# Are Wildfire Mitigation and Restoration of Historic Forest Structure Compatible? A Spatial Modeling Assessment

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In response to catastrophic wildfires, wide-reaching forest management policies have been enacted in recent years, most notably the Healthy Forests Restoration Act of 2003. A key premise underlying these policies is that fire suppression has resulted in denser forests than were present historically in some western forest types. Therefore, although reducing the threat of wildfire is the primary goal, forest managers commonly view fuel treatments as a means to restore historic forest structure in those forest types that are outside of their historic range of variation. This study evaluates where both wildfire mitigation and restoration of historic forest structure are potentially needed in the ponderosa pine–dominated montane forest zone of Boulder County, Colorado. Two spatial models were overlain: a model of potential fireline intensity and a model of historic fire frequency. The overlay was then aggregated by land management classes. Contrary to current assumptions, results of this study indicate that both wildfire mitigation and restoration of historic forest structure are needed in only a small part of the study area, primarily at low elevations. Furthermore, little of this land is located on Forest Service land where most of the current thinning projects are taking place. We question the validity of thinning as a means both to reduce the threat of wildfire and to restore historic forest structure in the absence of site-specific data collection on past and present landscape conditions. *Key Words: Colorado, ecological restoration, GIS, ponderosa pine, wildland urban interface.*

Widespread and severe wildfires in recent years in the western United States have resulted in large financial and environmental costs, and have prompted local fire mitigation plans as well as the federal Healthy Forests Restoration Act (HFRA) of 2003 (National Interagency Fire Center 2002; HFRA 2003; Front Range Fuels Treatment Partnership 2003). Many proposals for forest management, including the HFRA, are based on the premise that the root cause of recent catastrophic fires is the long-standing policy of fire exclusion. It is widely believed that fire exclusion has resulted in fuels buildup: an increase in dense stands, ladder fuels, understory vegetation, and dead and down wood in western forests. For example, the HFRA Web page (2003) states that "an estimated 190 million acres [79.89 million hectares] of Federal forests and rangelands in the United States, an area almost twice the size of California, continue to face an elevated risk of catastrophic fire due to unnatural, densely packed forest conditions."

The term "unnatural" is loosely used to describe vegetation that is outside of its historical range of variation (HRV), defined as the "ecological conditions and spatial/temporal variation in these conditions that are relatively unaffected by people, within a period of time and geographical area appropriate to an expressed goal" (Landres, Morgan, and Swanson 1999). In this context, a forest stand is considered to be outside the HRV if its density and age structure are substantially different from what would be expected in the pre–fire suppression era (ca. before 1920, though this varies by region). According to the HFRA, areas where the current fire regime and forest conditions represent large departures from historic conditions should be given priority for fuel treatment, as these are assumed to have the highest potential for catastrophic wildfire (HFRA 2003). In short, although wildfire mitigation is typically the primary goal of fuel treatment, forest managers also often view thinning as a means to restore historic forest structures (Winiger Ridge Project 1999; Front Range Fuels Treatment Partnership 2006).

The current study addresses the following questions: (1) In what areas of the montane zone (elevation = 1,830–2,740 m) of Boulder County, Colorado, are the goals of wildfire mitigation and restoration of historic forest structure both potentially needed? (2) What percentage of this land is on private versus public lands? To address these questions, two models were developed: a

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model of potential wildfire behavior was used to determine where wildfire mitigation is potentially needed; a model of historic patterns in fire occurrence based on reconstructed fire frequency was used to determine where restoration of historic forest structure is potentially needed. The results were then aggregated by land management classes.

The results of this study have important management implications but should be interpreted with the model limitations in mind. In particular, the methodology has three key limitations: the potential fireline intensity was measured at a coarse spatial resolution, differences in modern and historic fuel quantities were not directly measured, and specific treatments were not evaluated. Despite these limitations, we argue that the results provide a strategic guide to planning and prioritization of vegetation treatments for the dual purposes of fire mitigation and restoration of historic forest structure. Although the results are specific to the study area, the methodology developed for this study could be used in other forest types and geographical regions.

## Background

The assumption that wildfire mitigation and restoration of historic forest structure can be achieved simultaneously comes largely from research in dry ponderosa pine ecosystems in the West. For example, in the Southwestern United States numerous studies support a model of suppression of formerly frequent low-severity fires resulting in fuel accumulations that now permit crown fires (Covington and Moore 1994; Fule, Covington, and Moore 1997; Moore, Covington, and Fule 1999). Many ponderosa pine forests in the Southwest were historically (prior to the nineteenth century) characterized by frequent low-intensity surface fires at intervals of two to twenty years (Swetnam and Baisan 1996). In the Southwest, fire suppression and fuels reduction through grazing were followed by increases in stand densities and enhanced conditions for severe crown fires (Covington and Moore 1994). Studies of ponderosa pine–dominated ecosystems of the Southwest have also established that current stand densities, age distributions, fuel quantities, and configurations are now outside the HRV in many areas (Covington and Moore 1994; Fule, Covington, and Moore 1997; Moore, Covington, and Fule 1999). In short, the forest conditions seen today in much of the ponderosa pine–dominated ecosystems of the Southwest are denser than they were in the pre–fire suppression era and pose a greater risk of catastrophic wildfire. Therefore if properly conducted, forest thinning has the potential to both reduce the hazard of catastrophic wildfire and restore vegetation structure to within the HRV. These results, however, do not necessarily hold in other ponderosa pine–dominated ecosystems or other forest types with longer fire return intervals (Shinneman and Baker 1997; Veblen 2003).

In the U.S. West, the ponderosa pine cover type occurs extensively from the Pacific Northwest to the Southwest under varying conditions of climate, geology, and soils (Peet 2000). Variations in these environmental factors influence site productivity and hence patterns of fuel accumulation at broad biogeographic scales. Even within a single biogeographic region and at local scales, the spatial heterogeneity associated with topography and edaphic factors influences stand structures and hence fuel conditions and fire regime within the ponderosa pine cover type (Peet 2000).

In contrast to the fire regime of ponderosa pine in much of the Southwest, where open stands were maintained by frequent surface fires, ponderosa pine ecosystems in the Colorado Front Range were characterized by a mixed-severity fire regime in which severe crown fires occurred as well as surface fires (Veblen and Lorenz 1986; Mast, Veblen, and Linhart 1998; Brown, Kaufmann, and Shepperd 1999; Kaufmann, Regan, and Brown 2000; Veblen, Kitzberger, and Donnegan 2000; Ehle and Baker 2003; Sherriff 2004). Large, severe fires caused widespread mortality of canopy trees and often resulted in dense postfire stands of ponderosa pine and Douglas fir (Veblen and Lorenz 1986; Mast, Veblen, and Linhart 1998; Brown, Kaufmann, and Shepperd 1999; Kaufmann, Regan, and Brown 2000; Veblen, Kitzberger, and Donnegan 2000; Ehle and Baker 2003; Sherriff 2004). Reconstructions of past forest structures in combination with tree-ring-based fire history records indicate a high degree of spatial heterogeneity in past forest conditions within the ponderosa pine cover type in the Colorado Front Range (Kaufmann, Regan, and Brown 2000; Ehle and Baker 2003; Sherriff 2004). Such reconstructions can inform management decisions about the appropriateness of thinning as a tool for achieving the dual goals of wildfire mitigation and restoration of historic forest structure.

Since severe crown fires and patches of dense stands were common in the presettlement era within the ponderosa pine cover type in the Colorado Front Range, not all of the modern extent of this cover type is outside its HRV. Therefore, a major research and management challenge is to understand where dense stands are an inherent feature of the historic fire regime and where they are an artifact created by fire suppression or other land-use practices (i.e., are outside the HRV).

