Simulating fuel treatment effects in dry forests of the western United States: testing the principles of a fire-safe forest

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Abstract: We used the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) to simulate fuel treatment effects on 45 162 stands in low- to midelevation dry forests (e.g., ponderosa pine *(Pinus ponderosa* Dougl. ex. P. & C. Laws.) and Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) of the western United States. We evaluated treatment effects on predicted post-treatment fire behavior (fire type) and fire hazard (torching index). FFE-FVS predicts that thinning and surface fuel treatments reduced crown fire behavior relative to no treatment; a large proportion of stands were predicted to transition from active crown fire pre-treatment to surface fire post-treatment. Intense thinning treatments (125 and 250 residual trees•ha^{-1}) were predicted to be more effective than light thinning treatments (500 and 750 residual trees•ha^{-1}). Prescribed fire was predicted to be the most effective surface fuel treatment, whereas FFE-FVS predicted no difference between no surface fuel treatment and extraction of fuels. This inability to discriminate the effects of certain fuel treatments illuminates the consequence of a documented limitation in how FFE-FVS incorporates fuel models and we suggest improvements. The concurrence of results from modeling and empirical studies provides quantitative support for "fire-safe" principles of forest fuel reduction (sensu Agee and Skinner 2005. For. Ecol. Manag. 211: 83–96).

Resume : Nous avons utilise le module complementaire sur le feu et les combustibles du simulateur de la vegetation forestiere (u Fire and Fuels Extension – Forest Vegetation Simulator >> (FFE-FVS)) pour simuler les effets du traitement des combustibles sur 45 162 peuplements clans des for-as seches situees a une altitude allant de faible a moyenne (p. ex. pin ponderosa *(Pinus ponderosa* Doug]. ex P. & C. Laws.), douglas vert *(Pseudotsuga menziesii* (Mirb.) Franco)) dans l'ouest des Etats-Unis. Nous avons evalue les effets des traitements sur le comportement d'un feu potentiel a la suite du traitement (type de feu) et sur le risque do feu (indice d'embrasement des cimes). La simulation predit que 1'eclaircie et le traitement des combustibles de surface reduiraient les feux de cime comparativement a 1'absence de traitements; une forte proportion de peuplements potentiellement sujets a un feu de cime avant d'avoir ete traites ne seraient plus sujets qu'a un feu de surface apres avoir ete traites. Des traitements d'eclaircie forte (125 et 250 arbres residuels•ha^{-1}) seraient plus efficaces que des traitements d'eclaircie faible (500 et 750 arbres residuels•ha^{-1}) selon les predictions. La simulation a pi-edit que le brulage dirige serait le traitement des combustibles de surface le plus efficace tandis qu'il n'y avait pas de difference entre 1'absence de traitement des combustibles de surface et la recuperation des combustibles. Cette incapacite a distinguer les effets de certains traitements des combustibles illustre la consequence dune limite documentee concernant la fawn dont la simulation incorpore Ies modeles de combustibles et nous suggerons des ameliorations. La convergence des resultats provenant de la modelisation et des etudes empiriques appuie de fagon quantitative 1es principes de securite incendie qui pronent la reduction des combustibles (sensu Agee et Skinner 2005. For. Ecol. Manag. **211:** 83–96).

Introduction

Dry forest types prevalent in western North America historically exhibited high-frequency, low- to moderate-severity fire regimes (Agee 1993; Taylor and Skinner 1998). Past management practices such as livestock grazing, wildfire suppression, and timber harvest have modified the fuelbed characteristics (vegetation composition and structure) and fire behavior of these dry forest types (Weaver 1943; Bisweil 1959; Dodge 1972; Hessburg and Agee 2003; Hessburg et al. 2005). They now have large amounts of fuel loads and ladder fuels such as tall grasses, shrubs, tree branches, and understory trees (Parsons and DeBenedetti 1979; Bonnicksen and Stone 1982; Peterson et al. 2005). As a result, these forests are more susceptible to active crown fire and higher burn severity than they were historically (Laudenslayer et al. 1989; MacCleery 1995; Arno and Allison-Bunnell 2002).

Fuel treatments are advocated to reduce fire hazard caused by increased stem densities in low- to moderate-severity fire regimes (Graham et al. 2004; Peterson et al. 2005). Rather

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than stop wildfires (Finney and Cohen 2003), treatments are meant to decrease fireline intensity (i.e., rate of heat energy released), reduce crown fire initiation, and support suppression operations (Agee 1996). Silvicultural thinning practices such as thinning from below and pruning and the subsequent removal of surface fuels are effective options to reduce stand density, remove ladder fuels, and increase stand heterogeneity (Graham et al. 2004). With millions of hectares of dry forests in the western United States requiring fuel treatment, forest and fire managers need recommendations and information to support science-based decision making for fuel management (Graham et al. 1999; Peterson et al. 2005; Schmidt et al. 2008). Agee and Skinner (2005) proposed four guidelines to assist managers in developing effective treatments to reduce crown fire hazard and to understand treatment consequences: reduce surface fuels, increase canopy base height, decrease canopy bulk density, and retain large fire-resistant trees. These principles of a "fire-safe" forest are based on our current knowledge of crown fire theory (e.g., Van Wagner 1977) and are intended to increase the resilience of stands to wildfire (Agee and Skinner 2005).

Several constraints, including insufficient funding, logistics, and safety, prevent robust experimental testing of the effects of different fuel treatments (Finney and Cohen 2003). Consequently, most validation of fuel treatment effects on mitigating fire hazard is done post hoc without high-quality pre-wildfire data (Pollet and Omi 2002; Finney et al. 2006). As an alternative, simulation models provide quantitative prediction of the effects of modifying fuelbed characteristics on crown fire hazard and the probability of crown fire initiation (Graham et al. 2004). The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003) simulates forest growth and potential fire hazard and fire type of different vegetation types in the United States. FFE-FVS is the standard simulation model used by most federal, state, and tribal government agencies (Dixon 2003). In this study, we evaluated how FFE-FVS predicts the effects of fuel treatments (i.e., combinations of thinning and surface fuel treatments) on simulated fire hazard and potential fire behavior type in a set of stands from dry forests of the western United States. This study extends conceptual and analytical work on fuel treatments and fire behavior from the fuel treatment guidebook (Johnson et al. 2007). Unlike other studies that have used FFE-FVS to examine treatment effects for only a few stands in specific geographical areas (Fiedler et al. 2001; Calkin et al. 2005; Skog et al. 2006), we used a large set of stand data from several geographic regions to perform a virtual test of the four principles of a fire-safe forest (Agee and Skinner 2005) across a broad range of dry forest conditions.

Methods

Model description: FFE-FVS

We used FFE-FVS (version 6.21) (Reinhardt and Crookston 2003) to simulate the effects of thinning and surface fuel treatments on potential fire hazard and fire behavior at small spatial scales (tens of hectares). FFE-FVS can simulate a fire or estimate the potential effect of a fire under user-specified weather and fuel conditions. A simulated fire modifies stand and fuels conditions (e.g., kills trees, reduces fuel loading) and alters the trajectory of stand succession and fuel dynamics. FFE-FVS calculations of potential fire effects are conducted before the effects of a fire are simulated.

FFE-FVS is a consolidation of two computer modules, FVS and FFE. FVS is an individual-tree, distance-independent, growth-and-yield model that simulates tree growth, mortality, and the effects of a variety of silvicultural treatments (Dixon 2003). Stands are the basic unit of management, and projections depend on interactions among trees within the stands. Twenty variants have been developed and calibrated to cover most forestlands in the United States (Fig. 1). For example, the Southern Oregon/Northeastern California (SO) variant was fit to data representing forest types (33 species or species groups) in southern Oregon and northeastern California (Keyser 2008). The variant is applicable to a variety of tree species, forest types, and stand structures in the Deschutes, Fremont, Winema, Klamath, Lassen, Modoc, Plumas, Shasta, and Trinity national forests and corresponding Bureau of Land Management and industry lands (Keyser 2008). Data used to develop these equations were derived from numerous forest inventories, silvicultural stand examinations, research plots, and tree plantation studies (Keyser 2008). Major species modeled in the SO variant include western white pine (*Pinus monticola* Dougl. ex D. Don), sugar pine (*Pinus lambertiana* Dougl.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), white fir (*Abies concolor* (Cord. & Glend.) Lindl.), mountain hemlock (*Tsuga mertensiana* (Bong.) Carriere), incense cedar (*Libocedrus decurrens* Torr.), lodgepole pine (*Pinus contorta* Dougl. ex Loud.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), noble fir (*Abies magnifica* Rehd.), and ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.). For this study, we used seven of the 20 FVS variants (Fig. 1) and present the results of two of those variants in detail (with the remaining five in the supplementary material[1]).

