Spatial Model of Forest Management Strategies and Outcomes in the Wildland–Urban Interface

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Abstract: In fire-prone areas of the western United States, mechanical thinning is often seen as a way to achieve two outcomes: Wildfire mitigation and restoration of historical forest structure. In this study, a spatial modeling approach is used to (1) find which forests are likely to be thinned under different criteria; (2) for these forests, evaluate whether wildfire mitigation and restoration of historical forest structure are potentially needed; and (3) determine whether these results change under alternative assumptions related to weather and fire history. Effectively, the spatial models in this study allow us to "test" thinning criteria to see if they lead to the selection of land where the stated management goals are needed in the study area of the montane zone of Boulder County, Colo. The spatial modeling results indicate that common management practices—such as thinning dense stands on Forest Service land near communities—may be inappropriate if the desired outcome is both wildfire mitigation and restoration of historical forest structure. Instead, modeling results suggest that lower elevation forests in the study area should receive priority. Though specific to the montane zone of Boulder County, the results of this study support wider criticisms of national fire policy.

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Introduction

In response to recent catastrophic wildfires, several wide-reaching forest management policies have been enacted in recent years, including the National Fire Plan of 2000 and the Healthy Forest Restoration Act of 2003 (HFRA). These policies primarily aim to reduce the intensity of wildfire (wildfire mitigation) around values at risk such as structures, watersheds, or endangered species. A secondary goal, either expressed or implied, is to restore "forest health." Illustrating this, the National Fire Plan states that "hazardous fuels reduction treatments are designed to reduce the risks of catastrophic wildland fire to people, communities, and natural resources, simultaneously restoring forest and rangeland ecosystems to closely match their historical structure, function, diversity, and dynamics." (USDA Forest Service 2000). Similarly, the HFRA's primary purpose is to "reduce the risks of damage to communities, municipal water supplies, and some at-risk Federal lands from catastrophic wildfires" and "to protect, restore and enhance degraded forest ecosystem types" (HFRA 2003). Although HFRA does not explicitly state restoration of historical forest conditions as a goal, HFRA prioritizes areas characterized by high departure from the historical range of vegetation characteristics for treatment (HFRA 2003).

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At the local level, forest management projects often explicitly state restoration of historical forest structure as an important forest management goal. For example, the Front Range Fuel Treatment Partnership (FRFTP) in Colorado, which is comprised by federal and state land management agencies, aims to "enhance community sustainability and restore fire-adapted ecosystems through identification, prioritization, and rapid implementation of hazardous fuels treatment projects in the Front Range of Colorado" (FRFTP 2003). Although in many cases wildfire mitigation takes priority, FRFTP prioritizes "areas of overlap," where both wildfire mitigation and restoration of historical forest structure are needed (FRFTP 2006a).

The language of forest management documents, at both the national and local levels, promote the assumption that wildfire mitigation and restoration of historical forest structure are compatible outcomes in some ecosystems. The implication is that certain forest types have become denser and more hazardous due to the accumulation of small trees and surface fuels that would have burned if forest fires had not been suppressed since the early 1900s (Schoennagel et al. 2004). The assumption continues: Any reduction of fuels would make the forest less hazardous as well as move it toward a more "natural" state. Research on restoration and conservation of fire-prone landscapes suggests that many forested landscapes have not become denser since the advent of fire suppression, and thus the assumption may be invalid for many ecosystems (Noss et al. 2006; Kaufmann et al. 2006). Thus, to evaluate the assumption that wildfire mitigation and restoration of historical forest structure are compatible goals, researchers require spatially explicit data on both potential wildfire hazard and historic fire regimes.

Many studies have used spatial models to evaluate potential wildfire hazard (Cardille et al. 2001; Cova et al. 2004; Roloff et al. 2005). A major limitation of existing models is that wildfire hazard is spatially heterogeneous and dependent upon diverse factors, such as fuels, weather, and topography. Thus, wildfire hazard is difficult to map with precision and confidence over large areas (Stewart et al. 2007), and is always particularly dependent upon weather assumptions. Other studies have spatially modeled the departure from historic forest conditions (Schmidt et al. 2002; Hessburg et al. 2005; Sherriff and Veblen 2007; Theobald and Romme 2007). Like wildfire hazard, departure from historic forest conditions is spatially heterogeneous and difficult to map with confidence over all forest types. Where historic fire regimes are not well understood, intensive fire history (e.g., from tree ring studies) is required (Veblen 2003). Perhaps due to these difficulties, few studies have integrated such models to evaluate where wildfire mitigation and restoration of historic forest structure are compatible outcomes (see Platt et al. 2006 for an exception). Further, few if any peer-reviewed studies have used spatial models to evaluate whether land managers are actually likely to treat areas where the outcomes of wildfire mitigation or restoration of historic forest structure are needed. This is likely to change as additional studies follow the release of LANDFIRE data products which include national information on wildfire hazard as well as departure from historic forest conditions (LANDFIRE 2006).