## Study Area

The study area is the montane zone of Boulder County, Colorado, an area with elevation ranging from 1,830 to 2,740 m and bounded by the forest-grassland ecotone to the east and the subalpine zone to the west. Several local projects in Boulder County seek to restore historic forest structure and mitigate wildfire hazard. Two examples are the Winiger Ridge Project (1999) and the Sugarloaf Fuel Reduction Project (2004). Both projects emphasize coordination between land management agencies and landowners to reduce the potential for wildfire (a primary goal for the Sugarloaf Fuel Reduction Project, secondary for the Winiger Ridge Project) and promote forest health through vegetation treatments to return forests to historic conditions (a primary goal for the Winiger Ridge Project, secondary for the Sugarloaf Fuel Reduction Project). The Front Range Fuels Treatment Partnership (2006) is currently implementing further treatments, particularly in areas where both wildfire mitigation and restoraton of historic forest structure are needed. The montane zone of Boulder County is a challenging area for the implementation of wildfire mitigation and restoration projects because of the spatial heterogeneity of historic fire regimes, the intermingling of private and public lands, and rapid exurban growth. Approximately 42 percent of the study area is Forest Service land, 2 percent is Bureau of Land Management land, 8 percent is managed by the Boulder County and City Open Space and Mountain Parks (henceforth called "Open Space"), 28 percent is privately owned, and the remainder is managed by various other entities (Figure 1).

The historic fire regime in Boulder County varies along environmental gradients and includes both surface and high-severity fires; the former are nonlethal to large trees whereas the latter kill all or many of the large trees in a stand. The lower elevations of the montane zone (1,830–2,350 m) are composed of a mixture of grasses, shrubs, ponderosa pine (*Pinus ponderosa*), and Douglas fir (*Pseudotsuga menziesii*). This zone is characterized by relatively frequent, low-intensity surface fires at intervals of ten to forty years at a scale of approximately 100 ha (Veblen, Kitzberger, and Donnegan 2000; Sherriff 2004; Sherriff and Veblen, submitted a, submitted b). Repeat photography and stand age-structure studies in the lower montane zone along the plains grassland-forest ecotone (below 1,950 m) show that, in the aggregate, stands became denser during the twentieth century, encroaching on grasslands and coalescing with other forest patches (Mast, Veblen, and Hodgson 1997; Mast, Veblen, and Linhart 1998). At a stand scale, however, long intervals occurred between fires at some sites, leading to individual stands that were historically dense. Therefore, not all individual stands in the lower montane zone are outside their HRV even though in the aggregate it is this lower elevation area where tree densities have increased most obviously since fire exclusion (Sherriff and Veblen, submitted b).

Whereas the historic fire regime of the lower montane zone is relatively well understood, the historic fire regime of the mid to upper elevations of the montane zone

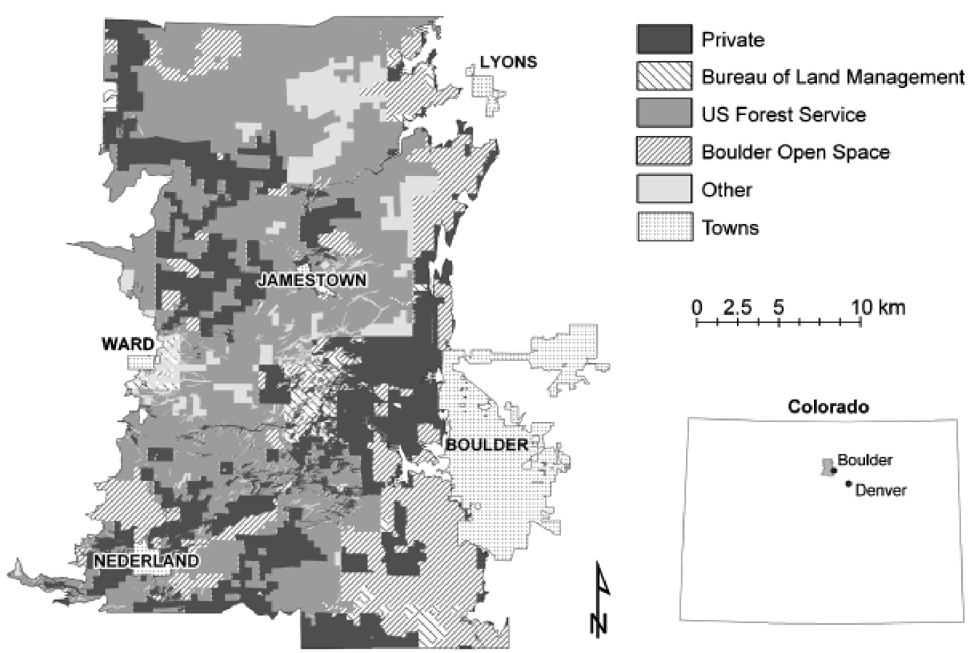


**Figure 1.** Land management classes in the montane zone of Boulder County, Colorado.

(2,100–2,740 m) is more complex. Forests at these elevations are dominated primarily by ponderosa pine and Douglas fir, but other species can also be important, such as aspen (*Populus tremuloides*), lodgepole pine (*Pinus contorta*), and limber pine (*Pinus flexilis*). In stands of approximately 100 ha, historic fire intervals (prior to twentieth-century fire suppression) at these elevations were 30 to 100+ years, longer than the lower montane zone, and included high-severity fires that killed most or all trees in a stand (Veblen and Lorenz 1986; Veblen, Kitzberger, and Donnegan 2000; Sherriff and Veblen, submitted b). For individual sites, however, fire intervals were highly variable, and fire severities varied widely across this landscape, resulting in a complex vegetation mosaic.

The vegetation structure and fire regimes throughout the montane zone have been influenced by climatic variation as well as by land-use practices. For example, during the second half of the nineteenth century fire occurrence increased, and though this increase coincided with increased anthropogenic ignitions associated with Euro-American settlement, it appears to have been driven primarily by climatic conditions more conducive to fire spread (Veblen, Kitzberger, and Donnegan 2000). Today, the legacy of these widespread nineteenth-century fires are even-aged stands that are approximately 100 to 140 years old (Veblen and Lorenz 1986; Sherriff 2004). The second half of the nineteenth century was also a time of widespread grazing, logging, and road construction, which triggered tree establishment that is reflected in tree ages in the modern landscape (Veblen and Lorenz 1986; Sherriff 2004). During the twentieth century, grazing and extractive resource use declined and low-density residential development became the dominant land-use pattern (Riebsame, Gosnell, and Theobald 1996). Since approximately 1920, when adequate resources and equipment were made available to fight fires in the national forest system, fire exclusion dramatically reduced the occurrence and extent of fires in the montane zone.

## Methods

The principal goal of this study is to model where restoration of historic forest structure and wildfire mitigation are potentially needed across the heterogeneous landscape of the montane zone of Boulder County. To do this, models of potential wildfire behavior (which indicate where wildfire mitigation is needed) and historic fire frequency (which indicate where restoration of historic forest structure is needed) were constructed and overlain as described in the following sections. We did not employ the Landfire data products (Landfire 2006) on fuels, fire regions, and departure for historic conditons because they were not available at the time of this study and do not use detailed fire history data for the study area.

### Model of Potential Fireline Intensity

It is assumed that wildfire mitigation is needed in areas of high potential fireline intensity, a measure of energy released per unit length along the flaming front of a fire. To analyze this spatially, a static model of potential fireline intensity was developed using the FlamMap (2003) software package, which maps spatial variations in potential wildfire behavior. FlamMap implements several fire behavior models including a surface fire model (Rothermel 1972), a model of crown fire initiation (Van Wagner 1977), a model of crown fire spread (Rothermel 1991), and a model of dead fuel moisture (Nelson 2000). Using these fire behavior models FlamMap generates raster grids of potential fire behavior such as rate of spread, flame length, fireline intensity (energy released per unit length along the flaming front of a fire), and crown fire activity (Finney 1995–2003). It is important to note that FlamMap models potential fire behavior pixel-by-pixel assuming an ignition source is always available; it does not model fire spread.

