Simulating Fire and Forest Dynamics for a Landscape Fuel Treatment Project in the Sierra Nevada

Brandon M. Collins, Scott L. Stephens, Gary B. Roller, and John J. Battles

Abstract: We evaluated an actual landscape fuel treatment project that was designed by local US Forest Service managers in the northern Sierra Nevada. We modeled the effects of this project on reducing landscape-level fire behavior at multiple time steps, up to nearly 30 years beyond treatment implementation. In addition, we modeled planned treatments under multiple diameter-limited thinning scenarios to assess potential impacts on fuel treatment effectiveness. The planned fuel treatments reduced modeled conditional burn probabilities substantially across the landscape relative to those for a scenario with no simulated treatments. This reduction relative to that for the no treatment landscape was evident approximately 20 years after simulated treatment implementation. Although diameter-limited thinning scenarios resulted in different residual forest stand structures, we detected no real differences in modeled landscape-level burn probabilities. The modeling adaptations we made with respect to fuel model selection and simulated ingrowth/regeneration over simulated time, as well as incorporation of variable winds in fire simulations, collectively contribute to a robust analysis of the study area. FOR. SCI. 57(2):77–88.

Keywords: wildfire modeling, fuels reduction, minimum travel time, fire exclusion

THE COMBINATION OF INCREASED susceptibility of forests to damaging wildland fire (Cooper 1960) and the homogenization of many forested landscapes across the western United States, resulting from fire exclusion policies (Hessburg et al. 2005), necessitate large-scale mitigation efforts. Land management obligations, along with numerous financial, administrative, and operational constraints, inhibit simply implementing such mitigation efforts, or fuel treatments, across entire landscapes (Weatherspoon and Skinner 1996, Stephens and Ruth 2005, Collins et al. 2010). Thus, there is a need to design an arrangement of discrete fuel treatments that collectively contribute to slow fire spread and reduce negative wildland fire effects across the intended landscape (Finney 2001, Ager et al. 2010). Several studies have explored various fuel treatment designs across landscapes, ranging from relatively continuous linear features (Weatherspoon and Skinner 1996, Agee et al. 2000) to regular, dispersed features (Finney 2001) to more complex, optimization algorithm-based treatment deployment (Finney 2007, Finney et al. 2007). Although these and other studies (Ager et al. 2007a, 2007b, Schmidt et al. 2008) compare fuel treatment arrangements and offer suggestions for managers implementing treatments across landscapes, there remains a disconnect between these well-supported theories and actual implementation. This disconnect is a result of area restrictions/constraints on management activities, project appeals, and lack of expertise to assemble necessary data and run models (Collins et al. 2010, Moghaddas et al. 2010).

In this study we evaluated an actual landscape fuel treatment project (called the Last Chance project) that was designed by local US Forest Service managers on the Tahoe National Forest, California, USA. This project presented an opportunity to analyze potential landscape-scale effects of a typical fuels treatment project in the region. The objectives of the project were to reduce the potential for large and destructive wildfires, and improve forest resilience to other disturbance agents and stressors. We evaluated the effectiveness of this fuel treatment project at reducing landscape-level fire behavior, specifically conditional burn probabilities. To gain insight into the duration of fuel treatment effectiveness, we evaluated burn probabilities for 30 years into the future. We intend this portion of our analysis to provide managers with estimates of landscape-scale fuel treatment longevity, i.e., how often they can expect to either maintain treated areas or establish new fuel treatments. Finney et al. (2007) demonstrated a treatment rate of 2% per year (treating 20% of the landscape every 10 years) results in consistent reductions in fire growth. We intend to compare these findings with those from our own analysis based on a one-time treatment that is simulated into the future.