The overall goal of this study is to evaluate whether in fact wildfire mitigation and restoration of historic forest structure are compatible outcomes in the areas likely to be prioritized for mechanical thinning in the study area of the montane zone of Boulder County, Colo. Toward this overall goal, the following questions are addressed:

1. Which areas are forest managers likely to prioritize for mechanical thinning? To answer this research question, a spatial model was constructed to identify the probable location of mechanical thinning based on criteria used by forest managers in the study area.
2. For these areas, are wildfire mitigation and restoration of historical forest structure needed? To answer this research question, the model of thinning location was overlaid on a second spatial model that shows where wildfire mitigation and restoration of historical forest structure are potentially needed. Note that the model only determines whether wildfire mitigation or restoration of historical forest conditions are *potentially* needed. Whether these outcomes are *actually* needed for any particular stand can only be determined with site-level data not available for the entire study area. Further, even if an outcome is needed, managers may decide that the monetary and ecological costs of an outcome are too high. These political and managerial considerations are not considered here.
3. Are the results robust to alternative assumptions related to weather and fire history? To answer this research question, a sensitivity analysis was performed based on assumptions related to weather and historical forest structure.

Study Area

The study area for this project is the montane zone of Boulder County, Colo., which is located 40 mi northwest of Denver. The study area is 76,400 ha (188,800 acres) in size and contains 2,576 km of roads, both paved and unimproved. Approximately 42% of the study area is Forest Service land, 2% is Bureau of Land Management land, 8% is Managed by the Boulder County and City Open Space and Mountain Parks, 28% is privately owned, and the remainder is managed by other groups. The private land in the study area contains extensive low-density residential development (approximately 6,000 homes) and several small towns (Nederland, Ward, and Jamestown).

The montane zone of Boulder, Colo. is located between, 1,830 and 2,740 m in elevation, and is characterized by rough topography. According to the fuel data collected and field verified by the Colorado State Forest Service (Boulder County Land Use Fuels Data 2002), the study area has 2,084 vegetation patches with an average patch size of 37 ha. A total of 76% of the study area comprises National Forest Fire Laboratory (NFFL) fuel models 2 and 9, which are characteristic of open ponderosa pine (*Pinus ponderosa*) and closed canopy mixed conifer (Anderson 1982).

The historical fire regimes of ponderosa pine and mixed conifer ecosystems comprise both low-severity surface and high-severity crown fires, which vary along environmental gradients. The lower elevations of the montane zone (1,830–2,350 m) are characterized by a mixture of grasses, shrubs, ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*). Historically, this lower part of the montane zone experienced predominantly low-severity surface fires at intervals of 10 to 40 years at a scale of ~100 hectares but also some intense stand-replacing fires above ~2,100 m (Veblen et al. 2000; Sherriff 2004). Stands in this zone have become denser during the 20th century, and have encroached on grasslands and coalesced with other forest patches (Mast et al. 1997, 1999). However, long intervals (>40 years) occurred between fires at some sites leading to individual stands that were historically dense during periods between fire events. The historical fire regime of the upper montane zone (2,100–2,740 m) is more complex. Ponderosa pine is dominant in this zone and typically occurs in mixtures with Douglas-fir, aspen (*Populus tremuloides*), and lodgepole pine (*Pinus contorta*). In this upper montane zone in ponderosa pine-dominated stands of ~100 ha, the historical fire intervals (i.e. prior to 20th-century fire suppression) were 30 to 100+ years, and included high-severity fires that killed most trees (Veblen and Lorenz 1986; Veblen et al. 2000; Sherriff 2004). However, fire intervals and severities varied widely across this landscape resulting in a complex vegetation mosaic.

Forest Management and Key Assumptions

Due to the spatial heterogeneity of historical forest structure and fire regimes, the montane zone of Boulder County, Colo. is a difficult area for the implementation of wildfire mitigation and restoration projects. The Winiger Ridge Project (Winiger Ridge Project 1999), the Sugarloaf Fuel Reduction Project (Sugarloaf Fuel Reduction Project 2004), and the City of Boulder Open Space and Mountain Parks (City of Boulder Open Space & Mountain Parks 1999) have all engaged in mechanical thinning for wildfire mitigation or restoration of historical forest structure. Currently, the Front Range Fuels Treatment Partnership is planning further treatments in the area (Front Range Fuels Treatment Partnership 2006a). Forest managers for these projects use a variety of criteria to identify treatment areas. These often include one or more of the following priorities: Low elevation areas, areas adjacent to communities, areas adjacent to roads, areas of steep slope, areas with high canopy cover, areas of high potential wildfire hazard, and areas within Forest Service boundaries.

It is sometimes unclear whether one or both forest management outcomes (i.e., wildfire mitigation and restoration of historic forest structure) are needed in the areas selected for treatment by forest managers. Whether these outcomes are needed depends in part on assumptions related to two factors: Weather and historic fire regimes. First, assumptions about weather affect estimates of potential wildfire behavior; over time factors such as wind, rela-

Table 1. Operationalized Criteria for Selecting Land for Mechanical Thinning Based on Common Management Practices in the Study Area

Variable name	Description	Rationale
Elevation	Prioritize cells at lowest elevations	Low elevation forests are thought to have experienced high fuel buildup
Exurban	Prioritize cells with highest housing density within a 3 cell radius	Areas near structures should be prioritized to reduce their risk exposure
Roads	Prioritize cells closest to paved roads	Areas adjacent to roads are (1) accessible and thus less expensive to thin and (2) a priority when near an at-risk community, according to the Healthy Forest Recreation Act Sec 101(16) (B(iii)) (HFRA 2003)
Slope	Prioritize areas of the steepest slope up to 30%	Steep slopes are hazardous but slopes >30% are inaccessible.
Canopy	Prioritize cells with highest canopy cover	Forests with high canopy cover contain contiguous fuel and are thought to have experienced high fuel buildup
Fireline	Prioritize cells with highest potential fireline intensity	Areas of highest hazard should be prioritized

tive humidity, and temperature determine fuel moisture. Fuel moisture, along with wind speed and direction, influences potential fireline intensity (the rate of heat release along a fire front; Pyne et al. 2006). Thus, depending on the assumed weather conditions, researchers may draw different conclusions about where wildfire mitigation is needed across the landscape.