This study focuses on a single descriptor of wildfire behavior: Byram's fireline intensity (Byram 1959) due to surface and crown fuels. Fireline intensity was selected over other measures of fire behavior in part because it incorporates rate of spread and heat per unit area.

$$I_b = H_A R/60, \tag{1}$$

where $I_b$ = Byram's fireline intensity (kW/m), $H_A$ = heat per unit area (kJ/m$^2$), and $R$ = rate of spread (m/min).

Fireline intensity has meaningful fire suppression interpretations, so it can be logically classified into low, high, or extreme potential fireline intensity. One threshold is the fireline intensity of 346 kW/m, above which fires should not be attacked by hand and above which control efforts at the head of the fire may not always be effective (Pyne, Andrews, and Laven 1996). In this study, 346 kW/m is the boundary between low and high potential fireline intensity. A second meaningful threshold is 1,730 kW/m, above which extreme wildfire behavior such as spotting, crowning, and torching is common. In this study, 1,730 kW/m is the boundary between high and extreme potential fireline intensity. We recognize that there are situations where fire control efforts may not be effective or where wildfire mitigation may be desired in areas of low potential fireline intensity.

However, all else equal, it is logical that wildfire mitigation is most needed in the areas of highest potential fireline intensity. Fireline intensity is a function of several key variables including topography, weather, and fuels (Bessie and Johnson 1995; Pyne, Andrews, and Laven 1996), the derivations of which are described in the following sections.

***Topography.*** Three characteristics of topography—aspect, slope, and elevation—were generated with available 30-m digital elevation models (DEMs). FlamMap uses this topographic information in several ways. First, aspect and slope together are used to calculate angle of incident solar radiation, which influences fuel moisture conditions (Finney 1995–2003). Second, slope is used in determining rate of spread, as it influences whether flames are tipped toward or away from fuels (Pyne, Andrews, and Laven 1996). Third, elevation is used to refine temperature and humidity to produce more accurate fuel moisture calculations.

***Weather.*** Weather is another important input to FlamMap because it directly influences fireline intensity (Pyne, Andrews, and Laven 1996). We assumed moderate wind conditions: upslope winds of 24 kph (15 mph), which are typical of the study area. We also assumed that fuel moisture was fixed at the level specified by the fuel model and was not further "conditioned" by wind, heat, or relative humidity. Though an assumption of constant conditions over space would be inadequate for modeling historic fires, it is sufficient for measuring potential fire behavior under hypothetical weather conditions.

We do not simulate extreme weather conditions because under such conditions effectively *all* areas are characterized by extreme fireline intensity (>1,730 kW/m) and it becomes difficult to prioritize areas based on potential wildfire behavior. Furthermore, fuel treatments are likely to be ineffective in many places under extreme weather conditions. Climate and weather—not fuels—are the primary driving forces behind the size and severity of fires in areas prone to infrequent but severe wildfires (Romme and Despain 1989; Turner and Romme 1994; Bessie and Johnson 1995; Rollins, Morgan, and Swetnam 2002; Schoennagel, Veblen, and Romme 2004). In such areas, which are extensive in the upper montane zone of Boulder County, mechanical thinning is unlikely to be effective under extreme conditions (Schoennagel, Veblen, and Romme 2004).

***Fuels.*** Another essential input to FlamMap is fuels, which are difficult to measure due to their high spatial heterogeneity (Roberts and Dennison 2003). Fuels are often characterized as the thirteen standard fuel models derived by the National Forest Fire Laboratory (NFFL; Albini 1976). Each fuel model comprises approximately thirty fuel-bed properties, such as live and dead fuel weight per unit area and fuel bed depth, which together determine how fire will propagate through a fuels complex (Anderson 1982). This study uses fuels data hand drawn on aerial photography (taken in the 1990s) and verified in the field for classification accuracy by the Colorado State Forest Service (Boulder County Land Use Fuels Data 2002). According to this fuels data set, a total of 76 percent of the study area is characterized by NFFL fuel models 2 and 9 (Table 1), which are characteristic of open ponderosa pine and closed canopy mixed conifer, respectively (Anderson 1982). In the study area, mixed canopy refers to stands dominated mainly by ponderosa pine and/or Douglas-fir with smaller components of lodgepole pine and limber pine also present. Although fuels are often associated with vegetation type, as they are here, it is important to note that other factors such as stand history, vegetation structure, and abiotic factors also play important roles in determining fuel type and amount (Keane et al. 1998).

***Canopy Cover.*** Another input to FlamMap, canopy cover, influences potential fireline intensity by modifying the shading of surface fuels and influencing wind speed. Canopy cover was estimated with Landsat imagery, dated 5 October 1999. An unsupervised classification was performed with the ISODATA algorithm (ten classes, minimum 1 pixel/class, maximum class standard deviation of 1, minimum class difference of 5, maximum number of merge pairs of 2). The classes were then aggregated to approximate the four canopy cover classes required by FlamMap: 1–20 percent, 21–50 percent, 51–80 percent, and 81–100 percent. For validation, a simple random sample of 87 points was generated. These points were then hand-classified with 1-m black-and-white digital orthophotos taken in April 1999. Quantitative goodness of fit was evaluated using variations on the Kappa statistic, which show sources of classification successes and error (Pontius 2000). The overall classification accuracy was 79 percent, and of this 26 percent was correct due to chance and 50 percent was correct due to the model's ability to predict location. Of the 21 percent of pixels that were misclassified, only one-third were incorrect by more than one category separated from the true class.

***Crown Fuels.*** Crown fuel characteristics include crown base height (CBH), stand height, and crown

**Table 1.** National Forest Fire Laboratory standard fuel models and associated FlamMap variables

| Fuel model | Associated vegetation types[a] | Percentage of study area | CBH (m) | CBD (kg/m3) |
|---|---|---|---|---|
| 1 | Short grass | 12% | 0 | 0 |
| 2 | Open ponderosa pine | 30% | 2 | 0.9 |
| 5 | Brush | 1% | 0.3 | 0.9 |
| 6 | Dormant brush, hardwood slash | <1% | 0.3 | 0.14 |
| 8 | Closed canopy, little ground litter, lodgepole pine | 8% | 2 | 0.22 |
| 9 | Closed canopy mixed conifer | 46% | 1 | 0.2 |
| 10 | Similar to model 9 with heavy ground fuels | 4% | 0.3 | 0.2 |

*Notes:* CBH = crown base height, the distance between the ground and the bottom of the crown. CBD = crown bulk density, the weight per volume of the crown biomass.
[a]From Anderson (1982).

bulk density (CBD). These variables (1) determine whether a fire remains on the surface, torches individual trees (a passive crown fire), or spreads through tree crowns (an active crown fire) and (2) influence fireline intensity (Finney 1995–2003). The most important crown fuel variable is CBH, defined as the distance between the ground and the bottom of the live crown fuels. CBH cannot be detected directly with remotely sensed imagery, short of prohibitively extensive fieldwork, so it must be inferred through expert knowledge. This study associates a CBH value with each fuel model using values developed for wildfire modeling in Boulder County (M. McClean, Redzone Software, November 2003, personal conversation; Table 1).