FFE simulates snag dynamics and woody fuel accumulation and decomposition through time using fuels information projected by FVS (Reinhardt and Crookston 2003). Fire behavior and crown fire hazard are computed using methods developed by Rothermel (1972), Albini (1976), and Scott and Reinhardt (2001).

Using the stand characteristics, FFE-FVS calculates two indices of crown fire hazard: torching index and crowning index (Table 1). Torching index is the windspeed (kilometres per hour) required for crown fire initiation and crowning index is the windspeed (kilometres per hour) required to support an active crown fire. Lower values of each of these indices indicate increased fire hazard. FFE-FVS also uses the stand data to classify the stand as one of four types of potential fire behavior associated with increasing fire hazard: surface fire, conditional fire, passive crown fire, and active crown fire (Table 1). In a stand classified as potential surface fire, a fire is predicted to spread primarily within the surface fuels (dead branches, leaves, needles, low vegetation). With potential conditional fire, conditions for sustained active crown fire spread are met, but conditions for crown fire initiation are not. In such a stand, FFE-FVS predicts that if the

[1](Supplementary data are available with the article through the journal Web site (http//www.nrcresearchpress.comlcjfr).

Fig. 1. There are 20 total FVS variants, each calibrated separately to a specific geographic area of the United States. We chose seven FFE-FVS variants to evaluate for the current study. The results for the East Cascades and Northern Idaho variants are presented in detail, with the results for the remaining variants presented in supplementary material. 1 mile = 1.61 km.[1]

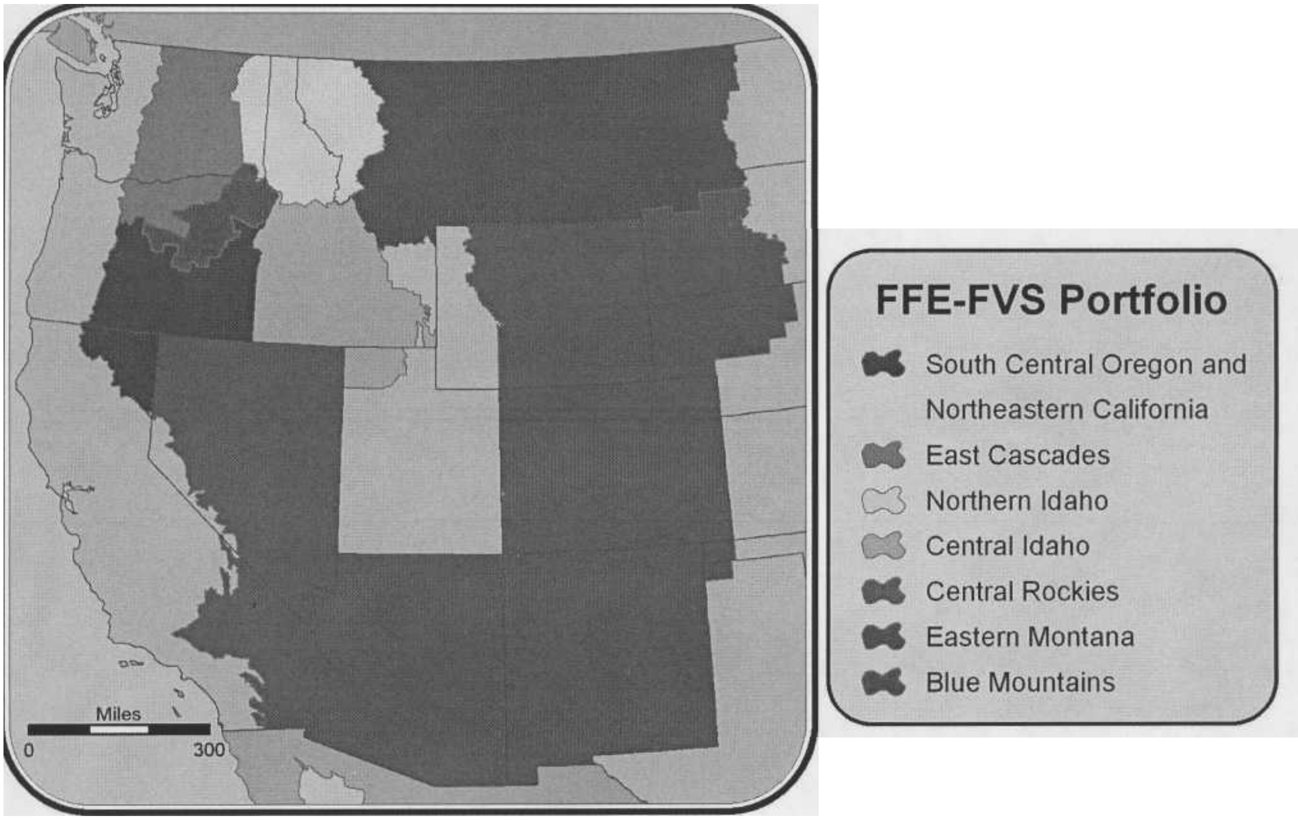


Table 1. The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003) simulates forest growth and potential fire hazard (e.g, torching index) and fire type (e.g., active crown fire) of different vegetation types in the United States.

	Description
Fire hazard	
Torching index	The 6.1 m wind speed (km•h^{-1}) at which a surface fire is expected to ignite the crown layer. This depends on surface fuels, surface fuel moisture, canopy base height, slope steepness, and wind reduction by the canopy
Crowning index	The 6.1 m wind speed (km•h^{-1}) needed to support an active or running crown fire. This depends on canopy bulk density, slope steepness, and surface fuel moisture content
Potential fire type	
Surface fire	Spreads primarily within the surface fuels
Conditional surface fire	Conditions for sustained active crown fire spread are met, but conditions for crown fire initiation are not. If the fire begins as a surface fire, then it is expected to remain so. If it begins as an active crown fire in an adjacent stand, then it may continue to spread as an active crown fire
Passive crown fire	Individual or small groups of trees ignite, but solid flaming in the canopy cannot be maintained except for short periods
Active crown fire	The entire fuel complex becomes involved, but the crowning phase remains dependent on heat released from the surface fuels for continued spread

fire begins as an active crown fire in an adjacent stand, it may continue to spread as an active crown fire (Scott and Reinhardt 2001). With potential passive crown fire (torching), a fire is predicted to occur when individual or small groups of trees ignite, but solid flaming in the canopy cannot be maintained except for short periods. In a stand classified as potential active crown fire, FFE-FVS predicts that the entire fuel complex becomes involved in a fire, but the crowning phase remains dependent on heat released from the surface fuels for continued spread (Van Wagner 1977). In this study, we evaluated simulated fuel treatment effects on the predicted torching index and the potential fire type classification.

Fig. 2. Study design. Seven FFE-FVS variants were evaluated in total, with the results for East Cascades and Northern Idaho (shaded) presented here in detail. Results for the remaining variants are presented in the supplementary material.[1] Foreach variant, the pre-treatment fire type and torching index were identified by FFE-FVS for each stand. (a) The stands in each variant were partitioned by their pre-treatment fire types. (b) Twelve combinations of thinning and surface fuel treatments were simulated for each stand in each pre-treatment fire type for each variant (in the example above, there are 800 stands in the Northern Idaho variant classified pre-treatment as potential active fire type). Post-treatment simulated values were change in log torching index (Δti) (eq. 1) and post-treatment potential type (Post-trt fire type). Twenty-eight separate analyses were conducted for each of the response variables (Δti, post-treatment fire type), with the predictor variables of thinning treatment and surface fuel treatment.

(a)

Variant	Pre-treatment fire type Surface	Conditional	Passive	Active
East Cascades	387	1123	276	340
Southern Oregon and Northeastern California	3630	2587	2054	983
Northern Idaho	893	2888	208	800
Central Idaho	463	1311	322	234
Central Rockies	5048	3487	6171	6297
Eastern Montana	201	2233	177	494
Blue Mountains	495	769	557	275

(b)

Stand
1
2
.
.
.
n=800

Surface fuel treatment	Thinning treatment (residual density; trees·ha^{-1}) 750	500	250	125
No action	Δti_{11}	Δti_{12}	Δti_{13}	Δti_{14}
	Post-trt fire type$_{11}$	Post-trt fire type$_{12}$	Post-trt fire type$_{13}$	Post-trt fire type$_{14}$
Extraction	Δti_{21}	Δti_{22}	Δti_{23}	Δti_{24}
	Post-trt fire type$_{21}$	Post-trt fire type$_{22}$	Post-trt fire type$_{23}$	Post-trt fire type$_{24}$
Prescribed fire	Δti_{31}	Δti_{32}	Δti_{33}	Δti_{34}
	Post-trt fire type$_{31}$	Post-trt fire type$_{32}$	Post-trt fire type$_{33}$	Post-trt fire type$_{34}$

Table 2. Weather variables used to estimate fire behavior across all stands pre-treatment and post-treatment and weather parameters used in the simulation of prescribed fire as a surface fuel treatment.