Second, there is a great deal of uncertainty about the potential fireline intensity in variable-severity fire regime areas, and hence it is difficult to say whether such forests are in need of restoration. Restoration of historic forest structure is needed in areas where forest structure is outside of the historical range of variability (HRV). HRV is 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 et al. 1999). Where forest structure is outside of the HRV (i.e., denser than prior to the fire suppression period), restoration of historical forest structure is potentially needed. For example, mechanical thinning in many ponderosa pine forests of the Southwest United States (Covington and Moore 1994; Fule et al. 1997) and the lowest elevations of the montane zone of the Colorado Front Range (Veblen 2003; Sherriff 2004) is seen as a way to reduce wildfire hazard and restore the historical forest conditions to within the HRV. Where forest structure is within the HRV, restoration of historical forest conditions is not needed. For example, lodgepole pine forests at higher elevations were historically dense so thinning could actually result in a stand structure that did not exist historically (Veblen 2003; Schoennagel et al. 2004).

Although the HRV of forest structure at the lowest elevations of the montane zone (<2,100 m) is well understood (Sherriff 2004), the HRV of mid-to-upper elevations is often uncertain because the fire regimes were variable, containing both surface and stand-replacing fires (Kaufmann et al. 2001; Sherriff 2004; Ehle and Baker 2004). Based on fire history and stand reconstruction evidence from the Cheesman area (located south of the study area), Kaufmann et al. (2001) conclude that restoration of historical forest structure is needed in the area of ponderosa pine forests characterized by variable-severity fire regimes. However, it is not clear that the specific thinning guidelines developed for the Cheesman landscape apply to other ponderosa pine forests characterized by variable-severity fire regimes. Thus, depending on whether variable severity fire regimes are assumed to be within or outside of the HRV, researchers may draw different conclusions about where wildfire mitigation is needed across the landscape.

Methods

To address the research questions, two spatial models were overlaid: A model of thinning location and a model of needed forest management outcomes. The model of thinning location selects land for thinning based on criteria used by forest managers in Boulder County, Colo. The selected locations are then overlaid on the model of needed forest management outcomes, which depend on assumptions of weather conditions and historical forest structure. In both models, the 76,400 ha (188,800 acre) landscape is represented as a grid of 14 ha (35 acre) cells.

Model of Thinning Location

The model of thinning location selects land suitable for mechanical thinning within the montane zone of Boulder County, Colo. under alternative thinning criteria. The thinning criteria are based on landscape-level practices employed by forest managers for three major forest management projects in Boulder County: The Sugarload Fuel Reduction Project (2004), the City of Boulder Open Space Forest Ecosystem Management Plan, and the Winiger Ridge Project (1999). We identified criteria employed by one or more project and operationalized them so that simple forest manager decision-making could be modeled (Table 1). The model is not designed to precisely emulate exact management practices. This would be nearly impossible as the actual management plans are still in the planning stage and involve the complex interaction of multiple criteria. Instead, the model is designed to explore "what if" questions. *What* land is likely to be prioritized for mechanical thinning *if* managers employed a given criterion?

The following example illustrates the operation of the model of thinning location. Assume that land adjacent to roads is prioritized for thinning. During a model run, the model selects cells closest to roads first and then selects cells farther out until the defined area for thinning has been reached. If the suitable cells exceed the defined area for thinning, the cells are selected at random from amongst suitable cells. Thus, the model yields slightly different results each time it is run. We modeled the outcome of each criterion in Table 1 individually, not in combination with other criteria. We also tested the outcome of each criterion assuming thinning could only take place on Forest Service land. For example, the model was used to evaluate the outcome of prioritizing land near all roads as well as near roads on Forest Service land.

Two model limitations require further explanation: (1) The model focuses exclusively on landscape-scale thinning and (2) it does not consider specific thinning treatments. First, the model focuses on landscape-scale thinning rather than defensible space or fire breaks. Defensible space in the "Home Ignition Zone" 60 m surrounding structures is the most effective way to reduce structure loss (Cohen 2000). Fire breaks are small treatments that can halt the spread of fire or facilitate fire fighting. These smaller treatments are not the focus of this study; the forest management projects in Boulder County explicitly propose widespread landscape-scale forest treatments.

Second, the model does not consider specific thinning treatments. Many factors can influence the effectiveness of treatments, including to what degree the canopy cover is opened up and the crown bulk density reduced, whether ladder fuels are removed to raise crown base height, whether the thinning treatment is maintained or if trees are allowed to regenerate, whether slash is removed, and if prescribed fire is used to reduce posttreatment surface fuels. The actual outcomes of thinning treatments also depend on factors related to firefighting, which are also beyond the scope of this study. We simply assume that best practices at the site level are used to design and maintain treatments.

Model of Needed Management Outcomes

For each run of the model of thinning location, the selected cells were overlaid on the model of needed forest management outcomes. To identify the needed forest management outcomes (i.e., wildfire mitigation and restoration of historical forest structure) across the study area, we compared present-day potential fireline intensity to historical fireline intensity inferred from historic fire frequency. Details of this model, along with a sensitivity analysis, are described in Platt et al. (2006) and Sherriff (2004); only a summary is provided here.