The two other crown fuel characteristics, stand height and CBD, were also estimated. In this study, stand height was assumed to be a constant of 15 m, which is a realistic average value, though locally it can be inaccurate. This value is often used for wildfire modeling in Boulder County (M. McClean, Redzone Software, November 2003, personal conversation). CBD is the weight per unit volume of crown fuels. In this study, CBD was estimated by associating fuel type to vegetation type/canopy cover and then to CBD according to approximations by Keane et al. (1998) for Rocky Mountain conifer cover types (Table 1).

***Model Uncertainty and Limitations.*** The model of potential fireline intensity has a number of limitations related to FlamMap and its sensitivity to variations in the input data. First, FlamMap itself has not been validated in the study area, though the fire behavior models within FlamMap have been validated more generally in a laboratory setting (Finney 1995–2003), and its sister program Farsite has been validated on conifer-dominated ecosystems of the Rocky Mountain region (Finney and Ryan 1995). Second, though we know that the input layers are imperfect, we do not know to what degree this could influence FlamMap output. To explore this uncertainty, a sensitivity analysis for the study area was conducted by altering the input layers and aspatial parameters one by one to see the effect on FlamMap output. The following changes were evaluated: (1) original topography → flat topography, (2) original canopy cover → closed canopy or open canopy assigned to entire study area, (3) upslope wind → westerly wind, (4) 24 kph wind → 48 kph wind, (5) original fuels → fuel models 2 or 10 assigned to the entire study area, (6) original CBH → half of original CBH, (7) original CBD → add 0.1 kg/m3 to original CBD, and (8) stand height 15 m → stand height 30 m. The purpose of the sensitivity analysis was twofold: to determine which factors contribute the most to potential fireline intensity in the study area and to evaluate whether errors in the input data could potentially have a major influence on the model results. The impact of these parameters can only be compared qualitatively since they are varied by different amounts in the sensitivity analysis.

## Model of Historic Fire Regime

To determine where restoration of historic forest structure is needed, one must know where stand structure could be theoretically outside the HRV as a consequence of fire suppression. A spatially-explicit reconstruction of fire regimes based on a statistical model of fire frequency classes was developed for the montane zone of Boulder County (Sherriff 2004; Sherriff and Veblen, submitted a). We do not attempt to directly locate areas that have experienced fuel accumulation (i.e., denser stands) since fire suppression began. Instead, we use a spatial model to locate areas that historically experienced relatively frequent low-severity fires but now do not, largely due to fire suppression. In the aggregate, it is expected that such areas will have experienced fuel accumulation and could be effectively treated with mechanical thinning. At the stand scale, however, many of these stands may be within the HRV. Therefore, while we present spatially explicit results, we interpret the results only in terms of broad zones.

Historic fire frequencies at fifty-four sample sites ranging in size from 30–200 ha were reconstructed using tree population age data and other tree-ring evidence collected in the field (Sherriff 2004). The sample sites were subjectively located across the entire elevational range of the ponderosa pine–dominated montane zone of Boulder County, predominately on Forest Service and Open Space land, and exclusively in areas that showed no significant signs of logging. Thus, the sites are representative of a larger landscape with minimal human disturbance that in many places across the study area has been lost. At these sites, a total of 779 fire-scarred trees were sampled and crossdated to determine the date of fire scars, number of fires, and number of trees with fire scars (Sherriff and Veblen, submitted b). Tree age ($>$3,200 tree establishment dates) and forest structure data supplemented the fire-scar records (Sherriff and Veblen, submitted a). This information was used to place each sample site into one of three fire frequency categories (Sherriff and Veblen, submitted a) for the era prior to European settlement (1700–1860):

- high fire frequency: $\geq$ 6 fire years or mean fire interval (MFI) of $<$30 years, 50 percent+ trees have multiple fire scars, three or more trees have at least three scars
- variable fire frequency: $\leq$ 5 fire years or MFI of 30–40 years
- low fire frequency: $\leq$ 3 fire years, MFI of $>$40 years or fewer than 4 fire dates, two or fewer trees with more than two scars. (Sherriff 2004)

The historic fire frequency categories represent an index of different fire regimes based on multiple criteria.

Although fireline intensity cannot be directly measured in studies of historic fire regimes, dendrochronological evidence of past fire effects was used to relate classes of historic fire frequency to fire severity (Sherriff 2004; Sherriff and Veblen, submitted b). Areas with shorter fire intervals (higher fire frequency) have all-aged tree age frequency distributions that indicate tree establishment was not associated primarily with fire events. In such areas, the dating of dead trees did not show that any mortality was temporally linked to fire-scar dates. Furthermore, at or near many of the sample sites classified into the high fire frequency class, historical photographs showed that in the late nineteenth century these were open stands that were unlikely to support crown fires (Veblen and Lorenz 1991). In contrast, for the variable fire frequency and low fire frequency classes, dendrochronological evidence indicated that the fire regime included some, if not mostly, high-severity fires (Sherriff 2004; Sherriff and Veblen, submitted b). This evidence included (1) high percentages of trees that established soon after fire-scar dates typically resulting in single or double postfire cohorts, (2) truncated tree recruitment several decades following fire dates resulting in the typical bell-shaped age frequency distribution for shade-intolerant trees following a coarse-scale disturbance event, and (3) presence of dead trees that died at the time of a dated fire. Areas of these high-severity fires, as inferred from patch size, were variable and ranged from a few hectares to much greater than 200 ha (the maximum sample area). Again, historical photographs show that in the landscape zones classified as variable fire frequency or low fire frequency there were extensive areas of dense, closed canopy stands in the nineteenth century (Veblen and Lorenz 1991).

A logistic regression was calibrated with data from forty of the sample sites. The remaining fourteen sample sites were reserved and combined with fifty randomly located qualitative evaluation sites for the validation process (Sherriff 2004; Sherriff and Veblen, submitted a). The logistic regression was used to predict the three historic fire frequency classes across the study area, largely in areas where no fire history data exist. The model used the following independent variables to predict historic fire frequency: elevation (significant for high and variable fire frequency), arcsine of aspect (significant for low fire frequency), distance to ravine (significant for moderate and low fire frequency), and slope (significant for low fire frequency). This statistical model is an improvement over current approaches, which either are based on research in limited portions of the range of montane cover types (e.g., Kaufmann et al. 2001; Kaufmann et al. 2003) or use simplistic assumptions linking vegetation type to fire frequency (e.g., Colorado State Forest Service 2002).

In the original model (Sherriff 2004) the three fire frequency classes were allowed to overlap; in this study a cell can belong to only one class. To eliminate overlap, sites were assigned to the higher fire frequency category in cases of conflict. For example, if a site was originally classified as low fire frequency and variable fire frequency, it would be reclassified as variable fire frequency for the purposes of this study. This step prevents over-prediction of low fire frequency areas, but also causes the classification accuracy to differ somewhat from the original model (Sherriff 2004).

***Model Uncertainty and Limitations.*** The model of historic fire frequency types, though validated, also has inherent uncertainty (Sherriff and Veblen, submitted a).

This model is based on tree-ring methods that have a number of limitations associated with fires that do not leave scars, data loss due to trees that burn or decompose, bias due to targeted sampling, and the difficulty of precisely dating cohort ages (Goldblum and Veblen 1992; Veblen, Kitzberger, and Donnegan 2000; Baker and Ehle 2001). From a statistical standpoint, the model also suffers from a low sample size, which may result in type II errors (failure to reject a false hypothesis) in t-tests of the independent variables. Given the extensive fieldwork required to increase the sample size, this obstacle is difficult to overcome. In fact, the number of field sample sites, fire-scar samples, and tree cores collected in the development of this model (Sherriff 2004; Sherriff and Veblen, submitted a) is large in comparison with other published fire history studies (see Baker and Ehle 2001).

