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# Fuel load reductions and fire risk in central hardwood forests of the United States: a spatial simulation study

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## Abstract

With wildfire suppression, accumulation of fine fuels and coarse fuels increases fire risk in Central Hardwood Forests. Assessment of fire risk provides guides for fuel treatments (prescribed fires, or coarse woody debris reduction) to avoid severe wildfires. A spatially explicit landscape model, LANDIS, was used to simulate fine and coarse fuels and their dynamics in the Missouri Ozarks as influenced by forest succession, species establishment, tree mortality, wildfire disturbance and fuel treatments. Three scenarios were selected and simulated for 200 years: (I) wildfire suppression only; (II) prescribed fire with wildfire suppression; and (III) prescribed fire and coarse fuel reduction with wildfire suppression. LANDIS evaluated the potential fire risk for each forest stand by rating the potential fire intensity and fire probability. About 5% of the stands with the highest potential fire risk were selected each decade for fuel treatment under scenarios II and III. Simulation results showed that fuels and potential fire risk gradually built up to high levels in scenario I. Prescribed fires in scenario II reduced potential wildfire risk at the beginning of the 200-year simulation, but became less effective in limiting wildfires in later years. Additional coarse fuel reduction coupled with prescribed fire in scenario III effectively controlled the coarse fuel loading and potential fire risk. The simulated mean wildfire return interval increased from 325 years in scenario I, to 496 years in scenario II, to 637 years in scenario III.

*Keywords:* Fuel; Fire risk; Fuel treatment; Prescribed fire; Landscape model; LANDIS

## 1. Introduction

Since 1940, forests in Missouri and throughout the Central Hardwood Region have experienced active wildfire suppression (Westin, 1992; Guyette et al., 2002), significantly extending the mean wildfire return

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interval relative to prior decades (Guyette and Larsen, 2000). This has led to changes in forest size structure and species composition. Wildfire suppression also results in the build up of fuels and increased fire risk with a greater probability for catastrophic wildfires. Recently, the Missouri Department of Conservation and the USDA Forest Service have used fuel treatments (e.g., prescribed fires and thinning), to manage wildfires and manipulate forest structure and composition in Missouri.

Fuel treatments are intended to limit wildfires directly by mitigating fire spread and severity and indirectly by facilitating suppression (Finney, 2001). Several fuel-treatment options have been suggested, including creation of fuel breaks of various widths, prescribed burning of understory and surface fuels (the duff, live fuels, and dead woody debris lying on the forest floor), thinning and chipping trees in smaller size classes, and removal of understory trees and branches to reduce ladder fuels (Van Wagtendonk, 1996). However, the effectiveness and efficiency of these treatments are largely unknown, and some means of evaluating them is necessary. Field experiments are a direct approach to test the effectiveness of various fuel treatments on subsequent wildfire behavior, but they remain difficult and costly to conduct in large areas and for long time periods. Spatial modeling is an effective tool for evaluating the ability of alternative fuel treatments to reduce fire risk and modify fire behaviors. Compared to field experiments, spatial modeling is fast and inexpensive approach for estimating the relative impacts of alternative fuel management regimes over space and time, and guiding the implementation of field studies.

Two approaches, mechanistic or stochastic modeling, are normally used to simulate fuel and wildfire dynamics (He and Mladenoff, 1999). Mechanistic models are usually used to simulate fire events over a short time period. They use the physical and chemical properties of fuel, weather and topographic data to simulate fire ignition, rate of spread and shape of spread. Examples include BEHAVE (Burgan and Rothermel, 1984; Andrews, 1986; Andrews and Chase, 1989), Fire-BGC (Keane et al., 1996), FOFEM (Reinhardt et al., 1997), FARSITE (Finney, 1994; Finney, 1998), FFE-FVS (Reinhardt and Crookston, 2003), and models by Rothermel (1972), Albini (1976), and Van Wagner (1977). In contrast, stochastic models were developed to simulate multiple wildfire events over long temporal scales and large areas. Some stochastic approaches (Van Wagner, 1978; Johnson, 1979; Johnson and Van Wagner, 1985) have been adapted and applied using landscape models such as DISPATCH (Baker et al., 1991; Baker, 1992) and LANDIS (Mladenoff and He, 1999; He and Mladenoff, 1999).

Fire and fuel behavior models are useful tools for evaluating the long-term vegetation and wildfire dynamics under fire suppression, and for making preliminary assessments of the effects of alternative fuel treatments on fuel loading, fire risk, wildfire behavior and forest succession. Johnson and Miyanishi (1995) simulated the effects of prescribed burning on fire behavior. Van Wagtendonk (1996) used the FARSITE model (Finney, 1994) to test multiple fuel treatment options for reducing fuels and wildfires. Finney (2001) studied the landscape fuel treatment patterns that modify fire behavior. Omi and Martinson (2002) simulated the effects of thinning and prescribed fires on wildfire severity. Baeza et al. (2002) studied the implications of using prescribed burning to reduce wildfire risk. Brose and Wade (2002) modeled the fire behavior under multiple fuel reduction treatments.

We used a stochastic, spatially explicit landscape model, LANDIS, to simulate the dynamics of species succession, fuel and fire disturbance, and to evaluate the effects of alternative fuel treatments. We selected three scenarios for study: (I) wildfire suppression only; (II) prescribed fire with wildfire suppression; and (III) prescribed fire and coarse fuel reduction with wildfire suppression. This study explores three hypotheses: (1) fuel and fire risk gradually build up under wildfire suppression; (2) prescribed fires can reduce the incidence of wildfires over time; and (3) coarse fuel removal can affect wildfire severity and area burned. Due to the stochastic nature of the LANDIS model and the generic scenarios used, the simulation of fuel treatments effects in this study should be regarded as a heuristic device, and not a prediction of the fuel situation and wildfire behavior in future.

