simulations and suggests that effective control of human fire ignitions can significantly reduce fire risk. However, we do not suggest that a total ban on burning practices will effectively control human ignitions. On the contrary, outlawing burn practices often leads to less control over when and where people burn (Wade and others 2005). Instead, the Wisconsin Department of Natural Resources has set up a simple no-cost permit process that limits debris burning to low risk periods (http://dnr.wi.gov/forestry/fire/burning-rp.htm). The relative ease of obtaining burn permits, combined with enforced consequences for non-compliance, is probably the most effective method for limiting the number of wildfires that escape from debris burns. Hence our results suggest that fire prevention and education will be an important strategy for reducing fire risk within the Lakewood area. Given current trends, however, housing density and landscape-scale fire risk are expected to increase over time (Radeloff and others 2001). Our future research will incorporate human development projections to evaluate how an expanding WUI may influence the relative success of fire and fuel mitigation strategies within this landscape.

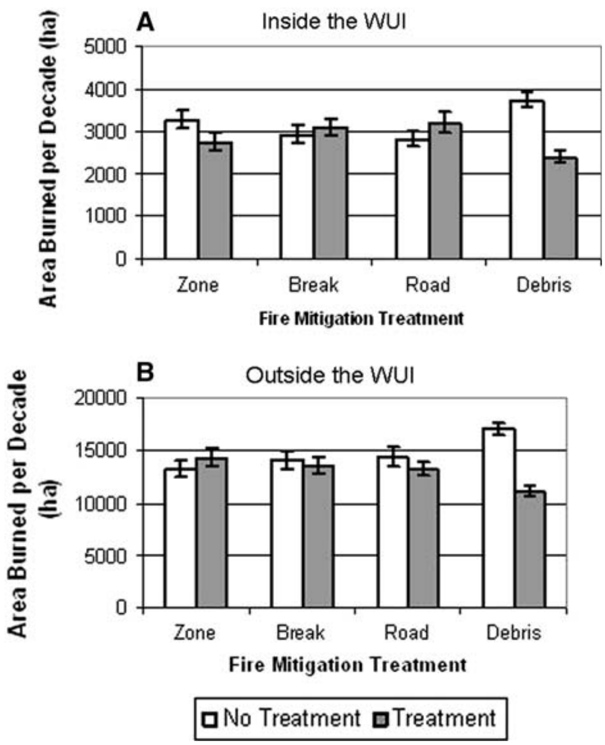

Figure 5. Area burned per decade (ha) **A** inside the WUI and **B** outside the WUI, in response to the four main fire mitigation treatments. Mean area burned values for treatments are back-transformed from $\log_{10}$ and averaged across the entire factorial experiment (n = 24 per treatment). Separate ANOVAs show the ZONE treatment was significant ($P < 0.01$) inside the WUI, and the DEBRIS treatment was significant ($P < 0.0001$) both inside and outside the WUI. No other treatments and no interaction terms were significant ($P < 0.05$). Error bars correspond to standard errors of the mean.

Many ''hot spots'' shown in the Lakewood fire probability map correspond with open fields and wetlands (Figure 3A). These open types can have flashy fuels that burn rapidly when dry and account for a large proportion of wildfires in northern Wisconsin (Cardille and Ventura 2001; Cardille and others 2001; Sturtevant and Cleland 2007). The Forest Service has little control over these cover types because nearly all open fields are located on private lands, and wetland vegetation types are excluded from vegetation management. However, managers can control the proximity of flammable forest types to open cover types to reduce the likelihood that fires in open types will spread into forested areas. Wetland cover types in particular are pervasive and have an important influence on spatial patterns of fire risk (Figure 3A). However, fire occurrence within wetland cover types is also sensitive to water levels that can change seasonally and over multi-year drought cycles. When fires cannot burn within wetlands, spatial patterns of fire risk change dramatically (Figure 3B).

Our simulation results suggest that redistribution of pine and oak communities away from human developments can decrease fire risk within the WUI (that is, ZONE treatment; Table 5). Sensitivity analyses further indicated that the degree to which this mitigation strategy is successful depends on the relative area of pine and oak on the landscape and on the amount of area that could be treated. For example, SEC parameters favoring species with fire-resistant fuel types (for example, aspen, sugar maple) eliminated the significance of the ZONE treatment. Without active management pine and oak types will convert to less flammable types; this successional trend explains why the proportion of private lands managed influenced the strength of the ZONE effect (Table 5). The effectiveness of the ZONE mitigation strategy was also sensitive to crown fire assumptions (that is, fire spread rates) for coniferous fuel types and also connectivity of fuels affected by roads and wetlands (Table 5). The latter underscores the importance of landscape context when understanding fire risk.