To calculate present-day potential fireline intensity across the landscape we used the FlamMap fire behavior simulator (Joint Fire Sciences Program 2003). We then classified every cell in the FlamMap output as high fireline intensity ($\geqslant 346$ kW/m) or low fireline intensity (<346 kW/m). This is the threshold above which fires should not be attacked by hand and control efforts at the head of the fire may not always be effective (Pyne et al. 1996).

To infer historical fireline intensity, we interpreted a statistical model of historical fire frequency calibrated with extensive fire history data. The statistical model was used to classify historical fireline intensity from 1800 to 1860 into three categories: Low (6+ fire years or mean fire interval (MFI) <30 years, 50% +trees have multiple fire scars, 3+ trees have at least 3 scars); variable (4 or fewer fire years or MFI 30–40 years); and high (3 or fewer fire years, MFI >40 years or fewer than 4 fire dates, 2 or fewer trees with >2 scars) (Sherriff 2004). In areas where fire frequency was high we assumed that fire-free intervals were too short for accumulation of fuels to support intense fires; this assumption is corroborated by tree age structure data and historical photographs showing open stands in the lower montane zone (Veblen and Lorenz 1991; Sherriff 2004). Conversely, in areas where fire frequency was low, we assumed that fuels could accumulate and support intense fires. In areas of variable fire frequency, the historic fireline intensity is ambiguous.

By overlaying potential present-day fireline intensity and historical fireline intensity, we determined which forest management outcomes are potentially needed (Table 2). If potential present-day fireline intensity is low, we assume that management is not needed regardless of historical fireline intensity. If potential present-day fireline intensity is high, we assume that wildfire mitigation is needed because it is unlikely that the fire could be fought by hand. This is a simplifying assumption; we recognize that in areas of low potential fireline intensity, there are cases where fire control efforts may not be effective or where wildfire mitigation may be appropriate. However, everything else equal, it is logical that wildfire mitigation is needed in the areas of highest potential fire hazard.

Table 2. Needed Management Outcomes Based on a Comparison of Estimated Present-Day and Historical Fireline Intensity

	Inferred historical fireline intensity		
Modeled present-day fireline intensity	High (low historical fire frequency)	Moderate (variable historical fire frequency)	Low (high historical fire frequency)
High ($\geqslant 346$ kW/m)	Only mitigation	Ambiguous	Both outcomes
Low (<346 kW/m)	Neither outcome; management not needed		

Within the areas of high present-day fireline intensity, we evaluate the historical fireline intensity inferred from historic fire frequency to see if restoration of historic forest structure is also needed. Where both present and historical fireline intensity is high, restoration of historical forest conditions is neither needed nor appropriate because these areas are naturally hazardous. Historically, such areas typically had dense single-age stands and low fire frequency; thinning would create a forest structure that did not previously exist. These areas are classified as "only mitigation" needed (Table 2).

Where present-day fireline intensity is high, but historical fireline intensity is low, restoration of historical forest conditions is needed because such areas are generally associated with relatively open stands that have become denser since the advent of fire suppression (Sherriff 2004; Veblen 2003). These areas are classified as "both outcomes" needed. Where the present-day fireline intensity is high and historical fireline intensity is moderate, the necessity of restoring historical forest conditions is ambiguous because it is not clear whether these areas are denser than they were historically. These areas are classified as "ambiguous" (Table 2). The consequences of this ambiguity are evaluated through the parameter scenarios described in the following section.

One limitation of this analysis is the assumption that conditions, including fuel type and configuration, are assumed to be constant over time. This assumption would be invalid if extensive land use change altered fuels, if a major disturbance, such as a fire or insect outbreak occurred, or if adequate vegetation growth took place. Within the temporal range (22 years) and spatial scale (14 ha cells) of the study, however, this is a reasonable and parsimonious assumption.

Parameter Scenarios for Model of Needed Management Outcomes

Parameters related to weather conditions and fire regimes (i.e., the departure from HRV of areas of variable-severity fire regimes) affect the model of needed management outcomes. To explore the influence of these parameters, we ran the model under four parameter scenarios, each of which represent a different set of assumptions about weather and historic fire regimes (Table 3).

Table 3. Parameter Scenarios of Weather and Departure from HRV in Areas Characterized by Variable-Severity Fire Regimes

Variable-severity fire regimes	Moderate weather conditions (M)	Extreme weather conditions (E)
Outside of HRV (O); restoration needed	M–O	E–O
Within HRV (W); restoration is not needed	M–W	E–W

Along the top of Table 3 are two possible weather conditions. For moderate conditions (M) we use the following parameters in FlamMap: upslope winds of 24 km/h (15 mi/hr) and the default fuel moisture specified in the 13 standard NFFL fuel models. Fuel data with updated fuel models (Scott and Burgan 2005) was not available at the time of the study.

For extreme conditions (E) we use the following parameters in FlamMap: upslope winds of 80 km/h (50 mi/hr) and fuels "conditioned" by three weeks of dry weather conditions with temperatures ranging from 68 to 86°F, relative humidity ranging from 5 to 12%, southwest winds averaging 23 km/h (14 mi/hr), no rain and no clouds. These conditions are rare, but representative of the conditions that occurred in the drought of 2002. During this time, much of Boulder County was 50–70% below average in terms of snowpack (April 2002 data), and precipitation was only 70–90% of the 1961–1990 average (Pielke et al. 2005). The Hayman Fire in Colorado, the largest fire in recent Colorado history, occurred in June 2002 during these extreme conditions (Graham 2003).