## 2. Methods

### 2.1. Study area

The study area, 71,142 ha in size, is located in the Mark Twain National Forest and within the Missouri

Ozark Highlands (Fig. 1). The study area contains the watershed for two rivers, the Current River and the Eleven Point River. Historic records of wildfire in Missouri from 1939 to 1991 (Westin, 1992) and dendrochronological studies (from 1680 to 1990) in the Current River watershed (Guyette et al., 2002) show that the average wildfire return interval in the Current River watershed (Guyette and Larsen, 2000) varied from 17.7 years in the depopulated period (1580–1700) and 12.4 years in the Native American repopulation period (1701–1820), to 3.7 years in the Euro-American settlement period (1821–1940). Effective wildfire suppression, wildfire prevention education, and increased timber values have resulted in a reduction in the area burned annually in the Current River watershed (Guyette and Larsen, 2000), from about 21% in 1940 to less than 1% in the 1990's, thus dramatically extending the wildfire return interval. Reconstruction of early nineteenth-century vegetation in the Missouri Ozarks Highlands (Guyette and Dey, 1997; Batek et al., 1999) shows extensive stands of shortleaf pine (*Pinus echinata* Mill.) and oak-dominated woodland (savanna) in frequently burned areas southwest of the Current River, and more mesophytic species such as red oaks (*Quercus rubra* L., *Q. coccinea* Muenchh.), maple (*Acer rubrum* L., *Acer saccharum* Marsh), and eastern red cedar (*Juniperus virginiana* L.) dominant in a "fire shadow" northeast of the Current River. The combination of logging followed by wildfire suppression in the 20th century favored the development of oak-dominated forests and prompted a decline in the abundance of shortleaf pine. Present shortleaf pine abundance is only 20–25% of that circa 1900 in Missouri (Guyette and Dey, 1997; Batek et al., 1999). Recently, the Missouri Department of Conservation and USDA Forest Service have begun using prescribed fires to reduce fire risk in the Missouri Ozark Highlands. The ecological effects of these fires, especially the long- term effects, are still unclear.

Our study area primarily consists of National Forest lands for which detailed information on vegetation, land types, and stand boundaries exists. There are some inclusions of private land where such information

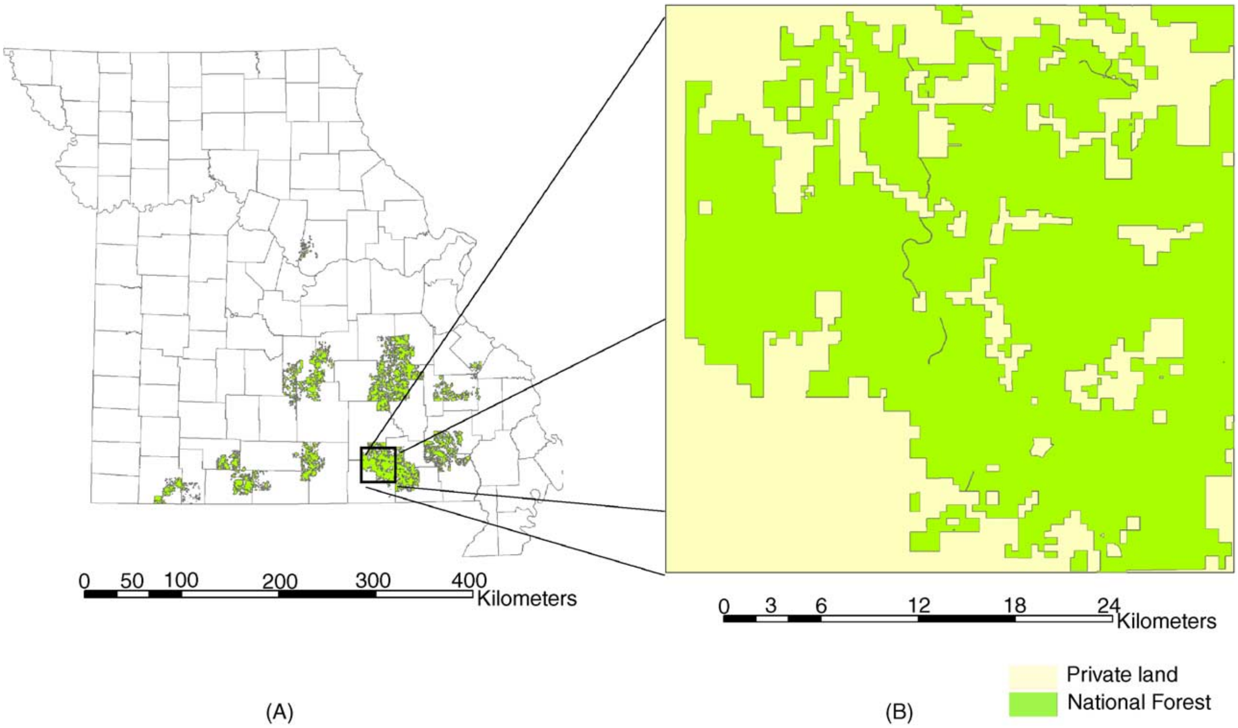

Fig. 1. Study area, a portion of the Mark Twain National Forest Park located in the Missouri Ozark Highlands. (A) National forests in Missouri State, US. (B) Private land and national forest in the study area.

is lacking. For these sites where inventory data were lacking we used a generic oak species (or pseudo-oak species) to describe the forest cover. This generic oak has attributes similar to the dominant oak species in the Ozark Highlands. This procedure simply allowed the fire to initiate in the private lands and spread from private lands to the national forest and vice versa. Our analyses of results were restricted to National Forest lands.

### 2.2. *LANDIS*

LANDIS, a spatially explicit simulation model of forest landscape disturbance, succession and management, is designed to integrate ecological processes across large and heterogeneous areas ($10^4$–$10^6$ ha), and over long periods of time (e.g., hundreds of years) (Mladenoff et al., 1996; Mladenoff and He, 1999; He et al., 1999). LANDIS is a raster-based model that simulates ecosystem dynamics including forest succession, seed dispersal, species establishment, fuel accumulation and decomposition, fire and windthrow disturbance, timber harvest, and fuel treatment with a 10-year time step. LANDIS 3.7 includes four components (or modules): species succession, fire disturbance, wind disturbance and harvest (He et al., 2003). Descriptions of species succession, fire and wind disturbance, and timber harvest in LANDIS can be found elsewhere (Mladenoff et al., 1996; Mladenoff and He, 1999; He et al., 1999; He and Mladenoff, 1999; Gustafson et al., 2000). A new LANDIS fuel module (Shang and He, 2003; He et al., 2004) has been added to LANDIS 3.7 to track live, fine and coarse fuels, to estimate potential fire risk, and to evaluate the effects of fuel treatments. Detailed information about fuel module design can be found in He et al. (2004). The following sections give an overview of fuel tracking, potential fire intensity, fire probability and fire risk, and fuel treatment in the LANDIS fuel module.