In response to ongoing debates regarding retention of

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large trees such that forest structure resembles more old forest characteristics, we additionally simulate the Last Chance project treatments by varying the upper tree diameter limit for cutting within the proposed thinning treatments. Stephens and Moghaddas (2005) and North et al. (2009) concluded that removing trees above the range of 25.4 to 40.6 cm (or 10 to 16 in.) dbh is not necessary for attaining fuel management objectives. We investigated three different diameter-limited thinning scenarios, 30.5 cm (12 in.), 50.8 cm (20 in.), and 76.2 cm (30 in.), for potential differences in residual forest stand structure and modeled landscape-scale burn probabilities. These three scenarios reflect the diameter limits imposed in the different Sierra Nevada-wide Forest Service planning documents (US Department of Agriculture 2001, 2004). We hypothesized that thinning only those trees 12 in. and less may not reduce stand susceptibility to fire, particularly at higher flame lengths, relative to 20- and 30-in. diameter limits on thinning.

Methods

Study Area

The Last Chance study area is located within the Tahoe National Forest and is situated in the northern Sierra Nevada (Figure 1). The climate is Mediterranean with a predominance of winter precipitation, a majority of which is snow, averaging 1,182 mm/year over the period of record 1990–2008 (Hell Hole Remote Automated Weather Station). Our core study area is defined by the boundaries of two adjacent watersheds in which landscape fuel treatments are scheduled for implementation between 2009 and 2011. This core area is approximately 4,300 ha, with elevation ranging from 800 m in the southwest to almost 2,200 m in the northeast portion of the study area. For fire modeling purposes (explained in the Fire Modeling section), we augmented the core study area with a square buffer that was a minimum of 1 km from the core area edge (Figure 1). The total buffered study area was 15,500 ha. Vegetation on this landscape is typical of west-slope Sierra Nevada: a mixed-conifer forest dominated by white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), and incense-cedar (*Calocedrus decurrens*) with sugar pine (*Pinus lambertiana*), ponderosa pine (*Pinus ponderosa*), and California black oak (*Quercus kelloggii*) appearing as a codominant at variable densities throughout. Stands of montane chaparral are interspersed throughout the area. Seven percent of the study area (approximately 300 ha) is classified as nonconifer forests, based on the Tahoe National Forest criteria (conifer trees constitute <10% of the tree crown area). Tree density varies by fire and timber management history, elevation, slope, aspect, and edaphic conditions. Fire history, inferred from fire scars recorded in tree rings, suggests a fire regime with predominantly frequent, low-severity fires occurring at intervals ranging from 5 to 15 years (Stephens and Collins 2004).