Along the left-hand side of Table 3 is whether areas are characterized by variable-severity fire regimes are outside (O) or within (W) the HRV. If they are outside of the HRV, restoration of historical stand structure is potentially needed in areas of variable-severity fire regimes. Otherwise, restoration of historical stand structure is not needed in areas of variable-severity fire regimes.

Overlay of the Model of Thinning Location and the Model of Needed Management Outcomes

The model of thinning location was run 100 times for each of 6 sets of thinning criteria (Table 2) and overlaid on the model of needed management outcomes under four parameter scenarios (Table 3). These model runs were then repeated with the additional constraint that thinning was only allowed on Forest Service land. In all, the model was run $100 \times 6 \times 4 \times 2$ times, for a total of 4,800 iterations. For each run, the model of thinning location selects 405 ha (1,000 acres) annually for thinning for years 2004–2026 for a total of 12% of the landscape. This is a conservative projection of annual thinning; the Sugarloaf Fuel Reduction Project proposes to thin 405–607 ha annually through 2009 (Sugarloaf Fuel Reduction Project 2004). For each model run, the outcomes needed on the land selected for thinning (both outcomes, "mitigation only," or "neither outcome") is computed. To separate the effects of parameter scenarios from the effects of thinning criteria, the analysis is divided into two parts. First, land is selected completely at random (the null model) to assess the effects of each parameter scenario. Second, the null model is compared to model runs that implement specific thinning criteria.

Results

Model of Needed Management Outcomes

To illustrate the effect of parameter scenarios across the landscape, the needed management outcomes are mapped (Figs. 1 and 2). In both moderate and extreme weather conditions, land classified as both outcomes needed is generally located at the lowest elevations. Also in both cases, areas classified as ambiguous are located at mid-to-upper elevations and follow stream drainages (Figs. 1 and 2). In the modeling process, the ambiguous areas are classified as both outcomes needed if areas characterized by variable severity fire regimes are assumed to be outside of the HRV and mitigation only if they are assumed to be within the HRV. Under moderate weather conditions, higher elevations are largely classified as neither outcome needed (Fig. 1). In contrast, under extreme weather conditions (E) similar to those during the Hayman Fire of 2002, the entire study area exceeds the threshold fireline intensity of 346 kW/m so no cells are classified as neither outcome needed (Fig. 1).

Model of Thinning Location: Null Model

The model of thinning location was then overlaid on the model of needed management outcomes. To evaluate the influence of the parameter scenarios in the absence of specific thinning criteria, a null model was used where land for thinning was selected at random. Fig. 3 shows the variation in the percentage of selected land under each parameter scenario where both outcomes are needed (shown both for the entire study area and restricted to Forest Service lands only, indicated by FS). Each box-and-whisker plot shows the first and third quartiles and extreme values. Under the null model of the M–O scenario, both outcomes are needed on a median of 22% of the selected land. The median results of all other parameter scenarios are statistically different from M–O at $p < 0.001$ according to a series of two tailed t-tests assuming unequal variances. Under the M–W parameter scenario, where it is assumed that restoration of historical forest conditions in variable-severity fire regimes is not needed, both outcomes are needed on a median of 12% of the selected land. The E–O scenario, where extreme conditions have raised the entire study area above the threshold fireline intensity of 346 kW/m, both outcomes are needed on a median of 43% of selected land. Finally, in the E–W scenario, with extreme conditions and restoration not needed in areas characterized by variable-severity fire regimes, both outcomes are needed on a median of 19% of selected land.

When only Forest Service land can be selected (Table 3, designated by FS), two differences are apparent. First, less land is selected where "both goals" are needed under each parameter scenario. Second, the variation in the results is less because there are fewer cells to choose from.

Fig. 4 shows the percent of selected land where only wildfire mitigation is needed. In the null M–O scenario, mitigation only is needed on a median of 25% of selected land. As before, the median results of all other parameter scenarios are statistically different from M–O at $p < 0.001$ according to a series of two tailed t-tests assuming unequal variances. For example, under the null E–W scenario a median of 82% need mitigation only. When mechanical thinning is restricted to Forest Service land, the median percentage of selected land where mitigation only is needed increases under every parameter scenario. The outcome is similar regardless of whether treatments are restricted to Forest Service land.