#### 2.2.1. *Fuel tracking*

The fuels that burn in a forest fire are generally separated into two classes, live fuels and dead fuels. Live fuels consist of leaves, twigs, and stems of growing plants. Most live fuels are difficult to ignite and often do not burn readily by themselves. Only when the moisture content of living plants is reduced by drought or dormancy and/or when they are dried and heated by a fire in dead fuels beneath them, can they burn, sometimes very intensely. However, some live trees, such as conifers, will readily burn intensely and have great chance to introduce a crown fire. Dead fuels consist of fallen leaves and needles, dead twigs and branches, and standing or fallen dead trees, grass and weeds. Fires start easily in dry, dead fuels and spread readily. The LANDIS fuel module tracks live and two kinds of dead fuels: fine fuels (light fuels) and coarse fuels. To reduce false precision and the parameterization burden, the fuel loads are converted into five categorical classes: very low, low, medium, high and very high.

Some live fuels (e.g., conifers), provide vertical continuity between strata and allow fire to be transmitted from the surface into the crowns of trees or shrubs. Species that frequently become ladder fuels can be specified in the process of model initialization. The model uses that information to generate a probability that a fire will become a crown fire (Shang and He, 2003; He et al., 2004).

Fine fuels include leaves, twigs, ground litter, needles, and fine woody debris. Forest species composition and age are two major factors associated with the production of fine fuels. The fine fuels fall annually and decompose quickly. Trofymow et al. (2002) found that about 80% of the original litter mass decomposed within a 6-year experiment in Canada. Therefore, we assume that most fine fuels decompose in one 10-year simulation time step. A curve was defined for each species to approximate how fine fuel loading varied with species age by balancing the accumulation and decomposition rate (Shang and He, 2003; He et al., 2004). Natural and human disturbances affect fine fuel loads; windthrow, insects and diseases, and timber harvest can greatly increase input of fine fuel. Wildfire can readily burn most fine fuels.

Coarse fuels, also called coarse woody debris, include snags, logs, large pieces of wood (which result from the disintegration of larger snags and logs), branches, stems and coarse roots. Tree mortality, breakage, windthrow and timber harvest move large quantities of coarse woody debris from living trees into the coarse fuel pool. Insects and disease may cause mortality and add coarse woody debris over extensive areas (Harmon et al., 1986). The decomposition rate of coarse woody debris varies by species, fuel sizes, and ecosystems (Harmon et al., 2000). However, the accumulation rate and decomposition rate eventually reach a balance.

The LANDIS fuel module uses accumulation and decomposition curves defined for each ecological land type to estimate coarse fuel loading (Shang and He, 2003; He et al., 2004).

Wildfires have two kinds of effects on the coarse fuels. Normally wildfires burn and reduce some coarse fuels, depending on the fire intensity. Sometimes wildfires cause tree mortality and add new snags to the pool of dead coarse fuels. The LANDIS fuel module (Shang and He, 2003; He et al., 2004) provides the flexibility to deal with these two situations by defining either negative or positive changes in coarse fuel abundance after wildfires.

### 2.2.2. *Potential fire intensity, fire ignition probability and potential fire risk*

Fuel types, fuel loads and fuel moisture are major factors that affect fire intensity. In LANDIS, information about soil moisture and topography are included in each ecological land type. Therefore, LANDIS uses the fine fuel load, the coarse fuel load, the quantity of ladder fuels, and ecological land type information to estimate the potential fire intensity. High fine fuel loads and high coarse fuel loads lead to higher probabilities of high intensity fires. If conifers exist in the forests, probabilities of high intensity fire are greater due to the increased opportunity for crown fires. Fire intensity is classified into five classes, ranging from very low (class 1) to very high (class 5).

LANDIS uses fire history information to evaluate the fire ignition probability. Fire ignition probability follows a negative exponential distribution based on time since last fire and on the mean wildfire return interval, which varies by ecological land type (He and Mladenoff, 1999; He et al., 2004). The probability of ignition increases with increasing time since last fire. The LANDIS fuel module reclassifies the fire ignition probability into five categories from very low (class 1) to very high (class 5).

An index, potential fire risk, is used to indicate the combined risk of occurrence and intensity of wildfires. High potential fire ignition probability and high potential fire intensity result in high potential fire risk (He et al., 2004). In the LANDIS fuel module, potential fire risk is assorted into five categories: very low, low, medium, high and very high. Potential fire risk is the guiding index for the fuel treatments described below.

### 2.2.3. *Fuel management*

Stands are the basic unit for forest management, and LANDIS implements management events by selecting stands for treatment. Management areas are comprised of groups of stands (not necessarily contiguous) that are managed in a similar way. Fuel treatments are applied in the context of management areas. Each management area may have unique management prescriptions, including single or multiple fuel treatments.

LANDIS computes the potential fire risk for each forest stand by evaluating the potential fire intensity and probability of fire occurrence, and selects the stands for treatment based on stand age, fire risk and adjacency. Each treatment prescription is specified by the proportion of stands to be treated, the rotation and frequency of treatment and the amount of fine fuel and coarse fuel removed.

## 2.3. *Data preparation and model initialization*

Forest inventory data for each stand in our study area in the Mark Twain National Forest included: (i) forest type, (ii) tree size class (sapling, pole, sawlog and nonstocked), (iii) age, (iv) basal area (low, medium and high stocking), and (v) ecological landtypes. The 20 ecological land types (ELTs) (Miller, 1981) represented in the inventory data were combined to create a reduced set of seven principal ecological land types (i.e., south and west slopes, north and east slopes, ridge tops and upland flats, savanna/glade, upland drainage, limestone slopes and mesic/floodplain) (Shifley et al., 2000). A digital elevation model (DEM) with 30 m × 30 m resolution in the Missouri Ozark Highlands was used to validate and confirm the geographic attributes (slope and aspect) and boundaries for each ecological land type. Species composition in the study area is represented by four species groups: the white oak group, predominantly white oak (*Quercus alba* L.) and post oak (*Q. stellata* Wangenh.); the red oak group, predominantly black oak (*Q. velutina* Lam.) and scarlet oak (*Q. coccinea* Muenchh.); the pine group, predominantly shortleaf pine (*Pinus echinata* Mill.); and the maple group, predominantly red maple (*Acer rubrum* L.) and sugar maple (*A. saccharum* Marsh.). Species proportions were estimated from forest inventory and analysis databases (FIA) (Hansen and Hahn, 1992; Hansen et al., 1992) and the nearby Missouri Ozark Forest Ecosystem Project (MOFEP) (Brookshire and

Shifley, 1997; Shifley and Brookshire, 2000; Shifley and Kabrick, 2002). Species locations were randomly assigned within each stand based on the species proportions. The majority of forest in the study area was in the 60- to 80-year age class (Shifley et al., 2000).