Measurement type	Windspeed (km·h^{-1})	Temperature (°C)	Fuel moisture (%) 1 h (<0.6 cm)	10 h (0.6–2.5 cm)	100 h (2.5–7.6 cm)	1000 h (>7.6 cm)	Duff	Live woody	Live herb
Fire behavior	40	29	3	4	6	10	15	70	70
Prescribed fire*	16	21	12	12	14	25	125	150	150

*Percentage of stand burned equals 75%.

Stand examination data

We downloaded data for 109 227 stands from a relational database that contains measurements collected in the field from national forests (FSVeg). The database contains plot vegetation data from field surveys such as Forest Inventory Analysis data, stand exams, inventories, and regeneration surveys (USDA Forest Service 1992). Of these 109 227 stands, we retained 45 162 (41%) that met the following selection criteria: initial stand density ≥750 trees•ha^{-1} (tph) (corresponding to the least intense thinning treatment in our study), slope ≤30% (standard maximum slope for fuel treatments), and species composition including at least 1% of dry tree species typically dominant in dry forests of the western United States (e.g., *Pinus ponderosa, Pseudotsuga menziesii).* We discarded several stands with low canopy fuels and dominated by hardwoods because FFE-FVS could not calculate fire hazard in these stands. We partitioned the stands into seven of the 20 FFE-FVS variants (Fig. 1): East Cascades, South Central Oregon and Northeastern California, Northern Idaho, Central Idaho, Central Rockies, Eastern Montana, and Blue Mountains. For each stand in each of the seven variants, we used FFE-FVS to predict the initial pre-treatment potential fire behavior type and torching index (Fig. 2a) with the same weather-related variables (e.g., fuel moisture and windspeed) for all variants (Table 2).

Thinning and surface fuel treatments

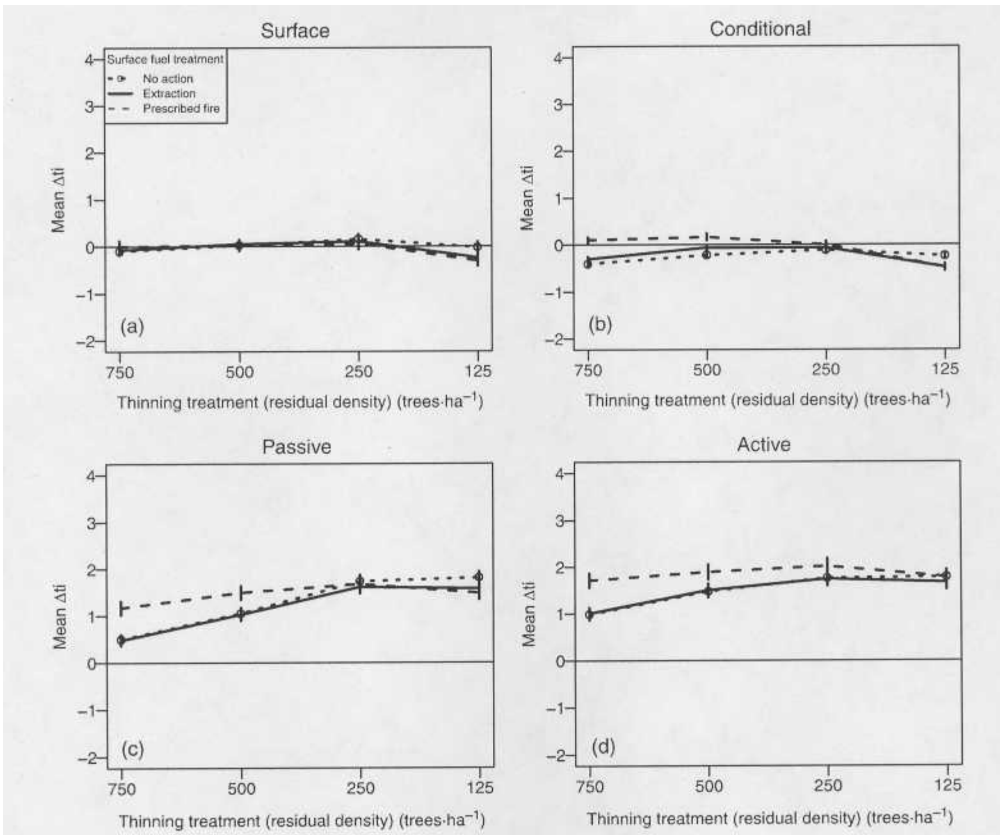
We developed a treatment matrix to emulate Agee and Skinner's (2005) four principles of a fire-safe forest (Fig. 2b). Four thinning treatments and three surface fuel treatments were programmed into FFE-FVS batch processing format for each variant. All four thinning prescriptions were to thin from below to a target residual density: 750, 500, 250, or 125 tph. Only trees up to 46 cm diameter breast height were removed in the simulation. For each thinning density, three surface fuel prescriptions were simulated: no action (all slash remained in the stand), extraction (all slash removed from the stand), and prescribed fire (trees <15 cm left in the stand, trees of 15–46 cm had boles removed and branches left in the stand). Each treatment combination was simulated separately for each stand, and the torching index and potential fire behavior type were recorded for the first year following treatment. We generated an individual FFE-FVS projection for each stand and treatment combination.

Simulation analysis

The simulations performed by FFE-FVS are deterministic, and in our study, we have a nonrandom sample of stand examination data. Therefore, our analysis applies only to the set of stands evaluated and in the context of the simulation model structure. In effect, we have a census of the stands

Fig. 3. Interaction plot showing the mean change in log torching index (Δti) for each combination of thinning (four levels) and surface fuel (three levels) treatments for the East Cascades variant for stands classified pre-treatment as (a) surface, (b) conditional, (c) passive, and (d) active fire types. Vertical lines represent ±2 SE for each treatment combination mean. Note that the x-axis is a categorical variable (thinning treatment) rather than a scalar. All plots are shown on the same y-axis to enable comparison of mean values among pre-treatment fire types. A positive value of mean Δti indicates that torching index increases post-treatment, thereby decreasing fire hazard. The mean Δti increases from the less intense thinning treatment (750 residual trees•ha^{-1}) up to the second most intense thinning treatment (250 residual trees · ha^{-1}) and then levels off or decreases from 250 residual to 125 residual trees•ha^{-1}. Overall, the mean Δti is higher for the prescribed fire surface fuel treatment than for the no action and extraction surface fuel treatments.

East Cascades Pre–treatment Fire Type



available to us that meet our criteria. In our analysis of the simulated results, our conclusions rely on interpretation of how patterns change across the treatment combinations. We make suggestions for how the results may apply more generally to dry forest types of the western United States.