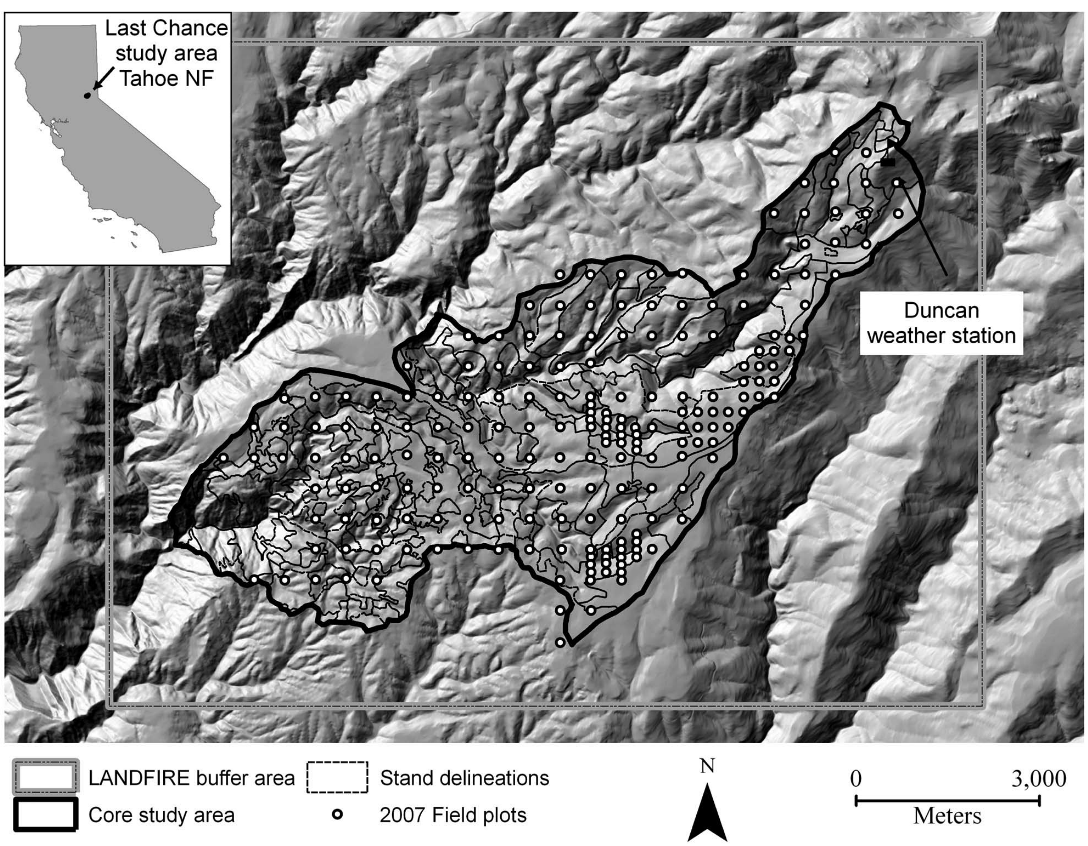

Figure 1. Field plot locations and stand delineations within the Last Chance study area, Tahoe National Forest, California. We used data from LANDFIRE (2010) to buffer the Last Chance study area for fire modeling. We obtained weather data for fire modeling from the Duncan Remote Automated Weather Station, which is also identified.

Field Sampling

We systematically established field plots at 500-m spacing across the Last Chance core study area, except the southwest corner of the core area due to extreme topography (Figure 1). We augmented sampling to 250- and 125-m spacing in areas more intensively studied as part the larger Sierra Nevada Adaptive Management Project (University of California Science Team 2009), resulting in a total of 199 sampled field plots. Plots were circular with an area of 0.05 ha and were navigated to using handheld global positioning systems (GPS). At each plot we recorded the slope, aspect, and GPS-derived elevation. We used three different sampling intensities based on tree size: ≥19.5 cm (throughout plot, 500 m^2), 5.0–19.4 cm (random one-third of plot, 167 m^2), and <5.0 cm (random belt transect, 76 m^2). We recorded tree species, vigor, crown position, dbh (1.37 m), total height, and height to live crown base (live trees only) for all trees in the upper two size classes. In the smallest tree size class, we recorded species and dbh. In addition, at each plot we cored, aged, and measured the height of a representative site tree to characterize differences in productivity across the study area.

We sampled downed woody, litter, and duff fuels on three randomly chosen transects within each plot. We used the line-intercept method to sample downed woody fuels (van Wagner 1968, Brown 1974). We measured duff, litter, and overall surface fuel depths at two points along each transect. We calculated fuel loads using the species-specific coefficients reported in van Wagtendonk et al. (1996, 1998), weighted by the proportion of total basal area of each species (Stephens 2001). On the same three transects we measured woody shrubs for cover (using transect intersections) and average height. We also made ocular estimates of total percent ground surface covered by herbaceous plants at each plot.

Modeling Forest Dynamics and Fuels Treatments

We used the Forest Vegetation Simulator (FVS) (Wycoff et al. 1982) with the Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003) to model fuel treatments under multiple diameter-limited thinning scenarios and to grow both treated and untreated forest stands into the future. We used the Timber Strata layer provided by the Tahoe National Forest to delineate individual stands (J. Babin, Tahoe National Forest, pers. comm., May 10, 2008). This geographic information system layer consisted of polygons, or stands, containing relatively similar forest composition and structure (n = 187). The stand delineations were based on aerial photo-interpreted classes of species, dominant tree size class, and tree density. Forest Service stands were used as the analysis unit rather than raster or grid cells to approximate the modeling used by Forest Service managers planning fuel treatment projects. Thus, the approaches we present may be more readily incorporated in actual land management planning. We "populated" each stand with trees sampled in the nearest field plot(s), either within or adjacent to each stand. We did not use a statistical imputation technique; plots were manually assigned for all 187 stands. For stands classified as plantations (n = 55), we used the nearest plot that fell wholly within a plantation (n = 20). As a result, some plots were used to populate multiple stands. In total, 199 plots were used to generate tree lists for 187 stands.

