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Efficacy of mechanical fuel treatments for reducing wildfire hazard

Robert J. Huggett Jr. [a,*], Karen L. Abt [a], Wayne Shepperd [b]

[a] Forestry Sciences Laboratory, Southern Research Station, USDA Forest Service, PO Box 12254, Research Triangle Park, NC 27709, United States
[b] Rocky Mountain Research Station, USDA Forest Service (retired), Ft. Collins, CO 80526, United States

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ABSTRACT

Mechanical fuel treatments are increasingly being used for wildfire hazard reduction in the western U.S. However, the efficacy of these treatments for reducing wildfire hazard at a landscape scale is difficult to quantify, especially when including growth following treatment. A set of uneven- and even-aged treatments designed to reduce fire hazard were simulated on 0.8 million hectares of timberland in Colorado. Wildfire hazard ratings using torching and crowning indices were developed; stands were selected for treatment; treatment was simulated and hazard ratings were reassessed. The results show that the even-aged treatments initially place more area within our hazard thresholds than do the uneven-aged treatments and that the uneven-aged treatment that removes more small stems reduces risk more than the treatment removing more large stems. The treatment costs follow the same pattern, with the even-aged treatments costing least. However, potential revenues are, as expected, higher for the uneven-aged large treatment. The results also show that both higher costs and higher revenues accrue to the treatments applied to the higher risk stands. Treatments also have differing risk reductions depending on the initial risk category. Even without considering growth or revenues, the outcomes of a state-level treatment program are difficult to estimate. This implies that at a minimum, forest-level, if not state-level analyses including overall measures of risk reduction, costs, revenues and long-term effects need to be conducted in concert with setting priorities for treating timberlands.

1. Introduction

Properly designed fuel treatments can increase wildfire resiliency and resistance in dry forests and change the behavior of subsequent wildfires (Agee, 1996; van Wagtendonk, 1996; Stephens, 1998; Wilson and Baker, 1998; Graham et al., 1999; Graham et al., 2004; Stratton, 2004; Agee and Skinner, 2005; Raymond and Peterson, 2005; Agee, 2007; Johnson et al., 2007). Recent legislative actions such as the Healthy Forests Restoration Act (HFRA, 2003) and policy initiatives like the Ten Year Comprehensive Strategy and Implementation Plan (WGA, 2001, 2002) envision broad-scale fuel reductions to reduce the likelihood and severity of uncharacteristic wildland fire. While these plans promote fuel treatments, we still have limited ability to model the overall effects of these treatments because fuel conditions as well as treatment and hazard have typically been evaluated at an individual stand level. In this paper, we develop fuel treatments and hazard ratings that are suitable for evaluating the economic impacts of landscape-level fuel treatments.

Many treatment options are available to land managers seeking to reduce fire hazard. Prescribed burning and mechanical thinning change fire hazard by reducing the hazardous fuels, while treatments such as mastication and mulching change fire hazard without a reduction in loading (Graham et al., 2004). Prescribed fire, while often the cheapest to implement, is not a viable option in many cases due to limited burning seasons, concerns about smoke, and the likelihood that a fire will escape in a populated area (USFS, 2003). Mechanical treatments create a variety of uneven-aged or even-aged stand structures depending on the desired treatment goals such as fuel reduction (to meet fire behavior goals), wildlife habitat maintenance requirements (for endangered species, for example), and restoration of spatial and structural conditions.

This paper reports on simulations of uneven- and even-aged fuel reduction treatments and their impacts on wildfire hazard ratings over time in Colorado. The Methods section describes our characterization of the FIA data and the metrics for quantifying wildfire hazard followed by a discussion of the treatments. The Results section shows how each treatment changes stand condition and wildfire hazard and discusses the associated product removals and estimated treatment costs. The paper concludes with a discussion of the implications of our findings for management and policy.

2. Methods

Information on Colorado forest conditions was obtained from Forest Inventory and Analysis (FIA) data provided by the U.S. Forest

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* Corresponding author. Tel.: +1 919 549 4025; fax: +1 919 549 4047.
E-mail address: rhuggett@fs.fed.us (R.J. Huggett).

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Table 1
Timberland eligible for treatment in Colorado (million hectares)

Total forestland	8.8
Less reserved	−1.1
Less non-timberland	−3.0
Less roadless	−0.9
Less lodgepole pine and spruce fir forest types	−1.3
Total eligible timberland	2.4

Service.[1] A set of screens was applied to the data to eliminate plots prior to the determination of pre-treatment wildfire risk. A plot was eliminated if it was classified as reserved (withdrawn by law for the production of timber products), located in a designated roadless area (road management activities mostly prohibited), or classified as non-timberland (productivity under 1.4 m^3 ha^{-1} yr^{-1}). These calculations are summarized in Table 1. There are 8.8 million hectares of forestland in Colorado, of which 7.7 million hectares are not reserved. Of the nonreserved forestland 4.7 million hectares are classified as timberland. Removal of roadless areas from consideration left approximately 3.8 million hectares of timberland. Excluding lodgepole pine and fir–spruce forest types reduced the potentially treatable area to 2.4 million hectares, of which 1.5 million are in ponderosa pine or Douglas fir forest types. The remainder are in hardwood, unclassified, pinyon–juniper and other forest types.