Based on historic fire data between 1970 and 1995 (Westin, 1992), the mean fire return interval (FRI) was initialized at around 300 years for most land types, and 20 years on managed savanna/glades (Shifley et al., 2000). Because wildfires burned frequently in the Euro-American settlement period (1821–1940) (FRI = 3.7 years) (Guyette and Larsen, 2000), and infrequently in the fire suppression period (Westin, 1992), we set the time since last fire to 70 or 80 years for most ecological land types. For savannas, no wildfires were reported after the prescribed fires in 1970s (William D. Dijak, personal communication). Therefore, we set the time since last fire to 20 years for savannas.

An uncertainty and sensitivity analysis (Shang et al., submitted for publication) showed that the simulation results were critically sensitive to some initialization parameters. For example, different initialization of species age structure influenced the species distribution (relative area) and the wildfire sizes. The initialized mean fire return interval and time since last fire had dramatically affected wildfire patterns.

### *2.4. Simulation scenarios*

We selected three scenarios (Table 1) to show the dynamics of forests under fire suppression, and to evaluate the effects of simulated fuel treatments in controlling fuel loading, fire risk and wildfires. Scenario I approximated the fire regime under fire suppression as practiced in the 1990s (Shifley et al., 2000). Scenario II incorporated a prescribed fire prescription in addition to fire suppression. For each decade, LANDIS selected about 5% of the stands with the highest potential fire risk and simulated prescribed fires that burned all the fine fuels and decreased the coarse fuel load by one class (Table 2). To further control the fuel loading, scenario III simulated fire suppression in conjunction with a high intensity of fuel treatment on both fine and coarse fuels. In each decade about 5% of the stands with the highest potential fire risk were selected for treatment (Table 3). If the coarse fuel loads in the stands were high or very high (≥class 4), a coarse fuel reduction was used to reduce coarse fuels to a low level, and then additional prescribed fires were implemented to reduce the quantity of fine fuels and some coarse fuels. If the coarse fuel loads were not high (≤class 3) in the selected stands, only prescribed fire was used to burn the fine fuels and decrease some of the coarse fuel load. All three scenarios were simulated for 200 years with a time step of 10 years, and a spatial resolution of 30 m ×30 m, using a common model initialization (i.e., same initial time since last fire, fire ignition density, fire size, species age and distribution map, land type map and management area map). We recorded the percent of the landscape with high levels (classes 4 and 5) of fine fuel load, coarse fuel load, and potential fire risk to illustrate the fuel treatment effects over the 200 years of simulation.

## 3. Results

### *3.1. Fuel loading*

Simulation results showed few differences in the fine fuel loading among the three scenarios (Fig. 2).

Table 1
Simulation approach for each fuel treatment scenario

| Scenario | Description | Fuel treatment proportion | Treatments on fine fuels | Treatments on coarse fuels |
|---|---|---|---|---|
| I | Forest under wildfire suppression | None | None | None |
| II | Prescribed fires fire on forest under wildfire suppression | Each decade select 5% stands with the highest potential fire risk | Remove all fine fuels | Reduce coarse fuel load by one category |
| III | Prescribed fire and coarse fuel reduction on forest under wildfire suppression | As scenario II | As scenario II | If coarse fuel load is high (class 4 or 5), then reduce to low level (class 1). Otherwise reduce coarse fuel load by one category |

Table 2
Fuel treatment parameters in scenario II (prescribed fires with wildfire suppression)[a]

| | | | | | | |
|---|---|---|---|---|---|---|
| [Fuel management prescription] prescribed fires | | | | | | |
| Management area identifier | 1 | | | | | |
| Rank algorithm (1 = highest fire risk processed first) | 1 | | | | | |
| Entry decade | 1 | | | | | |
| Final decade | 20 | | | | | |
| Reentry interval (decade) | 1 | | | | | |
| Proportion of the management area to treat | 5% | | | | | |
| Minimum potential fire risk for management | 3 | | | | | |
| [Treatment intensity] | | | | | | |
| Fine fuel load class before treatment | 0 | 1 | 2 | 3 | 4 | 5 |
| Fine fuel load class after treatment | 0 | 0 | 0 | 0 | 0 | 0 |
| Coarse fuel load class before treatment | 0 | 1 | 2 | 3 | 4 | 5 |
| Coarse fuel load class after treatment | 0 | 0 | 1 | 2 | 3 | 4 |

[a] This table provides an example of fuel treatment prescription for one management area. Forest management began at year 10 and ended at year 200. About 5% of the stands with the highest potential fire risks (≥class 3) were selected each decade for management. All of the fine fuels and some coarse fuels were burned in the selected stands. For example, coarse fuel loads were reduced from class 1 (very low) to class 0 (none), from class 2 (low) to class 1 (very low), from class 3 (medium) to class 2 (low), from class 4 (high) to class 3 (medium), and from class 5 (very high) to class 4 (high), respectively.

In scenario II and III, fuel treatments on the selected stands (5% of whole area each iteration) did reduce the fine fuel loads in these stands. However, as described previously, fine fuels accumulate annually and decompose within a 10-year model iteration. Therefore, fine fuels removed in the treated stands recovered in the next iteration. Hence, fine fuel did not differ distinctly among these three scenarios.