We simulated fuel treatments as prescribed in the Silviculturist Report prepared by the American River Ranger District, Tahoe National Forest (K. Jones, Tahoe National Forest, pers. comm., Jul. 29, 2008). This report identifies the individual stands to be treated and contains prescriptions for thinning and subsequent treatment of surface fuels, mastication, and underburning. Using multiple series of FVS and FFE keywords, we were able to match these prescriptions for our simulations. In general, the prescriptions call for treating 25% of the landscape (1,069 ha) by thinning from below, followed by mechanical/hand piling and burning (731 ha [17% of total]), mastication of shrubs and small trees (primarily within 20- to 30-year-old plantations: 105 ha [2.5%]), and underburning (233 ha [5.5%]). To investigate a potential effect of varying thinning diameter limits on overall landscape fuel treatment effectiveness, we used three different upper tree diameter limits, which were also associated with three different residual canopy cover targets. These targets also came from Forest Service planning documents (US Department of Agriculture 2001, 2004): 30.5 cm dbh (12 in.) and 60% canopy cover, 50.8 cm dbh (20 in.) and 50% canopy cover, and 76.2 cm (30 in.) and 40% canopy cover. Simulated thinning treatments involved thinning from below to a desired canopy cover target, such that no trees above the imposed diameter limit are cut. In other words, smaller trees are cut first and then progressively larger trees, but below the imposed diameter limit, until the overall canopy cover target is met. In a few cases the imposed diameter limit prevented achieving the stated canopy cover target; however, this was rare. The mastication and underburning treatments were unchanged for the three diameter limit/residual canopy cover scenarios.

We simulated the three diameter limit/residual canopy cover scenarios, along with a no treatment scenario, for four 10-year cycles. We modeled treatments according to the schedule projected by the Tahoe National Forest: thinning and mastication in 2009 and prescribed burning in 2010. FFE generates estimates of forest stand structural characteristics and surface (litter and downed woody) fuel loads, which we used as inputs for fire behavior modeling for four time steps using the ArcFuels interface: (1) 2007, pretreatment baseline; (2) 2017, first cycle after treatments; (3) 2027, second cycle after treatment, and (4) 2037, third cycle after treatment. Although thinning and mastication treatments were scheduled in 2009, FVS actually "implements" the treatments at the beginning of the cycle in which they occur. This means that in our simulations thinning and mastication actually occurred in 2007, whereas the prescribed burns were simulated as scheduled (i.e., 2010). As a result, our first posttreatment output (2017) does not represent immediate posttreatment; it represents 10 years postthinning and 7 years postburning. We could have simulated two shorter FVS cycles (3 and 7 years) to obtain more immediate posttreatment results; however, to keep growth cycles consistent throughout the simulation period and maintain consistency with underlying FVS growth models (Dixon 2002), we only used 10-year cycles. The forest and fuel parameter estimates output from FVS were then used to create the necessary stand structure/fuel input layers required by the fire behavior and spread model FlamMap (Finney 2006).

In the western Sierra variant of FVS, establishment of new trees in the absence of disturbance or ingrowth is not explicitly modeled. To simulate ingrowth, users must input the number, species, and frequency of establishment events. We modeled ingrowth for untreated stands in each cycle that favored shade-tolerant species, based on recommendations from Forest Service silviculture personnel within the region (R. Tompkins, Plumas National Forest, pers. comm., Jan. 5, 2009). We used a random number generator to choose the actual number of seedlings, within species-specific bounds, that established for a given stand, in a given FVS cycle. In addition, we regulated seedling height growth to simulate more realistic conditions under an intact canopy. We evaluated tree densities and stand canopy base height estimates to ensure that our ingrowth/regeneration assumptions were consistent with our own observations in the field and with local managers' knowledge of the study area. In the absence of any ingrowth/regeneration, stand canopy base heights increased considerably over time in untreated stands, which occurred at a rate that is difficult to justify ecologically, especially given the large proportion of shade-tolerant species present in many stands.