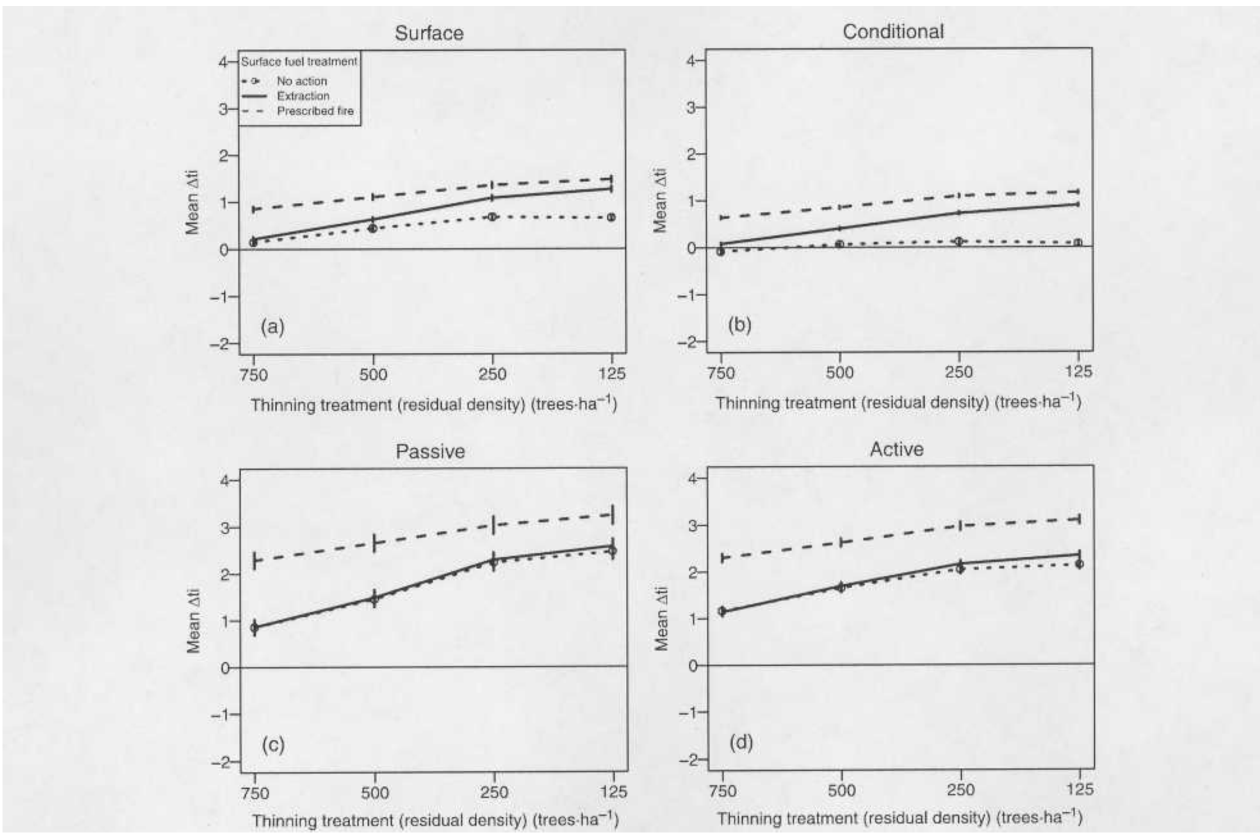
Each FFE-FVS variant uses unique algorithms to simulate fire hazard and fire behavior. We therefore performed a separate analysis for each variant. Furthermore, torching index is one component of the classification of potential crown fire hazard in FFE-FVS, so there will be significant dependence between torching index and potential fire behavior type as well as between pre-treatment and post-treatment fire types. To avoid confounding of those variables, we performed separate analyses for stands in each combination of FFE-FVS variant and pre-treatment fire type, resulting in 28 individual analyses each for torching index and pre-treatment potential fire behavior type (Fig. 2). Simulated effects of the fuel treatments tended to be similar across the variants, with minor deviations. For the sake of brevity, we report in detail on two variants that represent distinct trends in the torching index response to fuel treatment (East Cascades and Northern Idaho). The results from the remaining variants are shown in the supplementary material (Sl and S2[1]).

Torching index

To reduce crown fire hazard, the fuel treatment should increase the torching index relative to the pre-treatment stand condition. The most informative response variable for the purpose of management is the difference between the pre-treatment and the post-treatment torching indices. The value of the torching index is ≥0 and tends to be highly right-skewed, which makes interpretation of mean values and associated standard errors difficult because the mean value is sensitive to outliers. To aid interpretation of mean values, we use a log transformation of torching index (+1 to avoid taking the log of zero). The differences in torching index are also highly right-skewed, and they take both positive and negative values. Rather than log transform the change in torching index (which would require standardizing all values to the positive real line before taking the log, thereby losing

Fig. 4. Interaction plot showing the mean change in log torching index (Δti) for each combination of thinning (four levels) and surface fuel (three levels) treatments for the Northern Idaho variant for stands classified pre-treatment as (a) surface, (b) conditional, (c) passive, and (d) active fire types. Vertical lines represent ±2 SE for each treatment combination mean. Note that the *x*-axis is a categorical variable (thinning treatment) rather than a scalar. All plots are shown on the same v-axis to enable comparison of mean values among pre-treatment fire types. A positive value of mean Δti indicates that torching index increases post-treatment, thereby decreasing fire hazard. The mean Δti increases from the less intense thinning treatment (750 residual trees•ha^{-1}) to the most intense thinning treatment (125 residual trees•ha^{-1}). Overall, the mean Δti is higher for the prescribed fire surface fuel treatment than for the no action and extraction surface fuel treatments. The no action and extraction surface fuel treatments are similar in their mean Δti for stands classified pre-treatment as passive or active.

Northern Idaho Pre-treatment Fire Type



interpretability with respect to whether the post-treatment torching index is greater than the pre-treatment torching index), we choose to take the difference of the log-transformed values. This preserves the direction of the change in torching index (Δti), i.e., whether it is positive or negative:

$$[1] \quad \Delta ti = \log(ti_{post} + 1) - \log(ti_{pre} + 1) = \log[(ti_{post} + 1)/(ti_{pre} + 1)]$$

The use of log transformations in this context allows for the appropriate interpretation of means and standard errors for skewed data. A positive value for Δti means that the log (ti + 1) increases with fuel treatment relative to no treatment, which indicates a decrease in fire hazard. A negative value means that the log(ti + 1) decreases with fuel treatment, indicating that fire hazard worsens after treatment. We separated the data by FFE-FVS variants and classification of potential pre-treatment fire behavior type (surface fire, conditional surface fire, passive crown fire, or active crown fire). We calculated the mean Δti for each treatment combination, which yielded 12 means for each combination of variant and pre-treatment fire behavior type. We plotted the mean Δti across stands with changing thinning intensity and for each surface fuel treatment to evaluate differences in mean Δti among the treatment combinations (Figs. 3 and 4). We also report the group means for each treatment combination and calculate the standard error for each cell mean, which are included in the mean plots. In this case, the change in torching index is predicted by the combination of thinning and surface fuel treatment.

Classification of post-treatment potential fire type

Fire managers are concerned with designing and implementing treatments to change potential fire behavior. Although torching index is a component of the classification of potential fire type, a change in the torching index alone does not necessarily explain whether the potential fire behavior type (i.e., fire type predicted if a fire were simulated) will be effectively changed. We calculated the proportion of stands classified by FFE-FVS in each potential fire behavior type after treatment for each treatment combination. For example, suppose that 1000 stands classified pre-treatment as active fire type are evaluated. After treatment, suppose 300 (0.30) of those are still classified post-treatment as potential active crown fire (the treatment did not change their classification), 250 (0.25) as potential passive crown fire (the treatment marginally reduced their hazard classification), 250 (0.25) as potential conditional fire, and 200 (0.20) as potential surface fire (the treatment effectively reduced their hazard classification from potential active type to potential surface type).

The stands of greatest concern for the manager are those classified pre-treatment as potential active fire type. Across those stands, we calculated the proportion classified post-treatment in each of the four potential fire types. We compared those proportions across each combination of thinning and surface fuel treatment and calculated standard errors for the proportion for each treatment combination. This allows us to evaluate how the proportions change with each treatment combination for each FFE-FVS variant. An effective treatment would result in a lower proportion of stands that are classified pre-treatment as potential active type and remain classified post-treatment as potential active type. An effective treatment would also result in a higher proportion of stands that transition post-treatment to potential surface type. For this analysis, the proportion of stands classified post-treatment into each of the possible potential fire types is predicted by the combination of thinning and surface fuel treatment.

Results

Torching index

There are clear differences among the thinning and surface fuel treatments in predicting mean Δti for each of the seven FFE-FVS variants and four pre-treatment fire types (see Table 3 for cell means for the East Cascades and Northern Idaho variants and supplementary material S1[1] for the remaining variants). For stands with pre-treatment surface or conditional fire type, we observed two separate trends for thinning and surface fuel treatments in the seven variants. These two trends were represented by the East Cascades and Northern Idaho variants. For the East Cascades variant, FFE-FVS predicted that the mean Δti tended to be near zero regardless of the fuel treatment combination (Figs. 3a and 3b). This response suggests that, in the East Cascades variant for stands classified pre-treatment as surface or conditional surface fire, fuel treatments tend not to change the torching index. We observed this trend in all variants except Northern Idaho. For the Northern Idaho variant, FFE-FVS predicted that the mean Δti tended to be above zero for all surface and conditional fire stands (Figs. 4a and 4b). This trend indicates that all of the treatment combinations increased the mean Δti, thereby increasing the torching index and improving fire hazard.