Simulation results showed distinct effects of fuel treatments on the coarse fuel loads (Fig. 3). In scenario I, coarse fuels built up rapidly between years 60 and 120, and remained at high levels thereafter, covering over 40% of total landscape. The fuel treatment in scenario II delayed the build-up of coarse fuels, but after year 150, there was a larger proportion (over 50%) of the landscape with a high coarse fuel load in sce-

Table 3
Fuel treatment parameters in scenario III (prescribed fire and coarse fuel reduction with wildfire suppression)[a]

| | | | | | | |
|---|---|---|---|---|---|---|
| [Fuel management prescription] prescribed fires + coarse fuels reduction | | | | | | |
| Management area identifier | 1 | | | | | |
| Rank algorithm (1 = highest fire risk processed first) | 1 | | | | | |
| Entry decade | 1 | | | | | |
| Final decade | 20 | | | | | |
| Reentry interval (decade) | 1 | | | | | |
| Proportion of the management area to treat | 5% | | | | | |
| Minimum potential fire risk for management | 3 | | | | | |
| [Treatment intensity] | | | | | | |
| Fine fuel load class before treatment | 0 | 1 | 2 | 3 | 4 | 5 |
| Fine fuel load class after treatment | 0 | 0 | 0 | 0 | 0 | 0 |
| Coarse fuel load class before treatment | 0 | 1 | 2 | 3 | 4 | 5 |
| Coarse fuel load class after treatment | 0 | 0 | 1 | 2 | 1 | 1 |

[a] This table provides an example of fuel treatment prescription for one management area. Forest management began at year 10 and ended at year 200. About 5% of the stands with the highest potential fire risks (≥class 3) were selected each decade for management. For the selected stands, if coarse fuel loads were not high (≤class 3), only prescribed fires were used to burn all of the fine fuels and some coarse fuels. For example, coarse fuel loads were reduced from class 1 (very low) to class 0 (none), from class 2 (low) to class 1 (very low), and from class 3 (medium) to class 2 (low), respectively. If coarse fuel loads in the selected stands were high or very high (≥class 4), a coarse fuel reduction was used to reduce coarse fuels to a low level, and then additional prescribed fires were implemented to burn all of the fine fuels and some coarse fuels. For example, coarse fuel loads were reduced from class 4 (high) to class 1 (very low), and from class 5 (very high) to class 1 (very low), respectively.

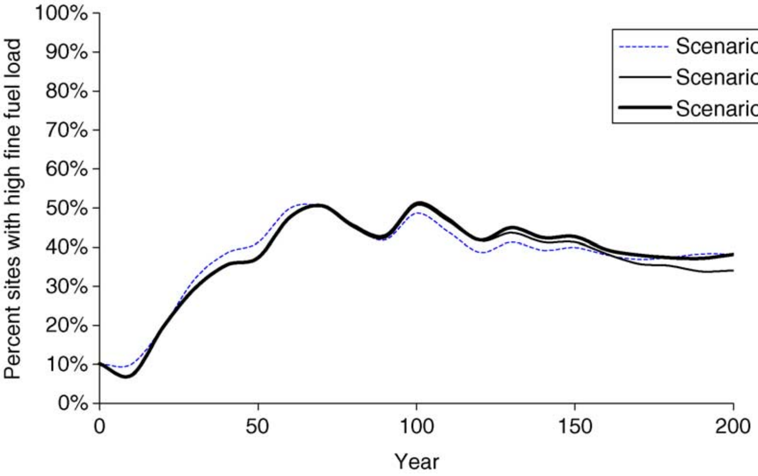

Fig. 2. Percent of sites with high fine fuel load in three simulation scenarios. Scenario I: wildfire suppression only; scenario II: prescribed fires with wildfire suppression; scenario III: prescribed fire and coarse fuel reduction with wildfire suppression.

nario II than that in the scenario I. The fuel treatment in scenario III was even more effective in controlling the coarse fuel loading during the 200-year simulation (less than 35% of the landscape had a high coarse fuel load after 150 years).

### 3.2. Potential fire risk

For selected decades of each simulation treatment we computed the proportion of the landscape that had a high potential fire risk (classes 4 and 5), and we used those results to illustrate the effects of fuel treatments on potential fire risk (Fig. 4). In scenario I, potential fire risk built up rapidly between years 60 and 120. After year 120, potential fire risk decreased but still remained high with over 40% of the landscape at high fire risk. In scenario II, the potential fire risk still increased between years 70 and 130, but slower than in scenario I. After year 130, half of the study area remained at high fire risk. The fuel treatment in scenario III decreased the

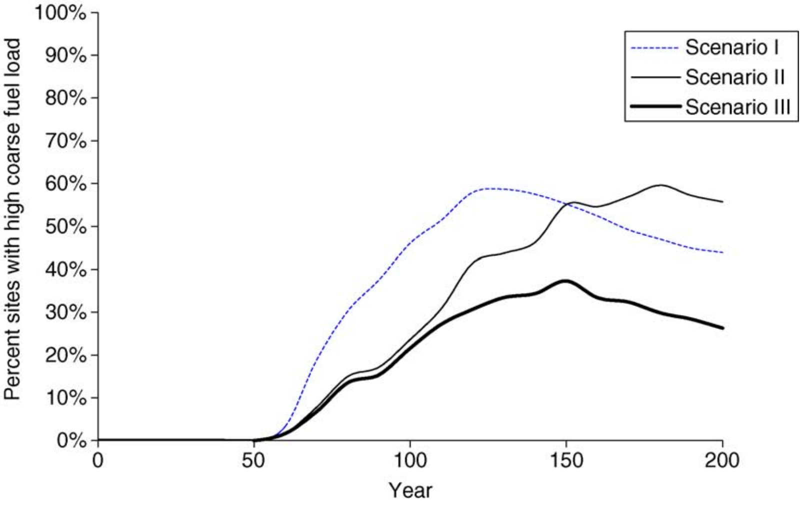

Fig. 3. Percent of sites with high coarse fuel load in three simulation scenarios. Scenario I: wildfire suppression only; scenario II: prescribed fires with wildfire suppression; scenario III: prescribed fire and coarse fuel reduction with wildfire suppression.