We found little evidence that a system of fire breaks will reduce landscape-scale fire risk in this area. Fire breaks are designed to restrict the spread of very large fires (Dupuy and Morvan 2005), but the vast majority of fires in northern Wisconsin is effectively suppressed and is therefore quite small (Appendix II). Fire breaks also add additional ignitions by increasing human access, and they do not always successfully contain large fires (Rhodes and Baker 2008). From the perspective of the CNNF, fire breaks are also limited to forested land cover types and on public lands, whereas much of the fire risk occurs on and adjacent to open field and wetland land cover (Figure 3). If pine systems generally burn as crown fires, fire risk may be influenced by fire breaks, but they can produce unintentional consequences (Table 5). In our case fire risk was enhanced by increased human access associated with creation of new fire breaks. Similarly our results suggest that roadside treatments may not consistently reduce fire risk in the Lakewood area. Roads allow ignitions in remote areas (Lefort and others 2004) that may require longer response time by suppression agencies, increasing the likelihood that fires will escape control (Arienti and others 2006). Yet roads also restrict surface fire spread and provide access for fire suppression agencies and their equipment (Prestemon and others 2002).

Table 5. Sensitivity of the Factorial Fire Mitigation Experiment to Different Assumptions

Fire mitigation treatment	Zone	Fire break	Road	Debris	Significant interactions
Inside the WUI					
Base experiment	−16**	6	14	−35***	
Probability of establishment	0	−7	5	−43***	ZxR
Fuel (conifers always crown)	−27***	12	1	−36***	
All private lands are managed	−14*	3	−2	−37***	
No private lands are managed	−17*	−1	−2	−45***	
Roads not permeable	−8	−4	0	−39***	ZxB
Roads completely permeable	3	8	−3	−40***	BxR
Wetlands never burn	−6	3	−10	−36***	
Outside the WUI					
Base experiment	8	−4	−8	−35***	
Probability of establishment	8	8	1	−38***	
Fuel (conifers always crown)	3	−14*	−3	−33***	
All private lands are managed	13*	4	−4	−34***	
No private lands are managed	5	0	−11	−34***	
Roads not permeable	1	6	−5	−26***	ZxB; ZxR
Roads completely permeable	−3	−3	−5	−22***	BxR
Wetlands never burn	−2	−7	−9	−31***	ZxD

Values represent average percent difference in area burned per decade caused by each of the different fire mitigation treatments for regions both inside and outside the WUI, where negative numbers indicate a decrease in area burned, and positive numbers indicate an increase in area burned due to the treatment. The base experiment is contrasted with the different assumptions identified for sensitivity analyses. Treatment significance and significant ($P < 0.05$) interaction terms are from separate ANOVAs applied to each factorial experiment.
$^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.0001$.

Ecological Goals

Forest composition trends in the Lakewood district indicate strong trends toward northern hardwood forest types, at the expense of fire-dependent forest types including aspen, oak, and pine (Figure 4A; Table 4). Fire rotations were simply too long to have any strong interaction with forest vegetation (Table 2), hence wildfire as a disturbance process is essentially excluded from the Lakewood study area. Active management including planting, prescribed burning, and short-rotation aspen harvest is required to maintain these fire-dependent systems in the absence of wildfire. Despite application of these management prescriptions, our results indicate that the CNNF may struggle to meet their ecological targets for fire-dependent ecosystems (Table 5).

Fire mitigation strategies had negligible effects on the ecological goals outlined within the CNNF forest plan. With the exception of the ZONE treatment, none of the other fire mitigation strategies directly affect forest management, and the ZONE treatment was designed to reallocate the locations of risky forest types without changing landscape-scale composition. The slight differences in forest composition between ZONE and BASE scenarios were due to a legacy effect—because aspen, pine, and oak prescriptions depend on harvesting stands with similar composition, adding additional constraints can result in missed opportunities for regenerating senescing stands to their previous composition. There was no evidence of any indirect effect of fire on forest composition, despite strong differences in the annual area burned (for example, 35% reduction caused by the DEBRIS treatment). However, because the legacy of previous forest composition is typically a prerequisite for the reestablishment and long-term maintenance of fire-dependent communities, strategic planning will be essential for identifying opportunities for ecosystem restoration while minimizing fire risk.

Model Limitations

We used fire records from the recent past to project future trends in fire patterns (Sturtevant and Cleland 2007). This empirical approach assumes that both weather and human influence on fire remain consistent through time. However, the relatively short time period (16 years) may not capture longer-term weather trends such as drought cycles or future climate change that can influence regional wildfire frequency and size (Hanson and Weltzin 2000; Prestemon and others 2002). We also found our results to be sensitive to large but rare fire events for which the 16-year fire record had limited records. Although we did not restrict the size of fires in the simulations, the calibrated fire regime matched the empirical data closely. Although some of the largest fires were caused by roadside ignition sources, there were too few very large fire records to be confident that large fires are more or less attributable to a given cause. Assuming that human-caused fire patterns are constant through time further ignores the fact that human behavior is dynamic and can be tied to social factors that can also change through time (Butry and others 2002). Future rural development is anticipated for the region that can further modify future fire patterns and long-term fire risk.

Some of our fuel assumptions are also problematic. We found that our results were sensitive to assumptions about crown fire dynamics, for which the fire records contain no information. Crown fire dynamics are one of the most challenging aspects of wildfire simulation (Cruz and others 2005). Our sensitivity analysis at least bounds the domain of uncertainty associated with crown fires, and provides some insight into the consequences of different fire behaviors.