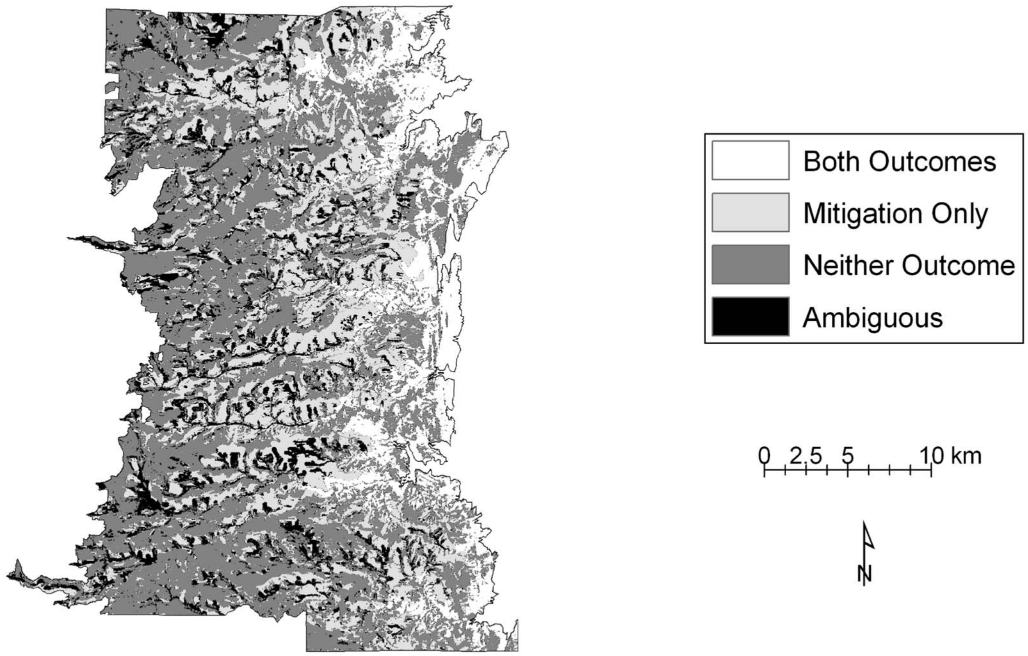

Fig. 1. Needed outcomes under moderate weather conditions. Note: Both outcomes indicates that both wildfire mitigation and restoration of historical forest conditions are needed; mitigation only indicates that only wildfire mitigation is needed; neither outcome indicates that management is not needed because potential fireline intensity is low; and ambiguous indicates that either both outcomes or mitigation only is needed depending on the parameter scenario (see Table 3).

Model of Thinning Location: Implementation of Criteria

In the following, the influence of thinning criteria on thinning location is evaluated. We report the mean deviation from the null model for each combination of thinning criterion and parameter scenario (Table 4).

Elevation

Prioritizing the cells with the lowest elevations increases the proportion of selected cells where both outcomes are needed compared to the null model (Table 4). Prioritizing low elevation under the E–O scenario leads to an additional 57% of selected land where both outcomes are needed compared to the null model. Prioritizing low elevation only on Forest Service land (the E–O FS scenario) also increases the amount of land where both outcomes are needed but only by 10% over the null model.

Exurban

Prioritizing the cells with the highest density of development within a three-cell radius has a small effect on the percent of selected land where both outcomes are needed, in most cases less a 2% difference from the null model (Table 4). One interesting result is that under the E–O or E–W parameter scenarios, prioritizing exurban increases the amount of land where both outcomes are needed by 4%. In contrast, when restricted to Forest Service land, prioritizing exurban *decreases* the amount of land where both outcomes are needed by 3–4%. Though modest in magnitude, this result indicates that prioritizing dense development near Forest Service land, a common forest management strategy, does not lead to the selection of additional land where both goals are needed.

Roads

Prioritizing land close to roads increases the amount of selected land where both outcomes are needed, assuming variable-severity fire regimes are outside of the HRV (Table 4). This effect is most pronounced in the M–O FS (4%) and E–O FS parameter scenarios (5%), and less pronounced under other parameter scenarios. The reason for this is that roads tend to follow ravines, which are associated with variable-severity fire regimes at mid-to-upper elevations of the montane zone (Sherriff 2004). Therefore, under the M–O FS and E–O FS parameter scenarios, thinning near roads yields a greater percentage of land where both outcomes are needed. This effect is eliminated under the M–W scenario, which assumes that variable-severity fire regimes are within of the HRV.

Canopy

Prioritizing the stands with the highest canopy cover decreases the percentage of selected land where both outcomes are needed (Table 4). Many of the stands where restoration of historical forest conditions is needed are open canopy and located on south facing slopes and at lower elevations. In contrast, many closed canopy stands are often located at higher elevations and on north-facing slopes where restoration of historical forest conditions is not needed. Prioritizing dense stands reduces the percentage of selected land where both outcomes are needed by 8% in the M–O scenario. When thinning is limited to Forest Service land the effect is less pronounced (2%) as stands tend to have high canopy cover on Forest Service land. Prioritizing stands with high canopy cover also reduces the percentage of selected land where only mitigation is needed under the M–O scenario. This is because much of the high canopy cover stands are located in