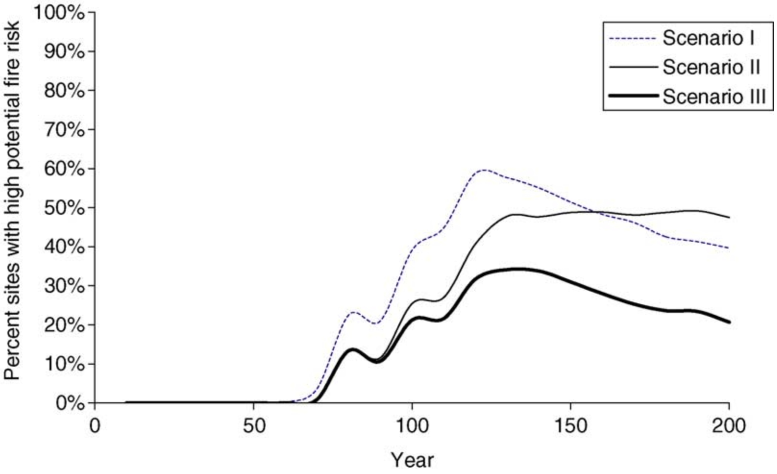

Fig. 4. Percent of sites with high potential fire risk in three simulation scenarios. Scenario I: wildfire suppression only; scenario II: prescribed fires with wildfire suppression; scenario III: prescribed fire and coarse fuel reduction with wildfire suppression.

proportion of the landscape at high potential fire risk to less than 30%.

### 3.3. Wildfires

Fuel treatments in scenarios II and III altered the simulated wildfire regimes compared to scenario I. In scenario I, the proportion of the landscape burned by low intensity wildfires (≤class 3) was low—about 0.4% of the landscape burned per decade (Fig. 5A). Prescribed fires in scenario II caused more low intensity wildfires than scenario I (Fig. 5A) with between 0.2% and 1.0% burned in scenario II. In scenario III, the area burned by low intensity wildfires increased gradually from 0.4% in the beginning to over 1.2% at the end of the simulation (Fig. 5A).

Fuel treatments greatly influenced high intensity (classes 4 and 5) wildfires (Fig. 5B). In scenario I, more high intensity wildfires occurred than for either of the other two scenarios. The area of burned sites in scenario I increased from 0% at the beginning, to about 4% per decade at the end. Prescribed fires in scenario II seem to be effective in controlling the high intensity wildfires in the first 150 years, with less than 2% of the landscape burned each decade by high intensity wildfires. However, after year 180, there were more high intensity wildfires in scenario II than in scenario I. The fuel treatments in scenario III decreased the high intensity wildfire to less than 2% of landscape burned each decade.

Comparisons of cumulative wildfires during the 200 years of simulation clearly show substantial differences among the three scenarios (Fig. 6). In scenario I, almost two thirds of the landscape burned by wildfire in the 200-year simulation period, with most wildfires either of high (class 4) and very high (class 5) intensity. In scenario II, less than half of the landscape burned by wildfire, and most wildfires were medium (class 3) and high (class 4) intensity. In scenario III, less than one third of the study area burned by wildfire, and most of the wildfires were medium (class 3) and high (class 4) intensity.

Simulation results for the three scenarios show notable differences in the mean wildfire return interval. Fire suppression in scenario I resulted in a mean wildfire return interval of 325 years. Prescribed fires with fire suppression in scenario II extend the mean wildfire return interval to 496 years, while the fuel treatment in scenario III increased the mean wildfire return interval to 637 years.

## 4. Discussion

Fuel treatments are intended to reduce fire risk and to control wildfires. The effectiveness of fuel treatments depends on the treatment intensity (amount of fuel re-

Fig. 5. Wildfire burned sites. (A) Low intensity wildfires (≤class 3) burned sites. (B) High intensity wildfires (classes 4 and 5) burned sites. Scenario I: wildfire suppression only; scenario II: prescribed fires with wildfire suppression; scenario III: prescribed fire and coarse fuel reduction with wildfire suppression.

moval), proportion of the landscape treated, and the treatment frequency. Different fuel treatments have different effects on the fuel loading and wildfire behavior. Prescribed fires burn most fine fuels, but do not greatly reduce coarse fuels. Hence, in scenario II, prescribed fires delay the build-up of coarse fuels, and reduce the area burned by high intensity wildfires (classes 4 and 5) in the first 150-year simulation. High intensity wildfires consume more coarse fuels than prescribed fires do (Brown et al., 1985). Consequently, in scenario II, the reduced area affected by high intensity wildfires in the first 150 years of the simulation encouraged the build-up of coarse fuels. Therefore, after year 150, there was a larger proportion of the landscape with a high coarse fuel load in scenario II than in scenario I. Additional coarse fuel removal in conjunction with prescribed fires in scenario III removed both fine and coarse fuels, and thus effectively controlled the coarse fuel loading and decreased the high intensity wildfires throughout 200 years of simulation.

Fig. 6. Wildfires accumulation over the 200-year simulation. Scenario I: wildfire suppression only; scenario II: prescribed fires with wildfire suppression; scenario III: prescribed fire and coarse fuel reduction with wildfire suppression.

This simulation study shows that fuel treatments mitigate intensities and sizes of wildfires, which is consistent with field observations (Edminster and Olsen, 1995; Scott, 1998; Pollet and Omi, 2002) and other simulation studies (Van Wagtendonk, 1996; Stephens, 1998; Brose and Wade, 2002). Fire suppression with no fuel treatment as modeled in scenario I led to the highest potential fire risk in the study area. The prescribed fires modeled in scenario II reduced the potential fire risk and area burned initially, but became less effective in controlling wildfires as the simulation progressed. Coarse fuel removal, in addition to the prescribed fires as modeled in scenario III, was more effective in controlling wildfires. Fuel treatments in scenario III substantially reduced coarse fuel loads and potential fire risk. Similar results were reported in a field study (Pollet and Omi, 2002), in which prescribed burns reduced the surface fuel loading in the short-term, while sites with thinning had more dramatically reduced fire severity compared to the site with prescribed fire only.

Fuel treatments also altered the fire regimes. In scenario I, both fine fuel loads and coarse fuel loads were high. Over time the wildfire size increased rapidly and most of the wildfires were high intensity fires. This fire regime had a high probability for catastrophic fires. Under scenario II, wildfire size was small initially but increased over the course of the simulation. After year 180, more area was burned by wildfire in scenario II than in scenario I. Fuel treatment in scenario III was effective in reducing the potential fire risk and area of wildfires. The simulated fire cycle increased from 325 years in scenario I, to 496 years in scenario II, to 637 years in scenario III.