2.1. Hazard assessment

Wildfire hazard for this study was assessed using the torching index (TI) and crowning index (CI) of Scott and Reinhardt (2001), which link the surface fire and crown fire models of Rothermel (1972, 1991) with the transition model of Van Wagner (1977). TI and CI have often been used to evaluate treatment effectiveness and are included in the outputs of many simulation models, including those used here (van Wagtendonk, 1996; Stratton, 2004; Stephens and Moghaddas, 2005). The innovation in this study was using these indices to determine the least intrusive treatment that would meet our hazard reduction goals. TI and CI are also used here to determine both pre- and post-risk levels, which could be used to prioritize stands for treatment.

We developed hazard thresholds using TI and CI, calculated the measures for each plot, then selected only those plots which did not meet the thresholds for further treatment. In general, fuels include both surface fuels and standing live and dead trees. This study holds surface fuels constant at fuel model 9 pre- and post-treatment. It is possible to see significant changes in TI and CI by treating nothing and merely specifying a different fuel model. The only way to isolate the impact of our treatments on fire hazard was to hold the fuel model constant and assume no change in surface fuels. Our primary fire hazard metrics, TI and CI, were assessed using standing live trees only. The simulation program treats only standing live trees to improve hazard ratings.

TI is the wind speed at a height of 6.1 m that is sufficient to create a crown fire, when fire moves vertically from surface fuels to the crowns of individual trees. TI is a function of surface fuel and foliar moisture content, canopy wind reduction, canopy base height (CBH), and slope (Scott and Reinhardt, 2001). CI is the wind speed at a height of 6.1 m that is sufficient to induce active crowning, when fire moves horizontally through the forest canopy. CI is influenced by surface fuel moisture content, canopy bulk density (CBD), and slope (Scott and Reinhardt, 2001). *Higher* values of TI and CI correspond to *less* hazardous fuel conditions. The TI and CI thresholds and corresponding risk levels applied to each plot were:

1. $TI \geq 40.2$ km h^{-1} and $CI \geq 40.2$ km h^{-1} (Very low risk) or
2. $TI < 40.2$ km h^{-1} and $CI \geq 64.4$ km h^{-1} (Low risk).

The first threshold, both TI and CI of at least 40.2 km h^{-1}, was assumed to protect most stands from both the initiation and active spreading of crown fire. The second threshold, CI of at least 64.4 km h^{-1}even if TI does not meet the 40.2 km h^{-1} objective, reflects the belief that if CI is high enough, a crown fire would not actively spread even if torching were to occur.

The use of TI and CI as hazard measures addresses only the stand-level hazard, and ignores the important issue of aggregate hazard resulting from the number and location of stands treated. In addition, treatments to improve TI and CI may lead to other effects that could exacerbate future fire hazard, for example, by opening the canopy and allowing increased understory growth such that TI once again increases. However, alternate measures of hazard are not suitable for application at large scales using the plot level detail needed for analysis of potential impacts of removals of products. Note that the mechanical treatments do not specifically address treatment of surface fuels. We assumed whole tree removal and no change in surface fuels pre- to post-treatment. This implies that all non-merchantable down material generated by the treatments was removed from the site through burning or hauling.

We classified a plot as “in-condition” if it met one of the two thresholds, and “out-of-condition” if the plot met neither threshold. Table 2 shows the TI and CI used to classify the in-condition and out-of-condition plots and shows the risk level assigned. Based on the initial hazard assessment, in-condition plots were excluded from treatment. Post-treatment, a plot was classified as in-condition if one of the two thresholds was met. If a plot is out-of-condition based on the initial hazard assessment then it was eligible for treatment. Post-treatment, out-of-condition refers to plots that fail to obtain one of the two thresholds.

On the out-of-condition plots, we simulated a change in stand characteristics, and hence CBD and CBH, through the level of each of the 6 treatment types that enabled each plot to reach one of the two thresholds. We defined hazard or risk levels for plots that did not meet these criteria pre- or post-treatment. Plots with $TI < 40.2$ and $40.2 < CI \leq 64.4$ were classified as medium hazard, plots with $TI \geq 40.2$ and $CI < 40.2$ were classified as medium-high hazard, and plots with $TI < 40.2$ and $CI < 40.2$ were classified as high hazard. These ratings reflect our goal of reducing active crown fire hazard through the treatment simulations.