For stands with pre-treatment passive or active fire type, FFE-FVS generated similar responses to thinning treatments. Overall, all of the treatment combinations increased mean Δti in the East Cascades and Northern Idaho variants. For both variants, the more intense thinning treatments (125 and 250 trees•ha^{-1}) had a greater Δti than did the less intense thinning treatments (500 and 750 trees•ha^{-1}) (Figs. 3c, 3d, 4c, and 4d). In the East Cascades variant, the mean Δti increased from the 750 to the 250 trees • ha^{-1} thinning treatment and then either leveled off or decreased from the 250 to the 125 trees • ha^{-1} thinning treatment (Figs. 3c and 3d). However, in the Northern Idaho variant, the mean Δ ti increased as thinning intensity increased and did not level off or decrease from the 250 to the 125 trees • ha^{-1} thinning treatment. The two trends observed in the East Cascades and Northern Idaho were also found in the other variants.

We observed unanticipated responses to the surface fuel treatments. In the East Cascades and Northern Idaho variants, we again observed two distinct trends to surface fuel treatments, one from prescribed fire and the other from no action and extraction. Overall, prescribed fire was most effective at increasing mean Δti. In the East Cascades variant, FFE-FVS predicted a higher mean Δti for prescribed fire at the less intense thinning treatments (500 and 750 trees•ha^{-1}) for all of the pre-treatment fire type classifications except surface (Figs. 3a and 3b). The mean Δti for the no action and extraction surface fuel treatments was similar for all thinning treatments (Figs. 3a and 3b). For the intense thinning treatments (125 and 250 trees•ha^{-1}), the mean simulated Δti was similar among the surface fuel treatments across the pre-treatment fire type classifications (Fig. 3). In the Northern Idaho variant, prescribed fire produced the highest mean Δti regardless of thinning intensity and across all of the pre-treatment fire type classifications (Fig. 4). No action and extraction treatments were similar for the passive and active pre-treatment fire type classifications (Figs. 4c and 4d) but not for the surface and conditional pre-treatment fire type classifications (Figs. 4a and 4b). For plots of mean Δti for the remaining five variants, see supplementary material S1[1].

Classification of post-treatment potential fire type

There are clear differences among the thinning and surface fuel treatments in predicting the post-treatment potential fire type for stands classified pre-treatment as active crown fire type. For the stands classified pre-treatment as active crown fire type, we present in detail the results for the East Cascades and Northern Idaho variants. For the results of the remaining variants, see supplementary material S2[1].

FFE-FVS predicted that the proportion of stands classified post-treatment as potential active fire type decreased with intense thinning treatment (decreasing residual trees per hectare) (Figs. 5d and 6d). The proportion of each post-treatment fire type with varying thinning intensity was similar for the no action and extraction surface fuel treatments (Figs. 5 and 6; see supplementary material S2[1]).

The effects of surface fuel treatments on the proportion of stands classified post-treatment in each of the fire type classifications were similar to surface fuel treatment effects observed on mean Δti. Prescribed fire was the most effective treatment for decreasing the proportion of active crown fire stands (Figs. 5d and 6d). The proportion of stands classified by FFE-FVS post-treatment as potential active fire type was zero for the combination of prescribed fire and less intense thinning treatments (750 and 500 residual trees•ha^{-1}). The effect of no action and extraction surface fuel treatment on the proportion of stands classified post-treatment as active fire type was nearly identical for all variants (Figs. 5d and 6d).

Table 3. Cell mean values of change in log torching index (Δti) for the East Cascades and Northern Idaho variants, with stands partitioned by the pre-treatment fire types.

		Thinning treatment (residual density, trees·ha^{-1})							
		East Cascades				Northern Idaho			
Pre-treatment fire type	Surface fuel treatment	750	500	250	125	750	500	250	125
Surface	No action	–0.106	0.024	0.150	–0.022	0.137	0.432	0.672	0.652
	Extraction	–0.080	0.052	0.104	–0.242	0.206	0.620	1.080	1.260
	Prescribed fire	–0.002	0.026	0.058	–0.308	0.846	1.100	1.350	1.470
Conditional	No action	–0.407	–0.222	–0.122	–0.242	–0.095	0.058	0.111	0.069
	Extraction	–0.302	–0.067	–0.064	–0.483	0.069	0.395	0.721	0.890
	Prescribed fire	0.096	0.162	–0.005	–0.483	0.631	0.845	1.080	1.160
Passive	No action	0.497	1.050	1.730	1.810	0.851	1.450	2.230	2.470
	Extraction	0.478	1.020	1.610	1.570	0.854	1.480	2.290	2.580
	Prescribed fire	1.170	1.490	1.670	1.480	2.290	2.650	3.030	3.240
Active	No action	0.983	1.470	1.760	1.780	1.160	1.650	2.040	2.130
	Extraction	0.999	1.500	1.740	1.660	1.130	1.680	2.150	2.340
	Prescribed fire	1.710	1.890	2.010	1.780	2.300	2.620	2.970	3.100

Note: Each value is the mean across stands for each thinning and surface fuel combination for each variant and pre-treatment fire type.

Fig. 5. Proportion of stands for the East Cascades variant that are classified pre-treatment as active fire type and classified post-treatment as (a) surface, (b) conditional, (c) passive, and (d) active fire types for each combination of thinning (four levels) and surface fuel (three levels) treatments. Vertical lines represent ±2 SE for each treatment combination proportion. Note that the x-axis is a categorical variable (not a scalar). The proportion of stands classified post-treatment as potential active fire type is indistinguishable between the no action and extraction surface fuel treatments and is near zero for all thinning intensities for the prescribed fire surface fuel treatment. For the no action and extraction surface fuel treatments, the proportion of stands classified post-treatment as potential active fire type declined from the less intense thinning treatment (750 residual trees•ha^{-1}) to the most intense thinning treatment (125 residual trees•ha^{-1}).

East Cascades Pre–treatment Active Fire Type

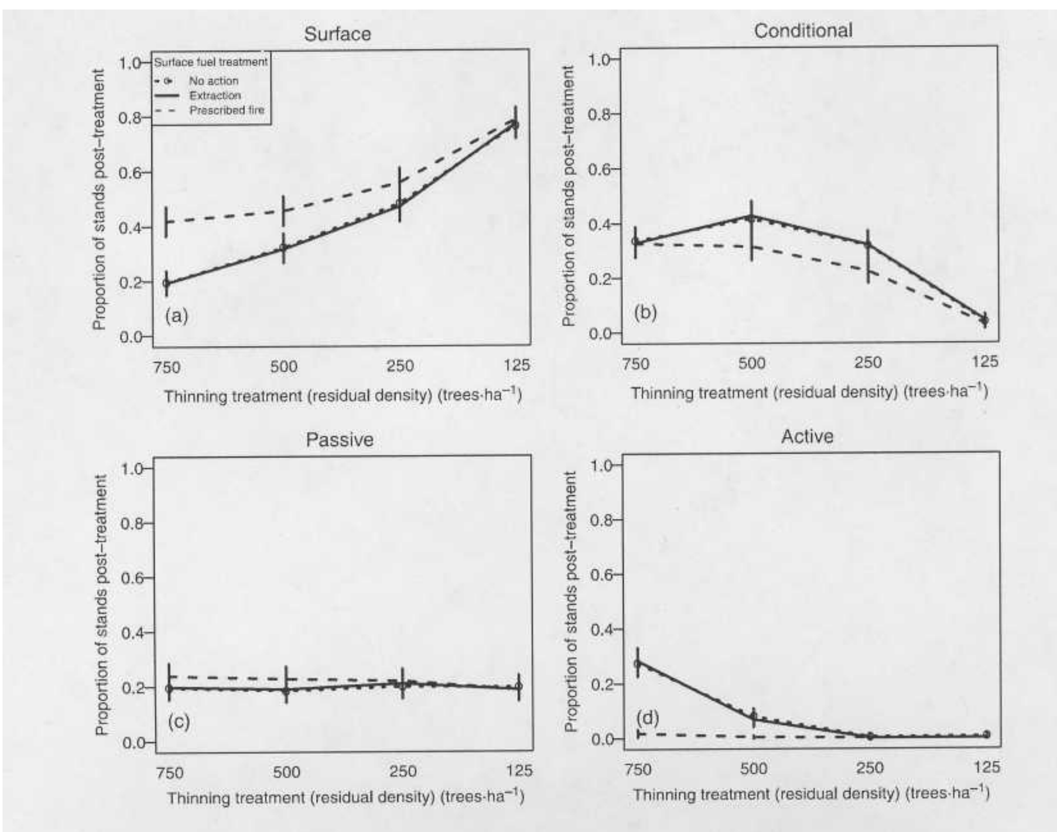
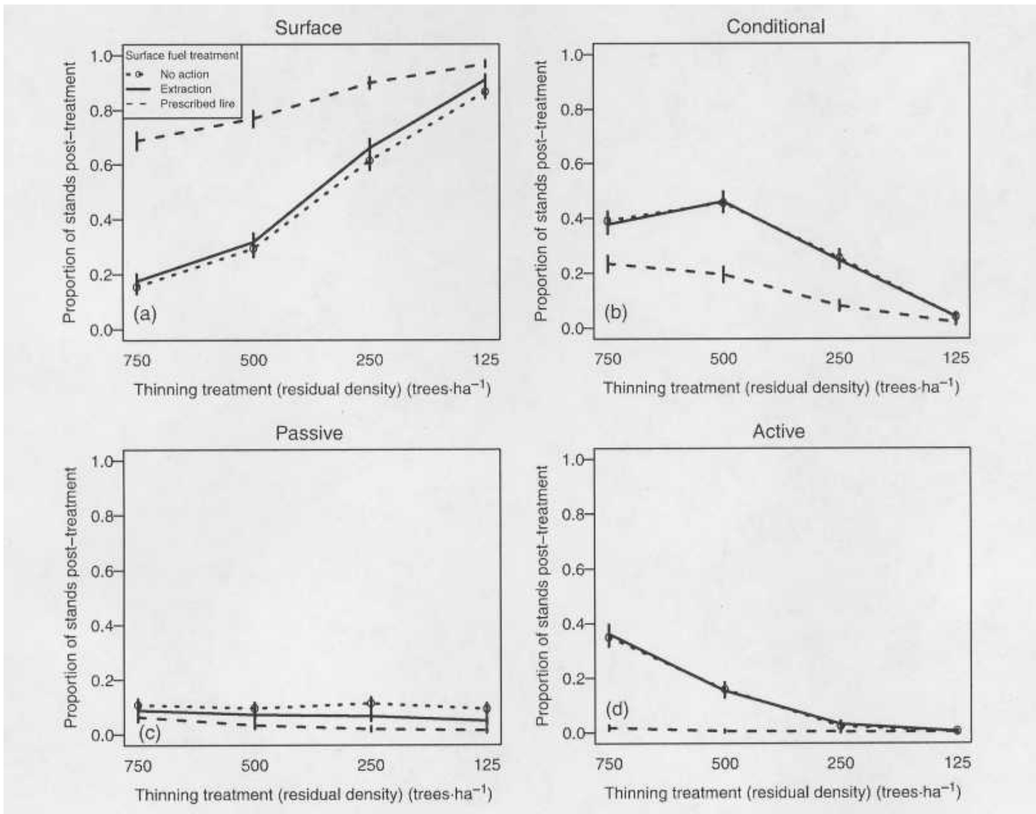