Comparison with Other Ecosystems

The human-dominated fire regime of northern Wisconsin is representative of the warm continental ecoregion of North America (Bailey 1998). Contemporary fire hazard, both in terms of fire frequency and size, is among the lowest in the United States (Malamud and others 2005). The current fire regime is strongly influenced by a combination of human and ecological factors (Sturtevant and Cleland 2007). The relatively humid temperate climate favors fire-resistant deciduous forests (Bailey 1998), lightning-caused fires are rare, and the primary fire season is restricted to a short spring period between snow melt and leaf-out when the understory is most desiccated (Cardille and Ventura 2001). Fire suppression is also effective, enhanced by a well-developed road infrastructure and a strong human presence able to rapidly detect wildfires (Hawbaker and others 2005; Malamud and others 2005).

Despite strong regional constraints on wildfire, there are fire-prone ''hotspots'' within the broader region that burned frequently prior to Euro-American settlement and have supported the majority of large contemporary wildfires (Radeloff and others 1999; Cleland and others 2004; Scheller and others 2008). Such hotspots are often associated with glacial landforms, such as sandy outwash plains, that are frequently drought-stressed and favor coniferous and other flammable vegetation (Cleland and others 2004). Many of these areas have attracted low-density rural development in recent decades due to ecological amenities such as extensive forests and abundant lakes (Radeloff and others 2001; Gustafson and others 2005). Because human development brings human ignitions, fire risk has increased within these local fire hot-spots (Haight and others 2004). Unlike many other regions of the country, however, continued fire suppression within fire-prone ecosystems of this region often causes long-term, self-reinforcing changes in vegetation that reduces fire risk over time (Frelich 2002). In addition, controlled burning practices are not as culturally accepted in Wisconsin as they are in other areas of the country, such as the southeastern United States (Wade and others 2005). Those that might consider prescribed burns in Wisconsin may be deterred by liability for suppression costs should their burns escape control (http://dnr.wi.gov/forestry/fire/burning-rp.htm).

Simulation experiments such as that presented here can provide insight into trade-offs in land management options by examining the logical consequences of alternative management actions. For example, our results suggest that systematic movement of fire-prone vegetation types away from anthropogenic ignition sources can reduce landscape-scale fire risk. In Wisconsin, this may be achieved by limiting silvicultural treatments that encourage fire-dependent vegetation (for example, prescribed burning, pine plantations, and so on) to sparsely populated areas and letting natural succession in the absence of fire proceed near rural developments (Ward and others 2005). Although an identical strategy applied in a different region could have disastrous consequences, analogous treatments that reduce flammability (such as prescribed burning in the southern United States) might be applied to achieve the same goal. Similarly, fire mitigation practices developed in more western regions of the United States, such as fire breaks, should be less influential in this region because large fires are rare and human infrastructure is already well established. Insights therefore emerge by understanding the nature of the interaction between humans, natural vegetation, and fire that can vary substantially between regions.

Conclusions

Fire-dependent ecosystems are becoming increasingly endangered across the United States and elsewhere (Noss and others 1995; Scheller and others 2005; Scheller and others 2008). Some examples of endangered species reliant on fire-dependent communities of concern to the CNNF include an expanding population of Kirtland's warbler (*Dendroica kirtlandii*) (Probst and others 2003), Karner blue butterfly (*Lycaeides melissa samuelis*) (Grundel and others 1998), and sharp-tailed grouse (*Tympanuchus phasianellus*) (Akcakaya and others 2004). We find that successional trends within the Lakewood area, in the absence of targeted management, are toward the northern hardwoods type, including a strong increase in red maple (*Acer rubrum*). This trend is consistent with regional forest composition trends of U.S. eastern deciduous forests (Abrams 1998; Schulte and others 2007). In addition to fire safety concerns, increasing rural development often limits forest management options on adjacent public lands with similar successional consequences (Ward and others 2005). Hence, one of the grand challenges facing public land managers is how to simultaneously restore fire-dependent ecosystems while remaining ''good neighbors'' to private landowners in the face of increasing rural development. Our results indicate that landscape-scale management strategies, such as broad-scale reduction of human-caused ignitions and the redistribution of fire-dependent forest types away from human ignition sources, can also offer viable solutions for mitigating long-term fire risk and reducing land-use conflict in multi-ownership landscapes.

ACKNOWLEDGMENTS

This study was a collaborative effort between the authors and personnel from the Chequamegon-Nicolet National Forest, conducted through a series of workshops and personal interviews and funded by the National Fire Plan, to inform landscape-scale fire and fuel mitigation strategies for the Lakewood subdistrict. Key participants in the discussions and workshops include: Joel H. Skjerven, Jim Grant, Mary Lucas, Jay Saunders, John Lampereur, Al Harrison, Mark Theisen, and Geoff Chandler. We thank Robert Costanza (US Forest Service) for his assistance with model calibration and output summary. We are also grateful to Sue Stewart (US Forest Service), Roger Hammer (Oregon State University), Volker Radeloff (University of Wisconsin), and two anonymous reviewers for helpful comments on the manuscript.

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