2.2. Treatments

We evaluated the hazard reduction from four uneven- and two even-aged treatments. The uneven-aged treatments are based on the Stand Density Index (SDI) of Reineke (1933) and remove trees from all size classes. The even-aged thin-from-below treatments remove smaller trees first.[2] Our approach differs from one that defines a very specific residual stand structure and then removes trees to achieve that end. Instead we minimize changes to the stand structure necessary to achieve our hazard reduction goals. The residual stand structure under each of our treatments is broadly defined by rules governing the overall age distribution of the stocking (uneven- or even-aged) and for the limited scenarios, the minimum post-treatment basal area. The algorithm for each treatment removes trees until the hazard goals are met or the constraint on basal area removed becomes binding. We recognize that the optimal treatments as defined by our algorithms may differ from prescriptions based on stand-level analyses in the field and therefore may not be generalized to every plot. Our method was the only practical way to automate prescription development to accommodate the infinite variety of

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[1] Colorado RPA periodic inventory, 1983 cycle 2.

[2] We use the term “even-aged” to generally describe a thin-from-below treatment. While thinning-from-below may leave a stand with more than one age class, it will move a stand away from a more uneven-aged structure and place it on a more even-aged trajectory.

Table 2
Hazard assessment, condition rating and risk levels

Risk level	Condition rating	Hazard assessment level (km h^{-1})	
		Torching index	Crowning index
Very low	In-condition	≥ 40.2	≥ 40.2
Low	In-condition	<40.2	≥ 64.4
Medium	Out-of-condition	<40.2	$40.2 \leq \text{CI} < 64.4$
Medium-high	Out-of-condition	≥ 40.2	<40.2
High	Out-of-condition	<40.2	<40.2

Table 3
Assumed fuel model and fuel moisture variables used for estimating crown fire hazard

Type	Variable	Value
Surface fuels: moisture	1-h fuel moisture (%)	4
	10-h fuel moisture (%)	5
	100-h fuel moisture (%)	7
	Live fuel moisture (%)	78
Surface fuels: model 9 loading and depth	1-h fuel loading (tonnes ha^{-1})	6.55
	10-h fuel loading (tonnes ha^{-1})	0.92
	100-h fuel loading tonnes ha^{-1})	0.34
	Fuel bed depth (m)	0.061
Site conditions	Foliar moisture content (%)	100
	Open windspeed (km h^{-1})	24.14
	Wind reduction factor (%)	25
	Canopy fuel load (tonnes ha^{-1})	8.97
	Canopy bulk density (kg m^{-3})	Plot specific
	Canopy base height (m)	Plot specific
	Slope (%)	Plot specific

stand conditions existing in different forest types covering such a large land base. This study compares the treatment impacts on fire behavior at a very aggregate level and should not be considered a blueprint for selecting a single treatment for an entire landscape, state, or region.

The uneven-aged treatments, which thin across all diameter classes, are referred to as SDI–FLEX (Shepperd, 2007) and begin with a forest type and ecoregion-specific maximum SDI for each plot. The maximum SDI is a benchmark for the maximum possible density of stems per hectare. Two variables are used to manipulate the shape and height of the stocking curve, which reflects the distribution of the number of trees per hectare by diameter class, for each plot. The flex factor (*flex*) determines how SDI is distributed among diameter classes while the SDI seed (*seed*) establishes the percent of maximum SDI stocking desired on the residual plot. With both *flex* and *seed* set at 1, the plot is stocked at the maximum SDI level with an equal distribution of SDI stocking in all diameter classes. Decreasing *seed* while keeping *flex* constant lowers the plot stocking curve while maintaining an equal distribution of SDI across diameter classes. Decreasing *flex* while keeping *seed* constant flattens the stocking curve (changes its slope) by reducing SDI in smaller diameter classes. The even-aged thin-from-below treatments remove a given amount of biomass from a plot by cutting the smallest diameter trees first and successively cutting those of larger diameter.

2.3. Treatment simulation algorithm

Several existing software tools were integrated in a single simulation process to calculate fire hazard and simulate treatment. Pre- and post-treatment CBD and CBH for each plot were determined using the algorithm of Reinhardt et al. (2006). Crown fire hazard was measured using NEXUS (Scott, 1999), a program that takes the plot-level CBD, CBH, and slope as well as assumptions on fuel moisture and fuel model to estimate a variety of fire behavior variables including TI and CI. Other fire behavior metrics are available as outputs, including rate of spread (m min^{-1}), heat per unit area (btu m^{-2}), fireline intensity (btu m^{-1} s^{-1}), and average flame length (m). Our use of TI and CI to measure the impact of the treatments is supported by the improvement in these other fire behavior metrics.

Fuel moisture conditions were assumed to be “summer drought” (Rothermel, 1991). The lack of plot-level information on surface fuels and the broad scope of the area being simulated forced us to make some simplifying assumptions. Fuel model 9 (Albini, 1976; Anderson, 1982), hardwood or long-needle pine litter, was assumed for all forest types both before and after treatment. Fuel model 9 represents a mid-range of fire behavior and allows us to make aggregate comparisons of fire hazard reduction in a study of this breadth (Skog et al., 2006). Table 3 shows the moisture, loading, and site variables that were used as inputs into NEXUS. Note that only slope, CBD, and CBH varied among plots, and only CBD and CBH were influenced by the treatments. All other variables were held constant.