Fig. 6. Proportion of stands for the Northern Idaho variant that are classified pre-treatment as active fire type and classified post-treatment as *(a)* surface, *(b)* conditional, (c) passive, and (d) active fire types for each combination of thinning (four levels) and surface fuel (three levels) treatments. Vertical lines represent ±2 SE for each treatment combination proportion. Note that the x-axis is a categorical variable (not a scalar). The proportion of stands classified post-treatment as potential active fire type is indistinguishable between the no action and extraction surface fuel treatments and is near zero for all thinning intensities for the prescribed fire surface fuel treatment. For the no action and extraction surface fuel treatments, the proportion of stands classified post-treatment as potential active fire type declined from the less intense thinning treatment (750 residual trees•ha^{-1}) to the most intense thinning treatment (125 residual trees•ha^{-1}).

Northern Idaho Pre-treatment Active Fire Type



These general patterns were similar across all seven variants (see supplementary material S2').

Discussion

Crown fire hazard and fire behavior

The results of our study are consistent with findings from other computer simulations and post-fire empirical studies that support the efficacy of fuel treatments for reducing crown fire hazard and severity in dry forest types across the western United States (Agee et at. 2000; Raymond and Peterson 2005; Stephens and Moghaddas 2005; Cram et al. 2006). FFE-FVS predicted that fuel treatment efficacy (indicated by a positive Δti and a transition from potential active fire to potential surface fire) was contingent on thinning treatment intensity. The intense thinning treatments (125 and 250 trees•ha^{-1}) were more effective than the less intense treatments (500 and 750 trees•ha^{-1}) in reducing fire hazard because these resulted in the greatest positive change in torching index (Figs. 3 and 4) and the greatest proportion of stands classified post-treatment as surface fire type (Figs. 5a and 6a). There were two distinct trends predicted between the East Cascades and Northern Idaho variants. In the East Cascades variant, the fuel treatment combinations decreased fire hazard only in stands classified pre-treatment as potential passive and active fire types (Fig. 3), as indicated by the near zero change in mean torching index for the surface and conditional pre-treatment fire type classifications and the positive change in mean torching index for the active and passive pre-treatment fire type classifications. In contrast, in the Northern Idaho variant, fuel treatments decreased fire hazard for stands classified in all of the pre-treatment potential fire types (Fig. 4), as indicated by the positive mean change in torching index.

These predictions by FFE-FVS for the stands that we evaluated should not be surprising because they validate the obvious conclusion that stands classified as potential surface and conditional fire types should have a low priority for treatments. The fuelbed characteristics of stands with surface and conditional fire type (low fuel loads, high canopy base height) prevent crown fire initiation, reduce fireline intensity, and reduce fire behavior. However, thinning treatments may sometimes be warranted in stands classified as conditional surface lire because the structural characteristics of these

Table 4. Fire behavior and fuel model assignments after thinning and surface fuel treatments (i.e., no action, extraction, and prescribed fire).

Response variable	Pretreatment	Thin to 125 trees·ha^{-1}			Thin to 250 trees·ha^{-1}		
		No action	Extraction	Prescribed fire	No action	Extraction	Prescribed fire
Crowning index (km·h^{-1})	24	48	48	53	34	34	39
Torching index (km·h^{-1})	17	155	69	51	173	116	93
Flame length (m)	140	6.6	9.2	9.2	7	8	9
Canopy base height (m)	3	37	37	37	36	36	36
Canopy bulk density (kg·m^{-3})	0.15	0.06	0.06	0.05	0.11	0.11	0.09
FFE-FVS fuel models	9 (82%) 10 (18%)	11 (62%) 5 (21%) 10 (15%) 1 (2%)	5 (92%) 1 (8%)	5 (78%) 1 (22%)	11 (45%) 5 (43%) 10 (11%) 8 (1%)	5 (91%) 10 (0.07) 8 (3%)	5 (100%)
Fire type	Active	Surface	Surface	Surface	Conditional	Conditional	Conditional

Note: The example is for an active fire type stand from the East Cascade FFE-FVS variant. Numbers in parentheses represent the weighted average of the NFFL fuel model (Albini 1976; Rothermel 1972) used to calculate fire behavior. The dynamic model approach in FFE-FVS selects two or more fuel models based on fuelbed characteristics, calculates the resulting fire behavior model for each model, and then takes a weighted average of the result.

stands (e.g., high canopy bulk density) can support and sustain an active crown fire (Scott and Reinhardt 2001). For example, stands characterized by conditional fire type in and around urban interface zones may be ideal for treatments designed to increase stand heterogeneity by reducing overstory continuity and canopy bulk density.

FFE-FVS predicts that thinning intensity influences fuel treatment efficacy in the stands that were evaluated. The more intense thinning treatments (125 and 250 trees•ha^{-1}) were predicted to be more effective than the less intense treatments (500 and 750 trees•ha^{-1}) in increasing mean Ati for stands classified pre-treatment as active or passive fire types (Figs. *3c, 3d, 4c,* and *4d)* and increasing the proportion of stands that transition from potential active fire type to potential surface fire type (Figs. 5a and 6a). In the simulation, more intense thinning treatments are associated with the removal of more ladder fuels and an increase in the vertical distance between the ground and the base of the live canopy (Van Wagner 1977; Agee 1996). The residual stand densities defined by the more intense thinning treatments are consistent with reconstructions of historical stand structures. Arno and Allison-Bunnell (2002) suggested that historical surface fire regimes perpetuated ponderosa pine dominated stands with 74-250 trees•ha^{-1}. Harrod et al. (1999) concluded that 125 trees•ha^{-1} represented historical stands in eastern Washington, and Covington and Moore (1994) proposed that 106 trees•ha^{-1} was typical for southwestern stands.