It is important to note that long-term climate patterns prevalent during the reference period heavily influence density and age structure of vegetation at a regional scale (Baker 2003; Veblen 2003). Therefore, when we evaluate whether stands are "unnatural" we must acknowledge possible changes in climatic patterns in addition to anthropogenic factors such as fire suppression.

### Model Overlay

By overlaying the results of the potential fireline intensity and historic fire frequency class models, the needed outcomes can be determined (Table 2). If the current potential fireline intensity is low (<376 kW/m), it is assumed that wildfires can be fought by hand and effectively contained and therefore wildfire mitigation is not needed. If potential fireline intensity is high or extreme ($\geq$ 376 kW/m), wildfire mitigation is needed because these fires cannot be fought by hand.

Within areas classified as high or extreme fireline intensity, stands whose historic fire regime is characterized by high fire frequency (and low severity) may have a forest structure outside the HRV due to fuels buildup following twentieth-century fire exclusion. In this case,

**Table 2.** Potentially needed management outcomes in the montane zone of Boulder County, Colorado, based on potential fireline intensity and historic fire frequency

| Potential fireline intensity | Historic fire frequency | | |
|---|---|---|---|
| | Low | Variable | High |
| Extreme/high | Mitigation only | Ambiguous | Both outcomes |
| Low | Neither outcome | | |

both wildfire mitigation and restoration of historic forest structure are potentially needed. Conversely, stands whose historic fire regime consisted of high-severity fires at relatively long intervals (>40–100 years) are dense today not due to suppression of surface fires but because they are postfire cohorts. In these stands, wildfire mitigation may be needed but not restoration of historic forest structure because the current stand density is likely within the range of what we would expect historically at a stand scale.

If potential fireline intensity is high or extreme and historic fire frequency is variable, the result is ambiguous. Though low and high fire frequency areas have a clear association with high and low stand densities, respectively, the relative importance of high-severity fires versus nonlethal surface fires is less clear in areas of variable fire frequency. Consequently, areas of variable fire frequency may or may not be able to be restored with mechanical thinning because tree densities were probably more spatially variable under that fire regime (Table 2). To address this uncertainty, the results of the model overlays are presented under the following scenarios: (1) that areas of variable historic fire frequency are outside the HRV and (2) that such areas are within the HRV. The overlay results were then spatially aggregated by land management classes (Figure 1).

## Results

### Potential Fireline Intensity

The prediction of fireline intensity based on the FlamMap model indicates that under the assumed weather conditions, 45 percent of the study area is characterized by low potential fireline intensity (< 376 kW/m), 25 percent by high fireline intensity (376–1,730 kW/m), and 30 percent by extreme fireline intensity (>1,730 kW/m); see Figure 2. As expected, the high and extreme hazard areas are located on steep, south-facing slopes. High and extreme potential fireline intensity land is located at all elevations, but concentrated at middle and lower elevations. This is probably because at these elevations terrain in this area is steeper and moisture levels are generally lower. It is important to note that under extreme weather conditions (i.e., extreme low humidity, high winds), fireline intensity also would be high in the upper elevations of the montane zone (i.e., in areas of the lodgepole pine cover type). Under weather conditions assumed in the present study, the most prevalent fuel models, including primarily open canopy ponderosa pine and closed canopy mixed conifer

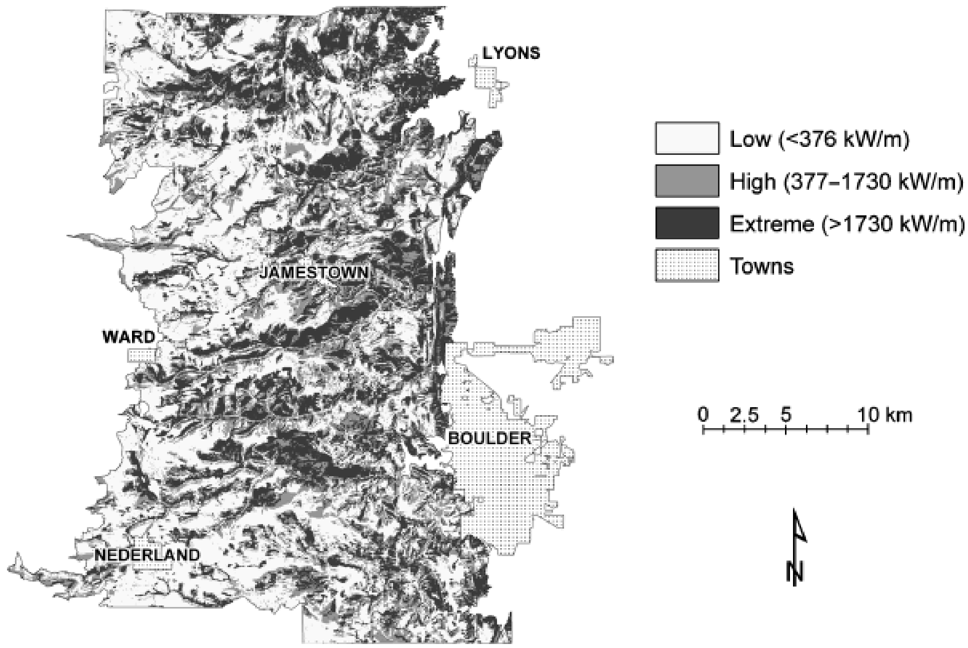


**Figure 2.** Potential fireline intensity in the montane zone of Boulder County under 24-kph upslope winds, classified from FlamMap output.

types, all appear to be spatially coincident with land of high and extreme potential fireline intensity.

The sensitivity analysis revealed that the percentage of the landscape classified as high or extreme fireline intensity is sensitive to changes in many of the parameters (Table 3). For one, it was found that potential fireline intensity is sensitive to changes in topography. If the terrain is "flattened," the portion characterized by potential high or extreme fireline intensity decreases by 22 percent. A flat slope reduces the spread of fire by tilting the source of the fire away from the fuel source so that fuels upslope are not preheated (Pyne, Andrews, and Laven 1996). Second, potential fireline intensity is sensitive to changes in canopy cover. Compared with the original conditions, a closed canopy would result in a 10 percent reduction in the area of high or extreme fireline intensity. In contrast, an open canopy has the opposite effect, increasing the area exposed to high or extreme fireline intensity by 36 percent. Though it may appear counterintuitive, when all else is equal open canopies lead to reduced fuel moisture and increased midflame windspeed, which increase potential fireline intensity. Third, wind has a pronounced effect on fireline intensity. West winds, for example, counteract the effects of slope

**Table 3.** Results of sensitivity analysis for FlamMap parameters

| Reference state | New state | Change in percentage of landscape classified as high or extreme potential fireline intensity |
|---|---|---|
| Original topography | Flat topography | – 22% |
| Original canopy cover | Closed canopy | – 10% |
| Original canopy cover | Open canopy | +36% |
| Upslope wind | Westerly wind | – 11% |
| 24 kph wind | 48 kph wind | +30% |
| Original fuels | All open ponderosa pine (fuel model 2) | +37% |
| Original fuels | All closed canopy mixed conifer (fuel model 10) | +30% |
| Original CBH | Half of original height | +13% |
| Original CBD | Add 0.1 kg/m$^3$ to original | +3% |
| Stand height 15 m | Stand height 30 m | +1% |

*Notes:* The sensitivity analysis helps to determine which factors contribute the most to fireline intensity in the study area and to evaluate whether errors in the input data could potentially have a major influence in the model results. CBH = crown base height, the distance between the ground and the bottom of the crown. CBD = crown bulk density, the weight per volume of the crown biomass.

in this study area and reduce the amount of land classified as high or extreme potential fireline intensity by 11 percent compared to upslope winds. Wind speed is perhaps the most important factor in determining wildfire behavior; during a wind event with gusts of 48 kph (30 mph) 30 percent more of the study area would be subject to high or extreme fireline intensity compared to 24 kph (15 mph) winds. Fourth, the fuel composition clearly has a large influence on potential fireline intensity. For example, if the study area was exclusively composed of fuel models 2 and 10, a greater percentage of the study area would be classified as high or extreme fireline intensity (37 percent and 30 percent respectively). Finally, crown fuels had a modest influence on the percentage of the landscape classified as high or extreme fireline intensity. Reducing the CBH to half of the original assumed height increased the percentage of the study area classified as high or extreme by 13 percent. Increasing CBD by 0.1 kg/m3 and doubling the stand height to 30 m had less of an effect, increasing the percentage classified as high or extreme by 3 percent and 1 percent, respectively. It is important to note that these results do not reflect any increases in fireline intensity within cells that already qualified as high or extreme. The sensitivity analysis revealed that potential fireline intensity is sensitive to shifts in all the parameters and that local errors in the source data could potentially affect the local output of FlamMap. Therefore, managers should interpret the results with caution. When the results are aggregated, however, we believe that the source data are sufficiently accurate for this application.