The treatment simulation can be broken into three phases: pre-treatment, treatment, and post-treatment. The pre-treatment phase began with an assessment of CBD, CBH, TI and CI on the plots representing the 2.4 million hectares of eligible timberland. Plots which met one of the two hazard threshold conditions were eliminated from the pool of eligible plots, leaving 0.8 million hectares of timberland in Colorado on which treatments were simulated.

Six treatments were simulated for each plot eligible for treatment (Table 4 summarizes the six treatment scenarios). Two uneven-aged stand density treatments (large, small) and one even-aged thin-from-below treatment were applied with (limited scenario) and without (unlimited scenario) a 50% limit on basal area removed. The basal area removal limits were designed to retain closure of the canopy. Loss of canopy closure may introduce conditions that intensify surface fires (Pollet and Omi, 2002) and stimulate the initiation of crown fires. The basal area limit was imposed for two additional reasons. First, experience has shown that removing more than half of a forest's biomass in one entry in these forest types can have adverse ecologic effects and is generally not socially acceptable (Shepperd, 2007). In addition, limiting the removals prevented the SDI harvest protocol from cutting all trees from even-aged single-storied stands in an attempt to raise crown base heights.

The limited and unlimited uneven-aged large scenarios, biased toward removing greater numbers of large trees and designed to result in high structural diversity, treated plots by setting *flex* = 1. The limited and unlimited uneven-aged small scenarios, designed to remove more small trees than the uneven-aged large and to result in limited structural diversity, treated plots by setting *flex* = 0.844421. The two even-aged (thin from below) treatments removed trees necessary to remove basal area in successive 1% increments, beginning with the smallest diameter and moving up.

Each plot's optimal prescription for the three limited treatments was determined by performing a search over the parameter space of each treatment to locate the highest values of *seed* for the two uneven-aged treatments and the lowest value of basal area removed for the even-aged treatment that achieved the first of (1) $\text{TI} \geq 40.2$ and $\text{CI} \geq 40.2$ (very low), (2) $\text{TI} < 40.2$, $\text{CI} \geq 64.4$ (low), or (3) 50% of beginning

Table 4
Summary of treatment scenarios simulated on eligible timberland in Colorado

Treatment scenario	Description	Removal limit*
Limited		
Uneven-aged large	Thin across diameter classes: cut more large trees	50%
Uneven-aged small	Thin across diameter classes: cut more small trees	50%
Even-aged	Thin from below	50%
Unlimited		
Uneven-aged large	Thin across diameter classes: cut more large trees	None
Uneven-aged small	Thin across diameter classes: cut more small trees	None
Even-aged	Thin from below	None

*As a percentage of beginning basal area.

Table 5
Average fire behavior statistics pre- and post-treatment for all treatment scenarios

Treatment Scenario	Canopy base height (m)	Canopy bulk density (kg m^{-3})	Torching index (km h^{-1})	Crowning index (km h^{-1})	Rate of spread (m min^{-1})	Heat per unit area (btu m^{-2})	Fireline intensity (btu m^{-1} s^{-1})	Flame length (m)
Pre-treatment	1.85	0.138	36.7	34.1	5.53	6906	1026	2.04
Post-treatment								
Limited								
Uneven-aged large	1.96	0.081	39.2	48.4	4.06	5537	500	1.33
Uneven-aged small	2.07	0.076	41.8	50.1	3.81	5292	426	1.23
Even-aged	3.18	0.078	64.5	48.4	3.16	4712	260	1.00
Unlimited								
Uneven-aged large	2.10	0.060	42.4	59.3	3.32	4878	284	1.04
Uneven-aged small	2.19	0.063	44.3	55.9	3.34	4888	288	1.05
Even-aged	3.24	0.072	65.6	49.9	3.14	4696	255	0.99

basal area had been removed. Note that under the limited scenario some plots did not meet either of the two risk thresholds due to the limit on basal area removed. For the unlimited scenario, a search was performed over the parameter space of each treatment to locate the highest values of *seed* for the uneven-aged treatments and the lowest value of basal area removed for the even-aged treatment that achieved the first of (1) $TI \geq 40.2$ and $CI \geq 40.2$ or (2) $TI < 40.2$, $CI \geq 64.4$. All plots reach one of the risk thresholds under the unlimited scenarios.

3. Results

All simulated treatments on the 0.8 million hectares of timberland that did not meet our initial thresholds resulted in reductions in CBH and CBD, with corresponding changes in TI and CI (see Table 5). Table 5 also shows other fire behavior statistics for each treatment scenario. The greatest improvements resulted from the even-aged treatments, including both the unlimited and limited treatments, while the uneven-aged small treatments had somewhat more improvement in fire behavior than did the uneven-aged large treatments. Pre-treatment CBH and CBD averaged 1.85 m and 0.138 kg m^{-3}, respectively, while average initial TI and CI were below the 40.2 km h^{-1} threshold. Average CBH was modestly improved by the uneven-aged treatments and increased by about two-thirds for the even-aged options. The TI improvements embody the CBH changes—only the uneven-aged large limited failed to meet the 40.2 km h^{-1} objective on average and the two even-aged treatments almost doubled TI from its initial average value. CBD improved by 41% to 56%, resulting in every treatment reaching an average CI above the threshold of 40.2 km h^{-1}. Mean fireline intensity was reduced by at least one-half under all options, with the even-aged thinnings resulting in the most dramatic decreases.