Implementing the most intense thinning treatments (125 and 250 trees•ha^{-1}) would require a major shift in stand structure compared with t'aditional stand prescriptions. Forest managers would need to design thinning treatments to increase the spacing between residual trees. For example, thinning prescriptions designed to retain 125 or 250 trees•ha^{-1} are equivalent to spacing between trees of 9 m x 9 m or 6 m x 6 m, respectively. In a stand with 1683 trees•ha^{-1}, the spacing between trees would be 2.4 m x 2.4 m; this spacing would triple or quadruple with the intense thinning treatment. Some forest and fire managers are already experimenting with treatments to increase the spacing between residual trees. Managers with the US Bureau of Land Management Medford district in southern Oregon are designing and implementing fuel projects with 8 m x 8 m residual spacing to adequately reduce fire hazard (Medford District Bureau of Land Management 2008).

The results from our simulation predict that the intense thinning treatments reduce fire hazard. In the field, the 125 and 250 trees•ha^{-1} thinning specifications may have unintended consequences for fuelbed characteristics and environmental variables that could increase wildfire behavior and fireline intensity. For example, the rapid release of growing space may stimulate ladder fuels (shrub and herb regeneration), increase surface windspeed, reduce dead fuel moistures, and increase surface fire intensity (Agee 1996; van Wagtendonk 1996). Regardless of these negative effects, the post-treatment forest structure should reduce crown fire initiation and fire severity (Agee 1996; Graham et al. 2004).

Surface fuel treatment effects

The FFE-FVS model predicts that for the less intense thinning treatments (500 and 750 trees•ha^{-1}), the prescribed fire surface fuel treatment tended to increase mean torching index relative to the no action and extraction surface fuel treatments (Figs. 3 and 4). This treatment also reduced the proportion of stands that are classified post-treatment as potential active fire type (Figs. 5 and 6) relative to the extraction and no surface fuel treatment; those two treatments exhibited similar responses with respect to fire hazard. In the field, prescribed fire modifies potential fire behavior by reducing fuel loads, duff and litter depths, and shrubs (Graham et al. 2004; Moghaddas and Stephens 2007). In high-density stands, prescribed fire can indirectly raise the canopy base height of a stand. In FFE-FVS, prescribed fire is simulated to reduce surface fuel loads and to raise the canopy base height of the stand through conventional heating (crown scorch). As a result, the prescribed fire surface fuel treatment is shown as the most effective option even at the less intense thinning treatments.

FFE-FVS predicted that, in the East Cascades variant, the fire hazard response was more similar among the three possible surface fuel treatments at the two more intense thinning treatments (125 and 250 trees•ha^{-1}) than at the two less intense thinning treatments (500 and 750 trees•ha^{-1}) (Figs. 3 and 5). In the Northern Idaho variant, fire hazard was lower for prescribed fire than for no action and extraction surface fuel treatments across the thinning treatment intensities (Figs. 4 and 6). According to these results, FFE-FVS considers that in some regions and regardless of surface fuel treatments, the reduction in canopy bulk density and increase in canopy base heights from the more intense thinning treatments are sufficient to reduce crown fire hazard without associated surface fuel treatment.

One of the principles of a fire-safe forest advocated by Agee and Skinner (2005) is to reduce surface fuels generated from thinning treatments. Reducing surface fuels following thinning treatments can reduce fireline intensity (potential flame length) and crown fire initiation. Crown fires occur when surface fires create enough energy to preheat and combust live canopy fuels. Several studies have shown that fireline intensity in thinned stands was significantly reduced only when treatments were accompanied by reducing the surface fuels (Graham et al. 1999; Stephens et al. 2009). In contrast, we found that FFE-FVS tended to predict no difference between the extraction and no action surface fuel treatment (Figs. 3-6). In many cases, the responses were similar across the surface fuel treatments for the thinning treatments that probably generated the highest slash loads (125 and 250 trees•ha^{-1}). The similarity among these responses contradicts our current understanding of fuel quantity and fire behavior. We would expect the most effective surface fuel treatments to be prescribed fire, extraction, and no action, respectively. It is possible that a limitation of the FFE-FVS model, described below, explains this discrepancy.

Model and study limitations

The FFE-FVS documentation outlines a number of limitations that present opportunities for model improvement, one of which is illustrated by the current study. The simulation results presented here imply that for the intense thinning treatments (125 and 250 trees•ha^{-1}), the effect of thinning on fire behavior without surface fuel treatments is equivalent to the effects of the extraction and prescribed fire surface fuel treatments. These nonintuitive response patterns are probably due to how FFE-FVS assigns fuel models to calculate fire behavior. Rather than use measured fuel loadings (Ottmar et al. 2007), FFE-FVS relies on a limited set of 13 National Forest Fire Laboratory stylized fuel models that represent fire behavior in homogeneous surface fuels (Rothermel 1972). These 13 fuel models may therefore limit the capability of the model to differentiate the effects of varying surface fuel treatments.

The FFE-FVS developers understood the potential limitations of using 13 fuel models to predict fire behavior for different management scenarios, and they tried to improve fire behavior calculations by designing a dynamic modeling approach. In the logic of this approach, one or more fuels are selected, the fireline intensity is calculated for each one, and a weighted average flame length is then computed by interpolation. The FFE-FVS dynamic modeling approach was designed to simulate a continuous transition in fire behavior instead of the ordinal-type transition that would occur between fire behavior fuel models (Reinhardt and Crookston 2003).This logic is reasonable, but it does not overcome the limitations of the small set of available fuel models to represent the effects of the surface fuel treatments. In our simulations, when extraction and prescribed fire surface fuel treatments were implemented, the model recognized the fuelbed modification and then selected a set of new fuel models. In many cases, FFE-FVS selected the identical fuel model or a combination of fuel models following different surface fuel treatments (Table 4). The selection of multiple fuel models masks any change in fire behavior that might be expected from the surface fuel treatments.

FFE-FVS is an evolving and dynamic tool for fire and forest managers. In the near future, the logic of fuel model selection will be restructured to incorporate Scott and Burgan's (2005) 40 fuel models, developed to represent a broader diversity of fuels and fire behavior (Dixon 2003). When this update is completed, the FFE-FVS model may be more sensitive to calculating the effect of surface fuel treatments. The capability to use actual fuel loading to directly simulate fire behavior (e.g., Ottmar et al. 2007) would potentially reduce the lack of precision now associated with fuel model assignment in FFE-FVS.

Forest and fire managers have many other questions about the efficacy of fuel treatments. What is the longevity of the fuel treatments in various forest types? Is there a threshold at which stand conditions become hazardous that could be used to guide fuel treatments? Most analyses, including our own, do not address these types of questions. To evaluate such questions, we would need to project our data through time. For this reason, we contemplated performing 50-year stand projections for each region to monitor changes in fire hazard. However, we decided against doing so because of the large number of assumptions that we would have had to incorporate into the model projections. For example, our main concern was estimating the density of seedling regeneration and mortality rates after each thinning and surface fuel treatment. We would need to develop different regeneration matrices (regeneration densities) for each region, for each thinning density (125, 250, 500, and 750 trees•ha^{-1}), and for each surface fuel treatment (leave slash, remove slash, and prescribe burn). As the FFE-FVS model evolves, we expect answers regarding the longevity of fuel treatment to become available.

Conclusions

Fuel treatment planning and management decisions are based on different considerations and encompass an array of choices available to policymakers and land managers. Credible scientific evidence is critical to understanding and informing those choices (Guldin et al. 2003). As demonstrated in this study, simulation modeling has the capability to examine a broad range of treatment options and a large number of forest stand conditions in diverse geographic locations. However, simulation results are limited in their scope of inference and are bounded by the limitations of the modeling system; they are not a substitute for strong empirical evidence (Peterson et al. 2005). Additional data that validate the effectiveness of fuel treatments in the field, combined with simulation modeling, will provide greater confidence for developing fuel treatment prescriptions.

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References

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C.

Agee, J.K. 1996. The influence of forest structure on fire behavior. *In* Proceedings of the 17th Annual Forest Vegetation Management, 16–18 January 1996, Redding, Calif. Shasta County Cooperative Extension, University of California, Redding, Calif. pp. 52–68.

Agee, J.K., and Skinner, C.N. 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manag. 211(1–2): 83–96. doi:l0.101 6/j. foreco.2005.0 1.034.

Agee, J.K., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N., van Wagtendonk, J.W., and Weatherspoon, C.P. 2000. The use of shaded fuelbreaks in landscape fire management. For. Ecol. Manag. 127(1–3): 55–66. doi:10.1016/S0378-I 127(99) 00116-4.

Albini, F.A. 1976. Estimating wildfire behavior and effects. U.S. For. Serv. Gen. Tech. Rep. INT-GTR-30.

Arno, S.F., and Allison-Bunnell, S. 2002. Flames in our forest: disaster or renewal? Island Press, Washington, D.C.