## Historic Fire Frequency

The model of historic fire frequency was calibrated with logistic regression to predict the probability of a given cell belonging to each fire frequency class. The regression coefficients indicate that high fire frequency was generally confined to elevations below 2,100 m. Elevation may be a proxy for other factors such as proximity to grasslands, given that the lowest elevations are adjacent to the plains-grassland ecotone, where the highest fire frequency sites occur (Sherriff and Veblen, submitted a). In contrast, the other two fire types occur across a broad range of elevation in relation to other environmental conditions. Low-frequency fires generally occur on steep, north-facing slopes farther from ravines. At mid to high elevation in the study area, variable-frequency fires often occur near ravines, which may act as a firebreak. The model classified 22 percent of the study area as high frequency, 25 percent as variable frequency, and 53 percent as low frequency (Figure 3). Overall, areas of historically lower fire frequency are associated with abundant postfire tree establishment predating fire exclusion, and areas of formerly frequent low-severity fires are associated with abundant tree establishment during the fire exclusion period (Sherriff 2004; Sherriff and Veblen, submitted b).

The model was validated on a random sample of fourteen of the original fifty-four fire history sites plus fifty additional qualitative evaluation sites for a total of sixty-four validation points (Sherriff and Veblen, submitted a). The qualitative evaluation sites were ran-

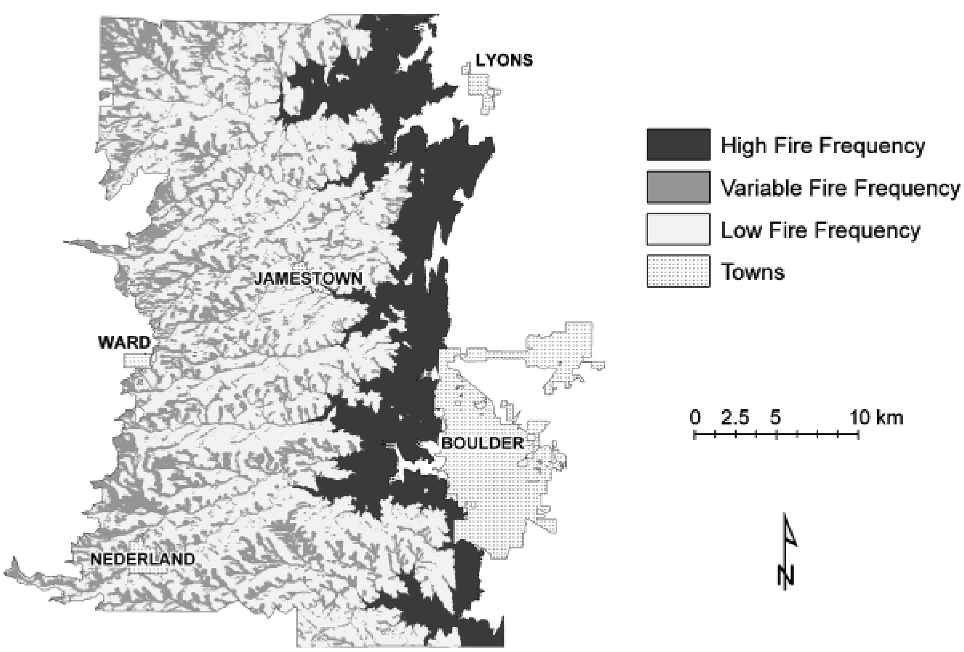


**Figure 3.** Historic fire frequency classes for the montane zone of Boulder County reconstructed from fire scar records for the years 1700–1860. High fire frequency criteria: 6+ fire years or mean fire interval (MFI) of < 30 years, 50 percent+ trees have multiple fire scars, 3+ trees have at least three scars. Variable fire frequency criteria: 4 or fewer fire years or MFI of 30–40 years. Low fire frequency criteria: 3 or fewer fire years, MFI of > 40 years or fewer than four fire dates, two or fewer trees with more than two scars.

domly located within the montane zone in Forest Service and Open Space land. Unlike the selection of field sites, random sampling was possible for qualitative evaluation sites because of their smaller size (100 $\times$ 300 m for evaluation sites vs. 30–200 ha for field sites). The evaluation site was moved to an adjacent site if evidence of logging was present. For each qualitative validation point, the fire frequency category was determined by the number of fire scarred trees, the number of scars per tree, and general age structure (Sherriff and Veblen, submitted a).

The validation procedure using all sixty-four validation points showed that the predictions of high fire frequency were 90 percent accurate, predictions of variable fire frequency were 71 percent accurate, and predictions of low fire frequency were 78 percent accurate, for an overall accuracy of 77 percent for the model as a whole. Under the first scenario, that areas of variable historic fire frequency are outside of the HRV, the high and variable fire frequency categories are combined, yielding an accuracy of 80 percent for the high-variable fire frequency category and 80 percent for the model as a whole. Under the second scenario, that areas of variable historic fire frequency are within the HRV, the variable and low fire frequency categories are combined, yielding an accuracy of 93 percent for the low-variable category and 91 percent for the model as a whole. This shows that variable and high fire frequency historic fire regimes are easily confused and the overall accuracy of the model increases when they are combined.

**Overlay of Potential Fireline Intensity and Historic Fire Frequency**

By overlaying the results of the model of potential fireline intensity and of reconstructed historic fire types, it was possible to infer where both wildfire mitigation and restoration of historic forest structure are potentially needed (Table 2). Under the first scenario (that areas of variable historic fire frequency are outside of the HRV) the overlay analysis shows that both outcomes are needed on a maximum of 27 percent of the total land area, in particular at low elevations, near ravines and on south-facing slopes (Figure 4). On an additional 27 percent of land area, wildfire mitigation is needed, but not restoration of historic forest structure. Areas suitable only for wildfire mitigation are characterized by high or extreme potential fireline intensity and a historic fire regime of infrequent fires. Such areas are located primarily at mid to high elevations on steep north-facing slopes. The remainder of the land is classified as "neither outcome needed." In these areas the potential fires have a low enough fireline intensity (< 346 kW/m) that they could be fought with hand tools and are historically dense. Under the assumed weather conditions, they are located at mid and upper elevations within the study area.