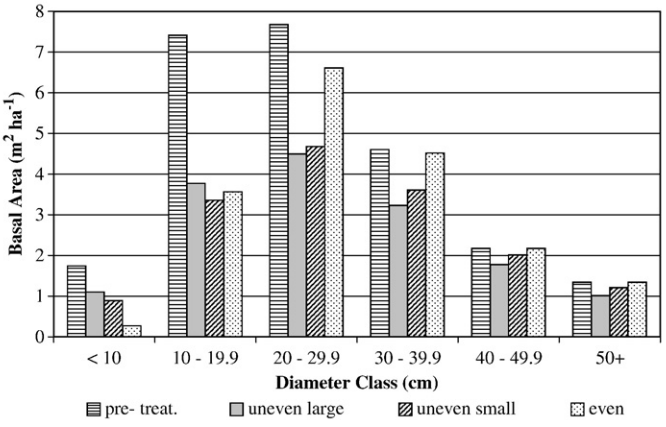

Fig. 1. Pre- and post-treatment average basal area per hectare by diameter class by treatment for the treatments with limits on basal area removals.

The pre- and post-treatment weighted average basal areas per hectare by diameter class with a 50% limit on basal area removed (limited scenario) are shown in Fig. 1. This chart illustrates the relative impact of each treatment on average stocking. Relative to pre-treatment conditions, the even-aged treatment removed the most basal area in the lower diameter classes while, as expected, the uneven-aged large treatment removed the most area in the larger classes. The uneven-aged small treatment removed more area in the under 10 cm class than the uneven-aged large, but less than the even-aged. This relationship inverts around the 20–29.9 cm class. In the larger classes the uneven-aged small removed more area than the even-aged but less than the uneven-aged large.

Application of these treatments moved area from out-of-condition to in-condition as shown in Table 6. Note that the unlimited treatments, which were not constrained by basal area removal limits, resulted in all hectares reaching the treatment goals, and thus were in-condition. In the limited scenarios, the even-aged treatments put 87% in-condition, while the uneven-aged treatments put 65% (small) and 53% (large) in-condition.

A further breakdown of these scenarios showing the risk level achieved for each treatment by initial risk level is shown in Table 7. The uneven-aged treatments applied to the initial medium risk level stands moved most of the area into the low risk level in both the limited and unlimited. Medium risk is defined by TI under our threshold of 40.2 km h^{-1} and CI over 40.2 km h^{-1} but under 64.4 km h^{-1}. The removal of larger trees with the uneven-aged scenarios induces an increase in CI to at least 64.4 km $h^{-1}$for most hectares initially in the medium risk category. Conversely, the uneven-aged treatments applied to the medium-high risk level moved most hectares into the

Table 6
Aggregate treatment summary by risk level by treatment scenario for all treated timberland

Treatment scenario	In-condition				Out-of-condition				
	Hectares (000s)*			Percent in-condition	Hectares (000s)**				Percent out-of-condition
	Very low	Low	Total		Med.	Med.-high	High	Total	
Pre-treatment					227	272	295	794	100
Post-treatment									
Limited									
Uneven-aged large	231	189	420	53	193	92	89	375	47
Uneven-aged small	307	208	515	65	154	70	55	279	35
Even-aged	533	158	691	87	32	69	2	103	13
Unlimited									
Uneven-aged large	386	409	794	100	0	0	0	0	0
Uneven-aged small	441	353	794	100	0	0	0	0	0
Even-aged	609	185	794	100	0	0	0	0	0

*Very low ≡ $TI \geq 40.2$ and $CI \geq 40.2$; Low ≡ $TI < 40.2$ and $CI \geq 64.4$.
**Medium ≡ $TI < 40.2$ and $40.2 \leq CI < 64.4$; Medium-high ≡ $TI \geq 40.2$ and $CI < 40.2$; High ≡ $TI < 40.2$ and $CI < 40.2$.

Table 7
Transition tables by treatment scenario for treated timberland in Colorado

Treatment scenario	Initial risk level**	Percent of area in each post-treatment risk level*,**				
		Very low	Low	Med.	Med.-high	High
Limited						
Uneven-aged large	Medium	8	75	18	0	0
	Medium-high	69	0	0	32	0
	High	9	6	52	2	30
Uneven-aged small	Medium	20	72	8	0	0
	Medium-high	76	0	0	24	0
	High	19	15	46	1	18
Even-aged	Medium	52	45	2	0	0
	Medium-high	86	0	0	14	0
	High	61	19	9	10	1
Unlimited						
Uneven-aged large	Medium	10	90	0	0	0
	Medium-high	100	0	0	0	0
	High	31	69	0	0	0
Uneven-aged small	Medium	21	79	0	0	0
	Medium-high	100	0	0	0	0
	High	41	59	0	0	0
Even-aged	Medium	53	47	0	0	0
	Medium-high	100	0	0	0	0
	High	73	27	0	0	0