Despite high occurrence of thunderstorms in Missouri (50–70 thunderstorm days per year) (Baldwin, 1973), anthropogenic ignitions have overwhelmed the influence of natural ignitions in the Missouri Ozarks, with more than 99% of the wildfires being of human-related origin (Westin, 1992). Human population density and culture has been one of the major factors influencing the frequency and effects of wildland fire over centuries in southeastern Missouri, including the Ozarks (Guyette et al., 2002). Historical timber harvests have distinctly affected the composition and structure of forests, and influenced wildfire occurrence and spread in Missouri (Guyette and Dey, 1997). Therefore, further studies are needed to evaluate the effects of both anthropogenic ignitions and timber harvests on the long-term vegetation and wildfire dynamics in Missouri.

The results of this study indicate that over the short term (<100 years) prescribed fire may be effective in reducing the burned area and intensity of wildfire in this region. Coarse fuel reduction may be required to maintain low levels of wildfire in the long term. However, coarse fuel reduction is expensive and labor intensive. Some additional management regimes including more frequent prescribed fires merit further exploration in simulation studies and field trials. The general simulation framework can be modified to explore a wide range of treatment alternatives.

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## References

Albini, A.F., 1976. Estimating wildfire behavior and effects. Gen. Tech. Rep., INT-30. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 93 pp.

Andrews, P.L., 1986. BEHAVE: fire behavior prediction and fuel modeling system—BURN subsystem. Part 1. Gen. Tech. Rep., INT-194. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 130 pp.

Andrews, P.L., Chase, C.H., 1989. BEHAVE: fire behavior prediction and fuel modeling system—BURN subsystem. Part 2. Gen. Tech. Rep., INT-260. United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 93 pp.

Baeza, M.J., Luis, M.D., Raventos, J., Escarre, A., 2002. Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk. J. Environ. Manage 65, 199–208.

Baker, W.L., Egbert, S.L., Frazier, G.F., 1991. A spatial model for studying the effects of climatic change on the structure of landscapes subject to large disturbances. Ecol. Modelling 56, 109–125.

Baker, W.L., 1992. Effects of settlement and fire suppression on landscape structure. Ecology 73, 1879–1887.

Baldwin, J.L., 1973. Climates of the United States. US Department of Commerce, National Oceanic and Atmospheric Administration, Environment Data Service, Washington, DC, 113 pp.

Batek, M.J., Rebertus, A.J., Schroeder, W.A., Haithcoat, T.L., Compas, E., Guyette, R.P., 1999. Reconstruction of early nineteenth-century vegetation and fire regimes in the Missouri Ozarks. J. Biogeogr. 26, 397–412.

Brookshire, B.L., Shifley, S.R. (Eds.), 1997. Proceedings of the Missouri Ozark Forest Ecosystem Project Symposium: an experimental approach to landscape research; Gen. Tech. Rep. NC-192. US Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, MN. 378 pp.

Brown, K.J., Marsden, A.M., Ryan, C.K., Reinhardt, D.E., 1985. Predicting duff and woody fuel consumed by prescribed fire in the Northern Rocky Mountains. Gen. Tech Rep., INT-337. United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 25 pp.

Brose, P., Wade, D., 2002. Potential fire behavior in pine flatwood forests following three different fuel reduction techniques. Forest Ecol. Manag. 163, 71–84.

Burgan, R.E., Rothermel, R.C., 1984. BEHAVE: fire behavior prediction and fuel modeling system—FUEL subsystem. Gen. Tech Rep., INT-167. United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 126 pp.

Edminster, C.B., Olsen, W.K., 1995. Thinning as a tool in resorting and maintaining diverse structure in stands of southwestern ponderosa pine. USDA Forest Service, Gen. Tech. Re RM-278. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT, pp. 62–68.

Finney, M.A., 1994. Modeling the spread and behavior of prescribed natural fires. In: Cohen, J.D., Saveland, J.M., Wade, D.D. (Eds.), Proceedings of the Twelfth Conference on Fire and Forest Meteorology. Society of American Forester, Bethesda, MD, pp. 138–143.

Finney, M.A., 1998. FARSITE: Fire area simulation—model development and evaluation. Research Paper RMRS-RP-4. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT, 47 pp.

Finney, M.A., 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. For. Sci. 47, 219–228.

Gustafson, E.J., Shifley, S.R., Mladenoff, D.J., Nimerfro, K.K., He, S.H., 2000. Spatial simulation of forest succession and timber harvesting using LANDIS. Can. J. For. Res. 30, 32–43.

Guytte, R.P., Dey, D.C., 1997. Historic Shortleaf Pine (*Pinus echinata* Mill.) abundance and fire frequency in a mixed oak–pine forest (MOFEP, Site 8). In: Proceedings of the Missouri Ozark Forest Ecosystem Project Symposium: An Experimental Approach to Landscape Research. Gen. Tech. Re NC-193. US Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN, pp. 136–149.

Guyette, R.P., Larsen, D.R., 2000. A History of Anthropogenic and Natural Disturbances in the Area of the Missouri Ozark Forest Ecosystem Project. In: Shifley, S.R., Brookshire, B.L. (Eds.), Missouri Ozark Forest Ecosystem Project Site History, Soils, Landforms, Woody and Herbaceous Vegetation, Down Wood, and Inventory Methods for the Landscape Experiment. Gen. Tech. Re NC-208. US Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN, pp. 19–40.

Guyette, R.P., Muzika, R.M., Dey, D.C., 2002. Dynamics of an Anthropogenic fire regime. Ecosystems 5, 472–486.

Hansen, M.H., Frieswyk, T., Glover, J.F., Kelly, J.F., 1992. The Eastwide Forest Inventory Data Base: Users Manual. Gen. Tech. Re NC-151. US Department of Agriculture, Forest Service, North Central Forest Experiment Station, St. Paul, MN, 48 pp.

Hansen, M.H., Hahn, J.T., 1992. Determining stocking, forest type, and stand-size class from forest inventory data. North J. Appl. For. 9, 82–89.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, J.R., Cummins, K.W., 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15, 133–302.