Biswell, H.H. 1959. Man and fire in ponderosa pine in the Sierra Nevada of California. Sierra Club Bull. 44: 44–53.

Bonnicksen, T.M., and Stone, E.P. 1982. Reconstruction of a pre-settlement giant sequoia-mixed conifer forest community using the aggregation approach. Ecology, 63(4): 1134–1148. doi:10.2307/ 1937250.

Calkin, D.E., Hummel, S.S., and Agee, J.K. 2005. Modeling trade-offs between fire threat reduction and late-sera] forest structure. Can. J. For. Res. **35(1** I): 2562–2574. doi:10. 1139/x05-177.

Covington, W.W., and Moore, M.M. 1994. Southwestern ponderosa forest structure: changes since Euro-American settlement. J. For. 92: 39–44.

Cram, D.D., Baker, T.T., and Boren, J.C. 2006. Wildland fire effects in silviculturally treated vs. untreated stands of New Mexico and Arizona. U.S. For. Serv. Res. Pap. RMRS-RP-055.

Dixon, G.E. 2003. Essential FVS: a user's guide to the Forest Vegetation Simulator. U.S. For. Serv. Int. Rep. (last revised: 7 April 2009).

Dodge, M. 1972. Forest fuel accumulation: a growing problem. Science, 177(4044): 139–142. doi:10.1126/science. 177.4044.139. PMID:17779906.

Fiedler, C.E., Keegan, C.E., Woodall, C.W., Morgan, T.A., Robertson, S.H., and Chmelik, J. 2001. A strategic assessment of fire hazard in Montana. Report submitted to the National Joint Fire Sciences Program, Boise, Id.

Finney, M.A., and Cohen, J.D. 2003. Expectation and evaluation of fuel management objectives. In Proceedings of the Conference on the Fire, Fuel Treatments, and Ecological Restoration, 14–17 April 2003, Fort Collins, Co. *Technical Editors:* R.N. Omi and L.A. Joyce. U.S. For. Serv. Proc. RMRS-P-29. pp. 353–366.

Finney, M.A., Seli, R.C., McHugh, C.W., Ager, A.A., Bahro, B., and Agee, J.K. 2006. Simulation of long-term landscape-level fuel treatment effects on large wildfires. In Proceedings of the Conference on Fuels Management — How to Measure Success, 28–30 March 2006, Portland, Ore. U.S. For. Serv. RMRS-P-41. pp. 125–147.

Graham, R.T., Harvey, A.E., Jain, T.B., and Tonn, J.R. 1999. The effects of thinning and similar stands treatments on tire behavior in western forests. U.S. For. Serv. Gen. Tech. Rep. PNW-GTR-463.

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

Guldin, J.M., Cawrse, D., Graham, R., Hemstrom, M., Joyce, L., Kessler, S., McNair, R., Peterson, G., Shaw, C.G., Stine, P., Twery, M., and Walter, J. 2003. The science consistency review: a tool to evaluate the use of scientific information in land management decisionmaking. U.S. For. Serv. Pub]. FS-772.

Harrod, R.J., McRae, B.H., and Hart], W.E. 1999. Historical stand reconstruction in ponderosa pine forests to guide silvicultural prescriptions. For. Ecol. Manag. 114(2–3): 433–446. doi:10.1016/ S0378-1127(98)00373-9.

Hessburg, P.F., and Agee, J.K. 2003. An environmental narrative of Inland Northwest United States forests, 1800–2000. For. Ecol. Manag. 178(1–2): 23–59. doi: 10.1016/S0378-1127(03)00052-5.

Hessburg, P.F., Agee, J.K., and Franklin, J.F. 2005. Dry forests and wildland fires of the Inland Northwest USA: contrasting the landscape ecology of the pre-settlement modern eras. For. Ecol. Manag. 211(1–2): 117–139. doi:10.1016/j.foreco.2005.02.016.

Johnson, M.C., Peterson, D.L., and Raymond, C.L. 2007. Guide to fuel treatments in dry forests of the western United States: assessing forest structure and fire hazard. U.S. For. Serv. Gen. Tech. Rep. PNW-GTR-686.

Keyser, C.E. 2008. South Central Oregon and Northeast California (SO) variant overview — Forest Vegetation Simulator. Intern. Rep. Fort Collins, Co. U.S. Department of Agriculture, Forest Service, Forest Management Service Center (revised 29 July 2010).

Laudenslayer, W.F., Darr, H.H., and Smith, S. 1989. Historical effects of forest management practices on eastside pine communities in northeastern California. U.S. For. Serv. Gen. Tech. Rep. RM-GTR-185.

MacCleery, D.W. 1995. The way to a healthy future for national forest ecosystems in the west: what role can silviculture and prescribed fire play? U.S. For. Serv. Gen. Tech. Rep. RM-GTR-267.

Medford District Bureau of Land Management. 2008. Ranch Stew categorical exclusion documentation. OR115-09-02. Available from http://www.blm.gov/or/districts/mcdford/plans/files/1150902.pdf.

Moghaddas, E., and Stephens, S.L. 2007. Thinning, burning, and thin-burn fuel treatment effects on soil properties in a Sierra Nevada mixed-conifer forest. For. Ecol. Manag. 250(3): 156—166. doi:10.1016/j.foreco.2007.05.0 I I .

Ottmar, R.D., Sandberg, D.V., Riccardi, C.L., and Prichard, S.J. 2007. An overview of the fuel characteristic classification system — quantifying, classifying, and creating fuelbeds for resource planning. Can. J. For. Res. 37(12): 2383—2393. doi:10.1139/X07-077.

Parsons, D.J., and DeBenedetti, S. 1979. hnpact of fire suppression on a mixed-conifer forest. For. Ecol. Manag. 2: 21—33. doi:10.1016/0378-1127(79)90034-3.

Peterson, D.L., Johnson, M.C., Agee, J.K., Jain, T.B., McKenzie, D., and Reinhardt, E.D. 2005. Forest structure and fire hazard in dry forests of the western United States. U.S. For. Serv. Gen. Tech. Rep. PNW-GTR-628.

Pollet, J., and Omi, P.N. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. Int. J. Wildland Fire, 11(1): 1—10. doi:10.1071/WF01045.

Raymond, C.L., and Peterson, D.L. 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Can. J. For. Res. 35(12): 2981—2995. doi:l0.l 139/x05-206.

Reinhardt, E.D., and Crookston, N.L. 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. U.S. For. Serv. Gen. Tech. Rep. RMRS-GTR-1 16.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. U.S. For. Serv. Res. Pap. INT-115.

Schmidt, D.A., Taylor, A.H., and Skinner, C.N. 2008. The influence of fuels treatment and landscape arrangement on simulated fire behavior, Southern Cascade range, California. For. Ecol. Manag. 255(8—9): 3170—3184. doi:10.1016/j.forcco.2008.01.023.

Scott, J.H., and Burgan, R.E. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. U.S. For. Serv. Gen. Tech. Rep. RMRS-GTR-153.

Scott, J.H., and Reinhardt, E.D. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. U.S. For. Serv. Res. Pap. RMRS-RP-29.

Skog, K.E., Barbour, R.J., Abt, K.L., Bilek, E.M., Burch, F., Fight, R. D, Hugget, R.J., Miles, P.D., Reinhardt, E.D., and Shepperd, W.D. 2006. Evaluation of silvicultural treatments and biomass use for reducing fire hazard in western states. U.S. For. Serv. Res. Pap. FPL-RP-634.

Stephens, S.L., and Moghaddas, J.J. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. For. Ecol. Manag. 215(1—3): 21—36. doi:10.1016/j.foreco.2005.03.070.

Stephens, S.L., Moghaddas, J.J., Edminster, C., Fiedler, C.E., Haase, S., Harrington, M., Keeley, J.E., Knapp, E.E., McIver, J.D., Metlen, K., Skinner, C.N., and Youngblood, A. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests. Ecol. Appl. 19(2): 305—320. doi:10.1890/07-1755.1. PMID:19323192.

Taylor, A.H., and Skinner, C.N. 1998. Fire history and landscape dynamics in late-successional reserve, Klamath Mountains, California USA. For. Ecol. Manag. 111(2—3): 285—301. doi:10.1016/S0378-1127(98)00342-9.

USDA Forest Service. 1992. Natural resource information system: field sampled vegetation: common stand exam user guide. Available from http://www.fs.fed.us/emc/nris/products/fsveg/.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7(1): 23—34. doi:10.1139/x77-004.

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

Weaver, H. 1943. Fire as an ecological and silvicultural factor in the ponderosa pine region of the Pacific slope. J. For. 41: 7-14.