*Very low ≡ TI ≥ 40.2 and CI ≥ 40.2; Low ≡ TI < 40.2 and CI ≥ 64.4.
**Medium ≡ TI < 40.2 and 40.2 ≤ CI < 64.4; Medium-high ≡ TI ≥ 40.2 and CI < 40.2; High ≡ TI < 40.2 and CI < 40.2.

very-low risk level in the limited scenario and all hectares into very-low risk in the unlimited scenario. Medium-high risk is defined by TI over and CI under our threshold of 40.2 km h^{-1}. Again the removal of larger trees with the uneven-aged treatments increased CI, in this case to at least 40.2 km h^{-1}, for most hectares initially in the medium-high risk category. As TI was already in the acceptable range these hectares moved into very low risk post-treatment. Only in the high initial risk stands under the limited scenario does treatment result in area moving into medium-high or, primarily, to medium risk, following treatment. For these hectares the basal area limits preclude the further treatment necessary to move them into low or very low risk.

From these results, it appears that the even-aged treatments are most efficacious in reducing risk in both the unlimited and basal-area-limited treatment scenarios. However, other factors, including both economic factors and long-term efficacy should be considered when selecting treatment scenarios. Economic factors include the cost of harvesting/cutting, the cost of slash removal/treatment, and the potential revenues derived from each treatment (Tables 8 and 9). Table 8 shows aggregate values for each treatment scenario applied to all 0.8 million hectares, including total sawlog volume removed, total chips produced and total treatment costs. Table 9 provides these values on a per hectare basis and further separates the volumes and costs by initial risk level.

Table 8
Total softwood sawlog volume removed, total chips removed, and total treatment costs by treatment type

Treatment scenario	Softwood sawlog volume (million m^3)	Chip volume (million m^3)	Total treatment costs (million $)
Limited			
Uneven-aged large	12.5	16.7	2325
Uneven-aged small	8.7	16.2	2302
Even-aged	1.4	8.9	1755
Unlimited			
Uneven-aged large	17.2	21.0	2805
Uneven-aged small	11.1	18.5	2769
Even-aged	1.9	9.8	2097

The estimated costs of harvesting/cutting shown in Tables 8 and 9 are influenced by the sawlog volume removed by stem size and the amount of material chipped and left on site. Additional costs will be incurred to dispose of these chips, either onsite by burning or scattering, or off-site (e.g., landfill, pulp mill, bioenergy production), but the prices for hauling or disposing proved difficult to assess during a time of anticipated market changes in the local areas. Even without these prices, however, the volumes alone provide important information on estimated cost comparisons between treatments. Tables 8 and 9 also provide the volume of sawlog material, which in the absence of specific price information can proxy for revenue differences by treatment scenario and initial risk level.

The even-aged treatments are the cheapest overall, and by hectare, with treatments limited by basal area removals having the lowest costs. Chip volumes and product volumes are lower in even-aged treatments for all initial risk levels, and overall, illustrating the relationship between volume treated and costs. Typically, even-aged treatments which remove the same volume as an uneven-aged treatment are more expensive, however, our use of TI and CI to limit treatments to the lowest removal level possible while achieving risk reduction goals means that these treatments are, in fact, less expensive because they treat lower volumes. Our initial choice of holding TI to a higher standard than CI to define in-condition stands means that removal of only smaller stems likely to contribute to torching may be all that is needed on many stands to bring stands into the low or very low risk categories.

Treatment cost calculations for Tables 8 and 9 include the cost of chipping all activity fuels, but does not include the costs of disposing of these fuels. Options for disposal include burning on site (e.g., broadcast or pile), hauling to a processing facility (e.g., bioenergy or pulp) or hauling to a landfill. The cost of each of these options is highly specific to each local market area which makes it impossible to include these costs in a state-wide study of this type. In addition, some uses, such as bioenergy, are part of emerging or changing markets and costs and revenues for these users may not be available. Thus we did not include disposal costs, instead using the volume of chips produced to provide a proxy for these cost differences between treatment scenarios.

Chip production is more variable by initial risk than are treatment costs or sawlog volumes. Total chip production is highest in the

Table 9
Softwood sawlog volume per hectare, chips per hectare, and treatment cost per hectare by initial risk level

Treatment Scenario	Initial risk level**	Softwood sawlog volume (m^3 ha^{-1})	Chip volume (m^3 ha^{-1})	Treatment costs ($ ha^{-1})
Limited				
Uneven-aged large	Medium	11.9	15.7	1960
	Medium-high	15.3	21.6	2664
	High	19.0	24.4	3914
Uneven-aged small	Medium	6.9	14.3	1922
	Medium-high	11.3	21.7	2641
	High	13.7	23.8	3889
Even-aged	Medium	0.1	2.4	1530
	Medium-high	2.5	16.5	2090
	High	2.3	13.2	2844
Unlimited				
Uneven-aged large	Medium	13.6	17.5	2076
	Medium-high	19.0	25.8	3022
	High	30.4	34.0	5122
Uneven-aged small	Medium	7.8	14.9	2024
	Medium-high	13.3	23.9	2995
	High	19.3	29.2	5066
Even-aged	Medium	0.1	2.6	1623
	Medium-high	3.3	17.8	2409
	High	3.2	14.6	3635