Harmon, M.E., Krankina, O.N., Sexton, J., 2000. Decomposition vectors: a new approach to estimating woody detritus decomposition dynamics. Can. J. For. Res. 30, 76–84.

He, H.S., Mladenoff, D.J., 1999. Spatially explicit and stochastic simulation of forest landscape fire disturbance and succession. Ecology 80, 81–99.

He, H.S., Mladenoff, D.J., Nimerfro K.K., Gustafson, E.J., 2003. LANDIS, A Spatially Explicit Model of Forest Landscape Disturbance, Management, and Succession. LANDIS 3.7 User's Guide. University of Missouri-Columbia, 63 pp.

He, H.S., Shang, Z.B., Crow, T.R., Gustafson, E.J., Shifley, S.R., 2004. Simulating forest fuel and fire risk dynamics across landscapes—LANDIS fuel module design. Ecol. Modelling.

Johnson, E.A., 1979. Fire recurrence in the subarctic and its implications for vegetation composition. Can. J. Bot. 57, 1374–1379.

Johnson, E.A., Van Wagner, C.E, 1985. The theory and use of two fire history models. Can. J. For. Res. 15, 214–220.

Johnson, E.A., Miyanishi, K., 1995. The need fore consideration of fire behavior and effects in prescribed burning. Restor. Ecol. 3, 271–278.

Keane, R.E., Morgan, P., Running, S.W., 1996. FIRE-BGC—A Mechanistic Ecological Process Model for Simulating Fire Succession on Coniferous Forest Landscapes of the Northern Rocky Mountanis. Research Paper, INT-RP-484. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT, 122 pp.

Miller, M.R., 1981. Ecological land classification terrestrial subsystem, a basic inventory system for planning and management on the Mark Twain National Forest. US Department of Agriculture, Forest Service, Eastern Region, 87 pp.

Mladenoff, D.J., Host, G.E., Boeder, J., Crow, T.R., 1996. LANDIS: a spatial model of forest landscape disturbance, succession, and management. In: Goodchild, M.F., Steyaert, L.T., Parks, B.O. (Eds.), GIS and Environmental Modeling: Progress and Research Issues.. GIS World Books, Fort Collins, Colorado, USA, pp. 175–180.

Mladenoff, D.J., He, H.S., 1999. Design and behavior of LANDIS, an object-oriented model of forest landscape disturbance and succession. In: Mladenoff, D.J., Baker, W.L. (Eds.), Spatial Modeling of Forest Landscape Change: Approaches and Applications. Cambridge University Press, New York, pp. 125–162.

Omi, P.N., Martinson, E.J., 2002. Final report: effect of fuels treatment on wildfire severity. Submitted to US Department of Interior, the Joint Fire Science Program Governing Board. Western Forest Fire Research Center, Colorado State University, 36 pp.

Pollet, J., Omi, P.N., 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. Int. J. Wildland Fire 11, 1–10.

Reinhardt, E.D., Keane, R.E., Brown, J.K., 1997. First Order Fire Effects Model: FOFEM 4.0, User's Guide. Gen. Tech. Re INT-GTR-344. United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 65 pp.

Reinhardt, E.D., Crookston, N.L., 2003. The fire and fuels extension to the forest vegetation simulator. Gen. Tech. Re RMRS-GTR-116. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT, 220 pp.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wild land fuels. Research Paper, INT-115. United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, 39 pp.

Scott, J., 1998. Fuel reduction in residential and scenic forests: a comparison of three treatments in a western Montana ponderosa pine stand. USDA Forest Service Research paper RMRS-5. United States Department of Agriculture, Forest Service, Rocky Mountain Research Station, Missoula, MT, 19 pp.

Shang, Z.B., He, S.H., 2003. LANDIS Fuel Module—for Tracking and Simulating Fuel Loading, Fire Intensity, Fire Risk and Fuel Management. LANDIS Fuel Module User's Guide. University of Missouri-Columbia, 46 pp.

Shang, Z.B., He, H.S., Crow, R.T., Shifley, S.R. Uncertainty analysis of a spatially explicit landscape model applied in the Central Hardwood Region, US. Environmental Modelling and Software, submitted for publication.

Shifley, S.R., Brookshire, B.L., 2000. Missouri Ozark forest ecosystem project: site history, soils, landforms, woody and herbaceous vegetation, down wood, and inventory methods for the landscape experiment. Gen. Tech. Re NC-208. US Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN, 314 pp.

Shifley, S.R., Kabrick, J.M., 2002. Proceedings of the Second Missouri Ozark Forest Ecosystem Project: post-treatment results of the landscape experiment. Gen. Tech. Re NC-227. Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN.

Shifley, S.R., Thompson III, F.R., Larsen, D.R., Mladenoff, D.J., Gustafson, E.J., 2000. Utilizing inventory information to calibrate a landscape simulation model. In: Proceedings of Integrated Tools for Natural Resources Inventories in the 21st Century, 1998. Gen. Tech. Re NC-212. US Department of Agriculture, Forest Service, North Central Research Station, St. Paul, MN, pp. 549–561.

Stephens, S.L., 1998. Evaluation of the effects of silvicultural and fuels treatment on potential fire behavior in Sierra Nevada mixed-conifer forests. For. Ecol. Manag. 105, 21–35.

Trofymow, J.A., Moore, T.R., Titus, B., Prescott, C., Morrison, I., Siltanen, M., Smith, S., Fyles, J., Wein, R., Camire, C., Duschene, L., Kozak, L., Kranabetter, M., Visser, S., 2002. Rates of litter decomposition over 6 years in Canadian forests: influence of litter quality and climate. Can. J. For. Res. 32, 789–804.

Van Wagner, C.E., 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7, 23–34.

Van Wagner, C.E., 1978. Age-class distribution and the forest fire cycle. Can. J. For. Res. 8, 220–227.

Van Wagtendonk, J.W., 1996. Use of a deterministic fire growth model to test fuel treatments. In: Sierra Nevada Ecosystem Project: Final Report to Congress, vol. II. Assessments and Scientific Basis for Management Options. Centers for Water and Wildland Resources, University of California, Davis, pp. 1155–1165.

Westin, S., 1992. Wildlife in Missouri. Missouri Department of Conservation, Jefferson City (MO), p. 161.