Under the second scenario (that areas of variable historic fire frequency are within the HRV) the model shows that both outcomes are needed on a maximum of 15 percent of the total land area, exclusively at the lowest elevations on south facing slopes. Only wildfire

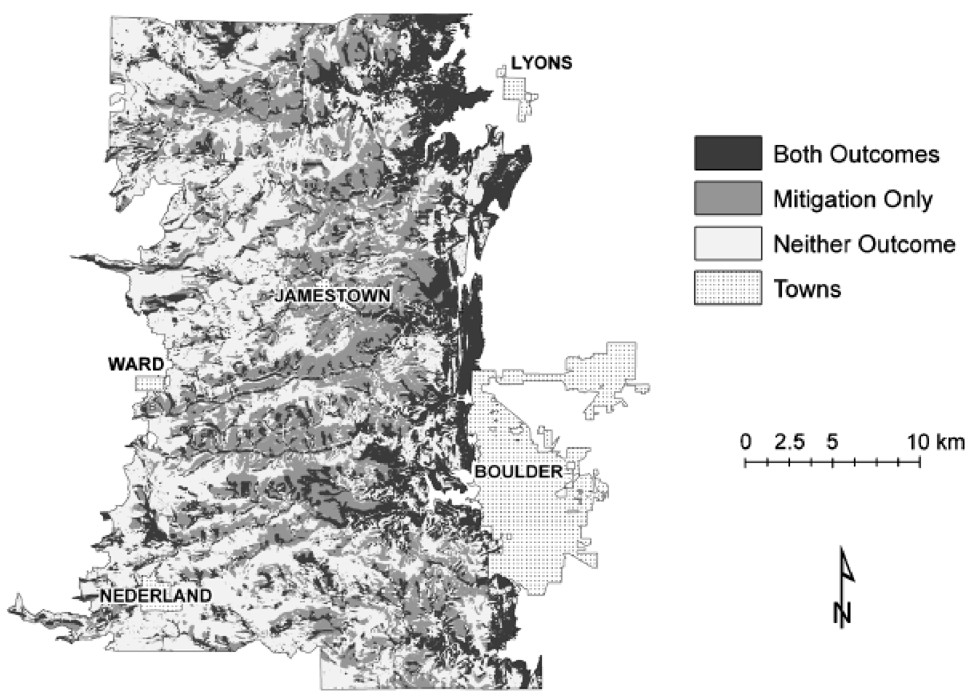


**Figure 4.** Needed forest management outcomes in the montane zone of Boulder County, Colorado, under the scenario that those areas characterized by variable-severity historic fire regimes are outside of the historic range of variation. "Both outcomes" indicates that wildfire mitigation and restoration of historic forest structure are potentially needed. "Mitigation only" indicates that wildfire mitigation is potentially needed, but not restoration of historic forest structure. "Neither outcome" indicates that neither wildfire mitigation nor ecological restoration is needed under the assumed weather conditions (i.e., 24-kph upslope winds).

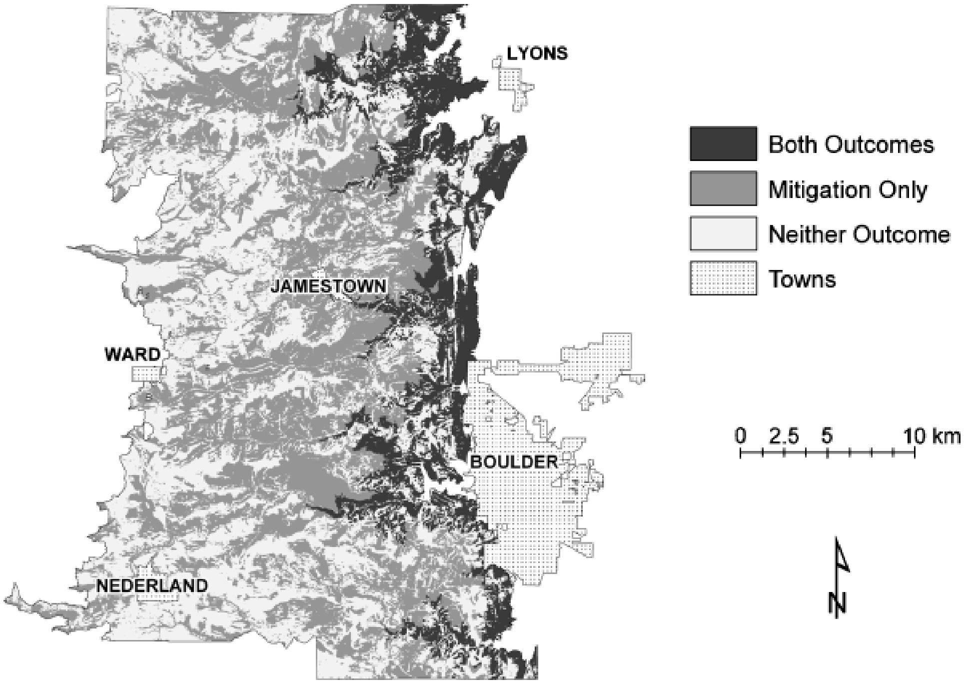


**Figure 5.** Needed forest management outcomes in the montane zone of Boulder County, Colorado, under the scenario that those areas characterized by variable-severity historic fire regimes are within the historic range of variation. "Both outcomes" indicates that wildfire mitigation and restoration of historic forest structure are potentially needed. "Mitigation only" indicates that wildfire mitigation is potentially needed, but not restoration of historic forest structure. "Neither outcome" indicates that neither wildfire mitigation nor ecological restoration is needed under the assumed weather conditions (i.e., 24-kph upslope winds).

mitigation is needed in 39 percent of the study area (Figure 5). The area defined as "neither outcome needed" is the same as before.

## Aggregation of Map Overlay by Land Management Classes

The results of the model overlays were then aggregated by land management classes (Figure 6). Under the first scenario, Open Space had the greatest percentage of land where both outcomes are needed (41 percent) and the lowest percentage where only wildfire mitigation is needed (18 percent). Private land followed a similar pattern. In contrast, Bureau of Land Management and Forest Service lands had a higher percentage of land where only wildfire mitigation is needed (34 percent and 37 percent, respectively) than where both outcomes are needed (28 percent and 18 percent, respectively).

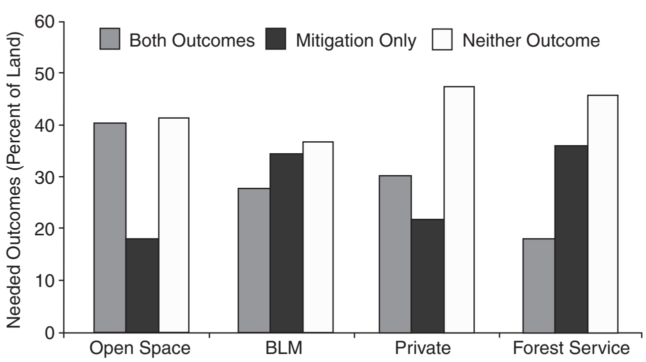


**Figure 6.** Percentage of land management classes in the montane zone of Boulder County, Colorado, where forest management outcomes are needed under the scenario that those areas characterized by variable-severity historic fire regimes are outside of the historic range of variation. "Both outcomes" indicates that wildfire mitigation and restoration of historic forest structure are potentially needed. "Mitigation only" indicates that wildfire mitigation is potentially needed, but not restoration of historic forest structure. "Neither outcome" indicates that neither wildfire mitigation nor ecological restoration is needed under the assumed weather conditions (i.e., 24-kph upslope winds).

A similar pattern of results holds under the second scenario. The amount of land where both outcomes are needed decreases in each land-use category, with a commensurate increase in the amount of land where only wildfire mitigation is needed (Figure 7). This time, both outcomes are needed on only 6 percent of Forest Service land, compared with 31 percent of Open Space and 16 percent of private land.