**Medium ≡ TI < 40.2 and 40.2 ≤ CI < 64.4; Medium-high ≡ TI ≥ 40.2 and CI < 40.2; High ≡ TI < 40.2 and CI < 40.2.

unlimited scenario, as expected, and lowest in the even-aged treatments. Splitting out the costs and volumes by initial risk level per hectare, however, is less consistent. In the limited scenario, chip production from even-aged treatments is generally lower (2.4–16.5 m^3 ha^{-1}) than uneven-aged small (14.3–23.8 m^3 ha^{-1}) or uneven-aged large (15.7–24.4 m^3 ha^{-1}) (Table 9). In addition, the medium risk stands are generally lower than the medium-high and high risk stands. Similar patterns hold for the unlimited scenario, although chip production increased across all treatment and risk combinations, consistent with higher levels of removals in the unlimited scenarios.

Total softwood sawlog volume produced from each treatment in each risk level, which represents merchantable volume removed, is shown in Table 8. The uneven-aged large treatment was designed to optimize sawlog volume while maintaining an uneven-aged structure with high fire resistance. Consistent with this, we found the aggregate sawlog volume higher in the uneven-aged large unlimited (17.2 million m^3) and lowest in the even-aged limited (1.4 million m^3). Also, as anticipated, volumes are higher for all three unlimited scenarios. Sawlog volumes per hectare conform to expectations, with lowest in even-aged and highest in uneven-aged large.

While estimated prices are available for the sawlog volumes, a program of this size would introduce a significant amount of product into the market, driving down prices (Abt and Prestemon, 2006) and thus increasing the net cost of treatment. Because the size of a program is unknown, the prices and hence the revenues from the program are also unknown, we did not calculate prices or revenues. The sawlog volumes serve as a proxy for revenues.

4. Conclusion

This analysis considered the efficacy of a suite of even- and uneven-aged treatments to address fire hazard in Colorado based on their ability to reduce crown fire initiation and spread. The treatment simulations were performed over a broad area using available forest inventory data and consistent assumptions about surface fuels and weather conditions. We assigned wildfire hazard ratings to timberland in Colorado based on inventoried FIA data and then simulated treatment alternatives designed to reduce that hazard level.

Efficacy in wildfire hazard reduction, costs and revenues vary both by treatment scenario and by initial risk level. This has implications for the current practice of setting priorities for treatment based solely on initial risk level without regard for cost, revenues or either short- or long-term benefits of treatment. Although the temptation to treat highest risk first is powerful, we may get more benefits and revenues, and/or lower costs by treating the medium or medium-high risk areas first. Overall costs and benefits, including the long-term wildfire hazard reduction benefits and short term costs and revenues, should be evaluated before priorities are set for treatment.

Our results show that the even-aged treatments move more hectares into condition (if limited by basal area), move more hectares into the very low risk category, have lower costs, and produce smaller amounts of chips. This result applies to all initial risk levels, making it tempting to conclude that the even-aged treatments are preferred. However, the even-aged treatments also produce less product volume, and thus will provide less revenues, increasing the net cost of treatment to the landowner. Whether the net costs will be greater or less than the other treatment scenarios will need to be determined at a local level in order to capture the price effects of the overall program as well as the local mill prices.

A second conclusion is that net costs and hazard reduction benefits vary by initial risk level. Thus, a program that established priorities based on only initial risk level alone (such as “highest risk first”) will be cost effective only by chance. A complete program should be designed to address all at-risk stands, calculating costs, revenues and hazard reduction benefits before determining which treatment priorities will provide the most ‘bang for the buck’. In addition, wildfire hazard reduction benefits in this study only addressed the immediate post-treatment benefits, which is clearly short-sighted. Future research should attempt to delineate the long-term benefits (e.g., measuring benefits including stand growth for, say, up to 25–40 years) of each treatment scenario on each initial risk level.

We described a process for assigning wildfire hazard to timberland in Colorado based on inventoried FIA data and then simulating treatment alternatives designed to reduce that hazard level. While this resulted in an objective, consistent measure of hazard, future work can further refine these findings and add additional policy context. For example, while we conjecture that the treatments would result in changes in fire behavior, we are not certain how these changes would translate into gains (or losses) in economic welfare. Both human and natural values at risk over various temporal and spatial scales within Colorado would be impacted by a large treatment effort encompassing 0.8 million hectares. Simulated treatments can be integrated with tools such as FARSITE (Finney, 1998) to estimate program effects at the landscape level which can then be translated into welfare impacts. Another avenue for further work is to modify and refine the assumptions made regarding surface fuels and weather conditions to allow for sensitivity analysis over a variety of scenarios. Additional screens could also be applied to the data or results to provide alternate estimates of treated area and volumes removed. For example, a requirement that a treated plot have a minimum amount of volume to ensure some threshold level of revenue. Integrating the impacts of insects and disease along with simulated prescribed fire could provide a more complete picture of management opportunities and impacts.