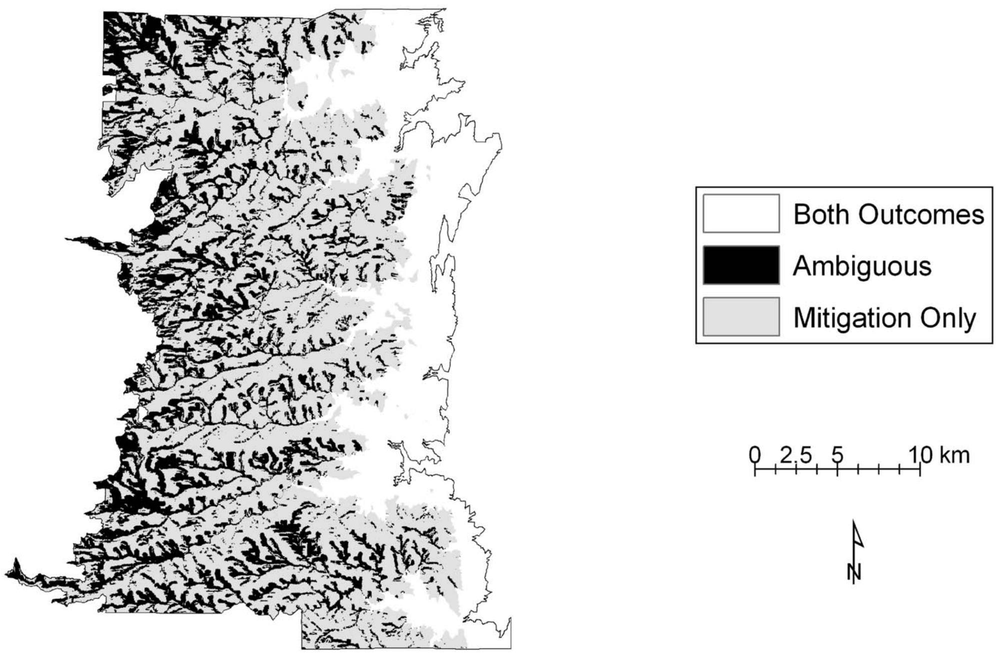

Fig. 2. Needed outcomes under extreme weather conditions. Note: Both outcomes indicates that both wildfire mitigation and restoration of historical forest conditions are needed; mitigation only indicates that only wildfire mitigation is needed; and ambiguous indicates that either both outcomes or mitigation only is needed depending on the parameter scenario (see Table 3).

mesic environments with low potential fireline intensity and therefore, under the M–O scenario neither management outcome is needed.

Fireline Intensity

Prioritizing areas with the highest potential fireline intensity yields a higher percentage of land where both outcomes are needed (Table 4). Under the M–O scenario, prioritizing fireline intensity increases this number by 10%, and under the E–O scenario it is increased by 11%. Prioritizing areas of high fireline intensity on Forest Service land (the E–O FS and E–W FS parameter scenarios) leads to a smaller increase in the percentage of selected land (3%), where both outcomes are needed than when treatments are allowed on all land (5–8%). On Forest Service land

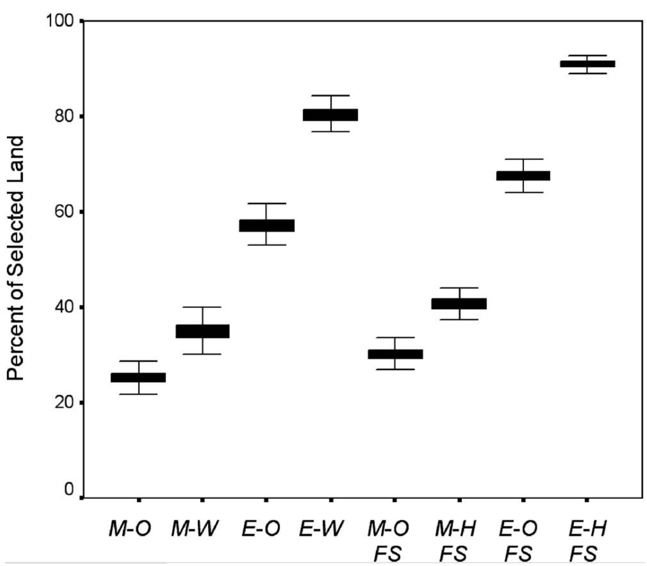

Fig. 3. Results of null model, both outcomes needed. Note: The box-and-whisker plot shows the percent of land selected at random that is classified as both outcomes needed. The result is reported for each parameter scenario (see Table 3 for descriptions). FS indicates that only Forest Service land may be selected.

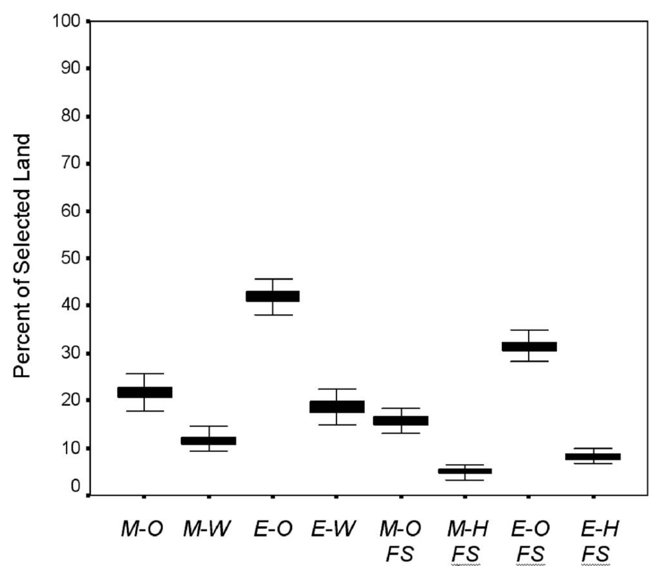

Fig. 4. Results of null model, mitigation only needed. Note: The box-and-whisker plot shows the percent of land selected at random that is classified as mitigation only needed. The result is reported for each parameter scenario (see Table 3 for descriptions). FS indicates that only Forest Service land may be selected.