# Discussion

## Key Findings

The results of two models—a model of potential fireline intensity and a model of historic fire frequency—were overlain and classified into areas where both wildfire mitigation and restoration of historic forest structure are needed, where only wildfire mitigation is needed, or where neither outcome is needed. An evaluation of this classification has led to several key findings. Under the scenario that areas of variable historic fire frequency are outside the HRV, this study shows that

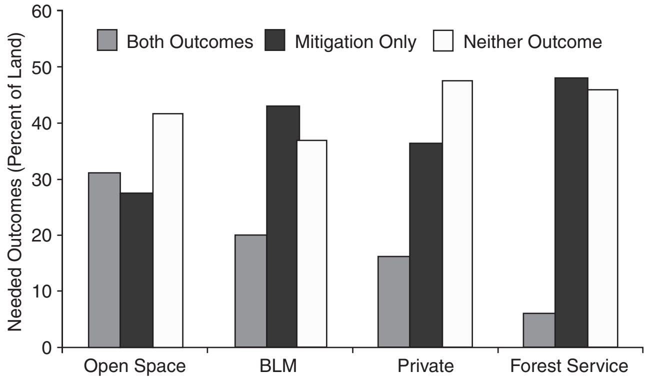


**Figure 7.** Percentage of land management classes in the montane zone of Boulder County, Colorado, where forest management outcomes are needed under the scenario that those areas characterized by variable-severity historic fire regimes are within the historic range of variation. "Both outcomes" indicates that wildfire mitigation and restoration of historic forest structure are potentially needed. "Mitigation only" indicates that wildfire mitigation is potentially needed, but not restoration of historic forest structure. "Neither outcome" indicates that neither wildfire mitigation nor ecological restoration is needed under the assumed weather conditions (i.e., 24-kph upslope winds).

both outcomes are neeed in 27 percent of the study area, primarily on private land and Open Space and on only a small amount on Forest Service land. This is a key result because the Forest Service receives the most money for mechanical thinning compared to other federal and nonfederal agencies, and yet has relatively little land in absolute and relative terms where both outcomes are needed. The areas where both outcomes are needed are located at low elevations, near ravines and on south-facing slopes. On an additional 27 percent of land area, only wildfire mitigation is needed. The remainder of land is classified as "neither outcome needed" under the assumed weather conditions (i.e., 24 kph wind). Under the scenario that areas of variable historic fire frequency are within the HRV, the amount of land where both outcomes are needed drops to 15 percent, and the amount of land where only mitigation is appropriate increases to 39 percent. In both cases, the amount of land where both outcomes are needed is relatively small and at lower elevations than areas historically characterized by large high severity fires. Open Space has the greatest percentage of land where both outcomes are needed; Forest Service land has the lowest percentage.

### Model Uncertainty and Limitations

At the start of this article, we presented three key limitations of the methodology. To be used in a management context, the findings of this study must be evaluated in relation to these limitations. We stress that results should be interpreted at an aggregate scale. Maps should be read as descriptors of general spatial trends and not as locators of stand targets for management prescriptions. Here are the limitations once again, and how they relate to the model results:

***1. Potential fireline intensity was measured at a spatially coarse resolution:*** As the sensitivity analysis for FlamMap inputs demonstrated, the modeled potential fireline intensity can be affected by errors in the source data. We believe that the spatial resolution of our source data (fuel type, canopy fuels, etc.) is too coarse to give us accurate results at the scale of small stands (e.g., a few ha), but yields acceptable results at the landscape and regional scales. Short of starting fires, however, we cannot validate this model further.

***2. Differences in modern and historic fuel quantities were not directly measured:*** The model should not be used to target individual stands for treatments, but should be seen as a general guide in the planning process. This study shows general locations where environmental factors lead to the prediction that current vegetation conditions are likely to be outside the HRV. However, site-specific data and observations would be required to determine the degree to which individual stands have actually experienced fuel accumulation outside the HRV.

***3. Specific treatments were not evaluated:*** The actual on-the-ground thinning specification may vary widely and may incorporate management goals not considered in the current study (e.g., effects on threatened and endangered species). Thus, it is impossible to know the actual effectiveness of the thinning treatment in advance. Several factors can influence the effect of thinning treatments on potential wildfire behavior, including to what degree the canopy cover is opened up and the CBD is reduced, whether ladder fuels are removed to raise CBH, whether the thinning treatment is maintained or if trees are allowed to regenerate, and whether prescribed fire is used to reduce posttreatment surface fuels. The actual outcomes of thinning treatments also depend on factors related to firefighting, which are beyond the scope of this study. Therefore, in the context of the limitations noted above, the results of the present study are most appropriate for strategic planning in the arena of fuels management and restoration of historic forest structure using thinning as the primary management tool.

## Management Implications

This study helps to evaluate the assumption that forest thinning can both reduce wildfire hazard and restore forest structure to conditions believed to have prevailed prior to the effects of twentieth-century fire suppression. A premise of national policies such as HFRA is that high stand densities are symptomatic of unhealthy forests and have resulted from the suppression of formerly frequent surface fires (HFRA 2003). Though the primary goal of HFRA is wildfire mitigation, land managers often view forest thinning also as a means to restore historic forest structure. Critics have questioned the applicability of this and other premises to the wide range of forest ecosystem types in the western United States (Veblen 2003; Schoennagel, Veblen, and Romme 2004). Our analysis provides transparent, quantitative estimates of where fire mitigation and restoration are potentially needed, and thus provides a pragmatic basis for considering the outcomes of thinning across a complex landscape. Indeed, in our study area, both outcomes are needed in only 15–27 percent of the study area. Furthermore, although Forest Service land accounts for 42 percent of Boulder County, most of the land on which both outcomes are needed is not on Forest Service land. This implies that to attain the dual outcomes of wildfire mitigation and restoration of historic forest structure, federal funding needs to be directed towards nonfederal lands. The current study was based on an unusually large dataset on fire history and tree ages that permitted spatially explicit reconstructions of historic fire regimes and forest conditions across a complex landscape (Sherriff 2004; Sherriff and Veblen, submitted a). We stress that data on fire history and past stand structures necessary for guiding and prioritizing vegetation treatment plans in a spatially heterogeneous landscape generally surpass the current availability of information for the application of the Fire Regime Condition Classification protocols on federal lands (Schmidt et al. 2002; Shlisky and Hann 2004).

Fire mitigation and restoration models derived from other ponderosa pine ecosystems (e.g., Covington and Moore 1994; Kaufmann et al. 2001; Kaufmann et al. 2003) should not be extrapolated to the montane zone of Boulder County in lieu of conducting intensive, site-specific data collection in the potential management area. Analogously, the specific results reported here should not be uncritically applied to other areas of ponderosa pine ecosystems. Rather, the approach and methodology of the current study can inform management discussion and guide data collection procedures in other ecosystems.

Although forest managers and policymakers may recognize that wildfire mitigation and restoration of historic forest structure often cannot be achieved simultaneously, the conflicts between these outcomes are sometimes not clearly articulated for areas of historically mixed-severity fire regimes. In places where restoration of historic forest structure is the primary goal and the historic fire regime included high-severity fires, forest managers must actively communicate the political, financial, and managerial difficulties of maintaining forests within a potentially hazardous state. In places where wildfire mitigation is the primary goal, managers should clearly articulate that the natural structure of the forest is not the desired structure to protect communities. The approach developed in the current study can aid managers in the articulation of these options in a spatially explicit manner.

In short, this study provides guidance for mechanical thinning in the montane zone of Boulder County and also raises issues important to forest management practices across the Western United States. It indicates that the complexity of wildfire, ecosystems, and land management precludes simple generalizations to guide policy. A thinning and fuels reduction plan for the objectives of fire mitigation and restoration of historic forest structure should not be applied in the absence of site-specific data collection on past and present landscape conditions. Spatial models of potential wildfire behavior and historic fire regimes, such as those in this study, can aid decision making in complex environments where such data are available.

## Acknowledgments

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