Fuel Model Selection

FFE explicitly models surface fuels at each time step, taking treatment effects on the various fuel loads into account. On the basis of the loads and distributions among fuel particle size classes and on other stand characteristics, FFE assigns fuel models to stands (Reinhardt and Crookston 2003). Our initial fire modeling runs and our familiarity with the Last Chance study area led us to conclude that the FFE fuel model assignments were not valid. Among other issues, crown fire activity and conditional burn probability under the no treatment alternative declined substantially over time. Seli et al. (2008) similarly expressed concern with FFE fuel model selection, and thus they created their own selection logic. We used some of the same criteria to develop our own fuel model selection logic. However, our approach involved using field plot-derived forest stand structure characteristics and site productivity to approximate stand fuel conditions. We used the statistical software package R to construct individual regression trees (De'ath and Fabricius 2000) predicting three plot-derived fuel variables: surface fuel load (includes litter and 1-, 10-, and 100-hour fuels), shrub cover, and coarse fuel load (1,000-hour fuels). We used basal area, tree density, canopy cover, dominant tree height, and site index summarized for each plot as predictor variables. Regression trees are ideal for such an analysis because they identify break values for predictor variables that can be used to repeatedly assign fuel models to stands. Statistical fits were moderate (R^2 = 0.21–0.27) but were deemed appropriate for "binning"

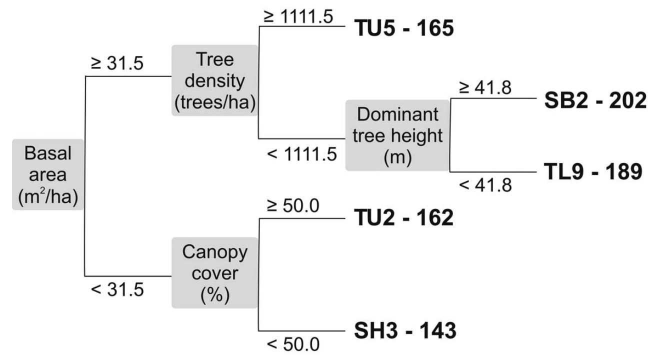

Figure 2. Surface fuel model selection logic for Last Chance stands. This logic did not apply to all treated stands in 2017 or to thinned/prescription-burned stands in 2027. The break values for the logic were determined from three separate regression tree analyses (see Methods for explanation). Surface fuel models were selected from Scott and Burgan (2005) and are identified in bold by code and number.

stands into discrete Scott and Burgan (2005) fuel models. Figure 2 displays our final fuel model selection logic based on results from the individual regression trees. The chosen fuel models for each terminal point in the selection logic were based on input from local fire managers and on our familiarity with the study area after two extensive field seasons. See Table 1 for descriptions of fuel models used and their proportions throughout the study area over the duration of simulations.

Posttreatment fuel models for treated stands were based on separate logic involving treatment type and time since treatment. In the first and second cycles after treatment, thinned stands were assigned timber-litter fuel models with progressively higher fuel loads (Table 1). Slash models were not assigned to thinned stands because of the prescribed and simulated modification of surface fuels after thinning. Stands that were underburned followed a similar progression of timber-litter fuel models but with slightly lower fuel loads (Table 1). By the third cycle, both thinned and underburned stands entered into the general logic used for untreated stands (Figure 2). Masticated stands were assigned a timber-litter fuel model with moderate litter and downed woody fuel loads in the first cycle after treatment (Table 1). For subsequent cycles, masticated stands were entered into the general fuel model selection logic described in Figure 2.