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References

Abt, K.L., Prestemon, J.P., 2006. Timber markets and fuel treatments in the Western U.S. Natural Resource Modeling 19, 15–43.

Agee, J.K., 1996. The influence of forest structure on fire behavior. In: Sherlock, J. chair. Proceedings of the 17th Annual Forest and Vegetation Management Conference. 1996 January 16–18, 52–68.

Agee, J.K., 2007. Keynote address: the role of silviculture in restoring fire-adapted ecosystems In: Powers, Robert F., tech. editor. Restoring fire-adapted ecosystems: proceedings of the 2005 National Silviculture Workshop. Gen. Tech. Rep. PSW-GTR-203, Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture: p. ix–xviii.

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211, 83–96.

Albini, F.A., 1976. Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. p. 92.

Anderson, H.E., 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. p. 22.

Finney, M.A., 1998. FARSITE: Fire Area Simulator—Model Development and Evaluation. Res. Pap. RMRS-RP-4. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT. p. 47.

Graham, R.T., Harvey, A.E., Jain, T.B., Tonn, J.R., 1999. The effects of thinning and similar stand treatments on fire behavior in western forests. Gen. Tech. Rep. PNW-GTR-463. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. p. 27.

Graham, R.T., McCaffrey, S., Jain, T.B., 2004. Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rep. RMRS-GTR-120. U.S.

Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. p. 43.

HFRA [Healthy Forest Restoration Act], 2003. HR 1904.

Johnson, M.C., Peterson, D.L., Raymond, C.L., 2007. Guide to fuel treatments in dry forests of the Western United States: assessing forest structure and fire hazard. Gen. Tech. Rep. PNW-GTR-686. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. p. 322.

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

Raymond, C.L., Peterson, D.L., 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Canadian Journal of Forestry Resources 35, 2981–2995.

Reineke, L.H., 1933. Perfecting a stand-density index for even-aged forests. Journal of Agriculture Research 46, 627–638.

Reinhardt, E.D., Lutes, D.C., Scott, J.H., 2006. FuelCalc: a method for estimating canopy fuel characteristics. Fuels Management—How to Measure Success: Conference Proceedings. 28–30 March 2006; Portland, OR. Proceedings RMRS-P-41. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 273–282.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT. p. 40.

Rothermel, R.C., 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. Res. Pap. INT-438. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT. p. 46.

Scott, J.H., 1999. NEXUS: a system for assessing crown fire hazard. Fire Management Notes 59, 20–24.

Scott, J.H., Reinhardt, E.D., 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Res. Pap. RMRS-RP-29. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO. p. 59.

Shepperd, W.D., 2007. SDI–Flex: a new technique of allocating growing stock for developing treatment prescriptions in uneven-aged forest stands. Restoring Fire-adapted Ecosystems: Proceedings of the 2005 National Silviculture Workshop. Gen. Tech. Rep. PSW-GTR-203. Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, Albany, CA, pp. 171–180.

Skog, K.E., Barbour, R.J., Abt, K.L., Bilek, E.M., Burch, F., Fight, R.D., Huggett, R.J., Miles, P.D., Reinhardt, E.D., Shepperd, W.D., 2006. Evaluation of silvicultural treatments and biomass use for reducing fire hazard in western states. Res. Pap. FPL-RP-634. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. p. 29.

Stephens, S.L., 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed-conifer forests. Forest Ecology and Management 105, 21–35.

Stephens, S.L., Moghaddas, J.J., 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. Forest Ecology and Management 215, 21–36.

Stratton, R.D., 2004. Assessing the effectiveness of landscape fuel treatments on fire growth and behavior. Journal of Forestry 32–40 Oct/Nov.

USFS [United States Forest Service], 2003. A strategic assessment of forest biomass and fuel reduction treatments in western states. Available online at http://www.fs.fed.us/research/infocenter.shtml.

Van Wagner, C.E., 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7, 23–34.

van Wagtendonk, J.W., 1996. Use of a deterministic fire growth model to test fuel treatments. Sierra Nevada Ecosystem Project, Final Report to Congress, Vol. II. Assessments and Scientific Basis for Management Options. Centers for Water and Wildland Resources, University of California, Davis, CA, pp. 1155–1166.

WGA [Western Governor's Association], 2001. Collaborative ten-year strategy for restoring health to fire-adapted ecosystems. Available online at http://www.westgov.org/wga_reports.htm.

WGA [Western Governor's Association], 2002. A collaborative approach for reducing wildland fire risks to communities and the environment: 10-year comprehensive strategy implementation plan. Available online at http://www.westgov.org/wga_reports.htm.

Wilson, J.S., Baker, P.J., 1998. Mitigating fire risk to late-successional forest reserves on the east slope of the Washington Cascade Range. Forest Ecology and Management 110, 59–75.