Table 4. Difference from the Null Model of the Percent of Selected Land in Each Needed Outcome Class (Table 2), under Each Criteria (Table 1) and Parameter Scenario (Table 3)

Criteria	M–O	M–W	E–O	E–W	M–O–FS	M–W–FS	E–O–FS	E–W–FS
Elevation								
Both outcomes	41	51	57	81	11	10	9	15
Mitigation only	−25	−35	−58	−82	8	9	−9	−15
Neither outcome	−16	−16	0	0	−19	−18	0	0
Exurban								
Both outcomes	0	0	4	4	−2	−1	−4	−3
Mitigation only	−2	−2	−4	−4	−1	−2	4	3
Neither outcome	1	1	0	0	2	3	0	0
Roads								
Both outcomes	2	−2	2	−4	4	1	5	−1
Mitigation only	−1	3	−3	3	−4	0	−6	0
Neither outcome	−1	−1	0	0	−2	−1	0	0
Slope								
Both outcomes	4	6	−8	6	2	3	−7	3
Mitigation only	20	18	7	−7	18	17	7	−3
Neither outcome	−24	−24	0	0	−21	−20	0	0
Canopy								
Both outcomes	−8	−7	−3	−7	−2	−2	0	−2
Mitigation only	−8	−11	2	6	−13	−9	0	2
Neither outcome	17	15	0	0	16	10	0	0
Fireline								
Both outcomes	10	3	11	8	10	3	3	3
Mitigation only	0	8	−3	0	9	16	−3	−3
Neither outcome	−10	−10			−19	−18		

the areas with the highest potential fireline intensities under extreme weather are likely to be dense stands where restoration is not a needed outcome.

Management Implications

The results point toward several ways to guide current management practices in the study area. First, prioritizing land at the lowest elevations leads to the selection of the most land where both wildfire mitigation and restoration of historical forest conditions are needed. When thinning is restricted to Forest Service land, less land is selected where both goals are needed under all parameter scenarios. This is because Forest Service land tends to be at higher elevations and comprises forest types that are within the HRV.

Several other results may also help to guide management practices in the study area. For one, prioritizing land with the densest canopy will not always cause the model to select land where both outcomes are needed. This is because the densest stands, often located on north-facing slopes at higher elevations, have low potential fireline intensity under moderate weather conditions due to their high moisture content. Further, the restoration of historical forest conditions is not needed because many of these stands are within the HRV (Sherriff 2004). Prioritizing less dense stands at lower elevations would lead to the selection of more land, where both outcomes are needed under moderate weather conditions.

The results also underscore that weather assumptions are essential for determining where forest management outcomes are needed. For example, under the E–O scenario, prioritizing the land with the highest potential fireline intensity leads to the selection of less land, where both outcomes are needed compared to the M–O scenario. This is because under extreme weather conditions the mid-to-upper elevation forests on steep slopes (naturally dense forests where restoration is not needed) tend to have higher fireline intensity, whereas under moderate weather conditions the ponderosa pine stands at mid-to-lower elevations (formerly open stands where restoration is needed) have higher fireline intensity.

The results suggest that prioritizing exurban development may either modestly increase or decrease the amount of selected land where both outcomes are needed, depending on the parameter scenario. For example, under the E–O and M–W parameter scenarios, prioritizing exurban development leads to the selection of 3–4% more land where both outcomes are needed than the null. However, this effect is modest and the sign is reversed under other parameter scenarios, such as when treatments are restricted to Forest Service land. A further finding is that, under the M–O FS scenario, prioritizing roads increases the amount of selected land where both outcomes are needed by 4–5%. This is because roads tend to follow ravines, which are statistically associated with variable-severity historical fire regimes (Sherriff 2004).

Conclusions

The general issues described in this paper will surely be familiar to those involved in other resource management issues where objectives potentially conflict, or are packaged in a particular way to garner political support. As stated in the introduction, the goals of wildfire mitigation and restoration of historic forest structure are often presented as compatible goals. This assumption is based on existing research from very few areas, such as ponderosa pine ecosystems in the southwest United States (Schoennagel et al. 2004). Our study shows that this assumption is not true in a large part of the study area, including most Forest Service lands. Thus current management practices—such as prioritizing on dense stands on Forest Service land near communities—may not lead to the selection of land where both wildfire mitigation and restoration of historic forest structure are needed.

Though specific to the montane zone of Boulder County, these results speak to wider criticisms of fire management practices—and even resource management in general. At the national level, policy such as HFRA and the National Fire Plan should make explicitly clear either that (1) restoration of historic forest structure is not a policy goal, or that (2) it is a goal that may conflict with the primary objective of wildfire mitigation. At the local level, managers often recognize the uncertainty in scientific knowledge and the contradiction in management objectives. However, the uncertainty is not always "embraced" (Borchers 2005) and the policy contradictions are not always communicated clearly to other agencies or to the public. A happy exception is "Living with Fire: Protecting Communities and Restoring Forests" published by the Front Range Fuels Treatment Partnership (2006a, b), which makes clear that the dual goals of forest management are not always compatible.

The integration of conservation and restoration objectives must be grounded in several elements: a scientifically rigorous foundation, a regional approach, and skepticism of "one-size fits all" approaches (Noss et al. 2006). A spatial modeling approach, such as the one employed in this study, can integrate all three elements. In the current analysis we explicitly model which forest outcomes are needed in likely thinning locations under scenarios of weather conditions and fire history. Managers could use such an analysis to test "what if" questions related to forest thinning criteria, or to evaluate forest management plans at coarse scales. Future research should focus on expanding the geographic scope of the model to a greater range of forest ecosystems, a step which will require extensive fire history data. In addition, future models should incorporate specific forest treatments and recent research on their efficacy. Once these next steps have been taken, the model will be a fully realized decision support system for evaluating forest management alternatives in the wildland–urban interface.

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