Fire Modeling

We used a command-line version of FlamMap (Finney 2006) called RANDIG to model fires across the Last Chance landscape. RANDIG uses the minimum travel time method (Finney 2002) to simulate fire spread based on user inputs for number/pattern of ignitions, fire duration, wind speed and direction, fuel moistures, topography, stand structure, and fuels. For each scenario and time step, we simulated 5,000 randomly placed ignitions, burning for 240 minutes (one 4-hour burn period). This burn period duration was selected such that simulated fire sizes (for one burn period) approximated large spread events (daily) observed in actual fires that occurred near the study area (Ager et al.

Table 1. Fuel model assignments for stands within the Last Chance study area and their proportion throughout the study area over the simulation duration

Scott and Burgan (2005) fuel model	Description of stands with fuel model assigned	Pretreatment (2007)	2017		2027		2037	
			NoTrt	Trt	NoTrt	Trt	NoTrt	Trt
143	Low basal area, low canopy cover	0.09	0.29	0.26	0.12	0.13	0.08	0.12
162	Low basal area, high canopy cover	0.41	0.09	0.09	0.04	0.03	0.01	0.02
165	Moderate to high basal area, high tree density	0.24	0.31	0.22	0.40	0.30	0.48	0.39
181	Post-prescribed fire (first cycle)	—	—	0.05	—	—	—	—
183	Post-prescribed fire (second cycle) Post-thin/pile burn (first cycle)	—	—	0.17	—	0.05	—	—
184	Postmastication (first cycle)	—	—	0.02	—	—	—	—
185	Post-thin/pile burn (second cycle)	—	—	—	—	0.17	—	—
189	Moderate to high basal area, moderate to low tree density, moderate to low site productivity	0.25	0.30	0.18	0.43	0.31	0.41	0.45
202	Moderate to high basal area, moderate to low tree density, high site productivity	0.01	0.01	0.01	0.01	0.01	0.02	0.02

Fuel model selection logic was based on multiple regression tree analyses using plot-level data for both dependent variables (fuel loads by category) and independent variables (forest structure attributes).
Trt, with simulated treatments; NoTrt, without simulated treatments.

2010). There were two fairly recent fires that burned near the Last Chance study area for which daily spread information existed: the 2001 Star fire and the 2008 American River complex. The largest daily spread event for each of these fires was approximately 1,300 ha, which was under the range of average simulated fire sizes for our no treatment scenarios: approximately 1,500–2,100 ha. Given that we only have two fires from which to compare large spread events and that in other areas of the Sierra Nevada daily fire growth in excess of 2,000 ha has been observed in recent fires (Fites et al. 2007, Dailey et al. 2008), we believe our burn period calibration represents a reasonable "middle ground" for large spread events in Sierra Nevada mixed-conifer forests.

We obtained weather information from the Duncan Peak Remote Automated Weather Stations, restricting the analysis period to the dominant fire season for the area (June 1–September 30). Observations were available from 2002 to 2009. We used 90th percentile and above wind speeds, based on hourly observations, to generate multiple wind scenarios under which fires were simulated. We identified the dominant direction and average speed of all observations at or above the 90th percentile value, 24 km hour^{-1}. This resulted in four different dominant wind directions, each with its own wind speed and relative frequency (based on the proportion of observations recorded at or above the 90th percentile value for each dominant direction) (Table 2). The modeled wind speeds were similar to those recorded during large spread events in two relatively recent and nearby fires: 2001 Star fire and 2008 American River complex. We used 95th percentile fuel moistures, as these are the conditions associated with large fire growth and difficulty in control.

We derived the necessary topographic inputs, slope, aspect, and elevation, using a 30-m digital elevation model obtained from the National Elevation Dataset (US Geological Survey 2006). Stand structure and fuels layers were derived from FVS outputs. For each stand, at each time step,

Table 2. Weather parameters for fire simulations using RANDIG

Weather parameter	Speed (km h^{-1})	Direction (° azimuth)	Relative frequency	Percent
Winds	29	180	0.31	
	31	90	0.31	
	27	135	0.31	
	27	315	0.07	
Fuel moisture				
1 h				2
10 h				3
100 h				5
Live herbaceous				30
Live woody				60

Parameters were drawn from the Duncan Peak Remote Automated Weather Stations and represent the 90th percentile and above winds and the 95th percentile fuel moistures for the predominant fire season in the area (June 1–September 30).

FVS outputs for canopy cover, canopy bulk density, canopy base height, and dominant tree height, along with a fuel model assignment (computed outside of FVS), were compiled to develop continuous layers for each of these five variables across the core Last Chance study area. This resulted in 12 different simulated landscapes: no treatment (NoTrt), 30.5 cm (12 in) dbh thinning limit (Trt12), 50.8 cm (20 in) dbh thinning limit (Trt20), and 76.2 cm (30 in) dbh thinning limit (Trt30), all at three time steps (2017, 2027, and 2037). In addition, we ran a pretreatment baseline landscape for 2007, totaling 13 different simulated landscapes.

To allow for ingress and egress of simulated fires we buffered the irregularly shaped core study area using a rectangle that was a minimum of 1 km for the core area edge (Figure 1). Doing so ensured that certain areas were not "sheltered" from simulated fire spread. Because our field plots were confined to just the core study area, we were unable to use the same approach toward modeling forest dynamics over time for the buffer area. We opted to use

LANDFIRE (2010) vegetation and fuels layers for the area outside the core study area. The drawback of this approach is that LANDFIRE layers remain static throughout the simulation duration. Given that for our analyses we extract the RANDIG output from only the core area, we believe the impact of the buffered area layers being both from a different source and static is likely to be small.

For each simulated landscape, RANDIG outputs conditional burn probabilities, both overall and proportional for 20 flame length classes (0–10 m in 0.5-m increments) for individual 60-m pixels, spanning the entire buffered study area. Conditional burn probabilities are computed by dividing the total number of times a pixel burned by the total number of simulated fires ($n = 5{,}000$). To separate out more problematic simulated fire occurrence, both from a fire effects and a fire suppression standpoint, we only performed analysis on the burn probabilities for which modeled flame lengths were >2 m. Flame lengths >2 m typically correspond with crown fire initiation and present substantial challenges for suppression efforts (National Wildfire Coordinating Group 2004). We imported conditional burn probability surfaces, for modeled flame lengths >2 m, into ArcGIS software for further data analysis. For each of the 13 simulated landscapes we computed overall mean conditional burn probability, only using those pixels within the Last Chance core study area. To estimate potential offsite effects from treatments we extracted conditional burn probability pixel values within three distance ranges outside treatment boundaries. We used the Multiple Ring Buffer tool in ArcToolbox to construct concentric, nonoverlapping buffers extending 0–299, 300–599, and 600–900 m from treatment boundaries. Within each ring buffer we calculated mean conditional burn probabilities, again using only those probabilities associated with flame lengths >2 m.

Results

Simulated Stand-Level Treatments

Under each of the three diameter-limited thinning scenarios, stand averages for tree density, basal area, canopy cover, and canopy bulk density decreased, whereas canopy base height increased, relative to the NoTrt scenario (Figure 3). It is important to note that initial (pretreatment) canopy cover estimates (2007) for the thinned stands averaged near 50%, and as a result the canopy cover targets in the less intensive thinning scenarios (60% for the 30.5-cm dbh limit and 50% for 50.8-cm dbh limit) were already met for several stands (Figure 3). In such stands, simulated thinning primarily involved removing understory trees. This removal of trees is evident in the density changes for all three thinning scenarios after treatment (Figure 3). The stand structural changes in each of the thinning scenarios relative to the NoTrt scenario persisted throughout the simulation duration, with canopy base height being the only exception. In 2037 average canopy base height for all three thinning scenarios was nearly indistinguishable from that for the NoTrt scenario. Tree density, basal area, canopy cover, and canopy bulk density among the three diameter-limited thinning scenarios followed a nearly linear decreasing trend as the thinning diameter limit increased for all three modeled time periods (Figure 3).

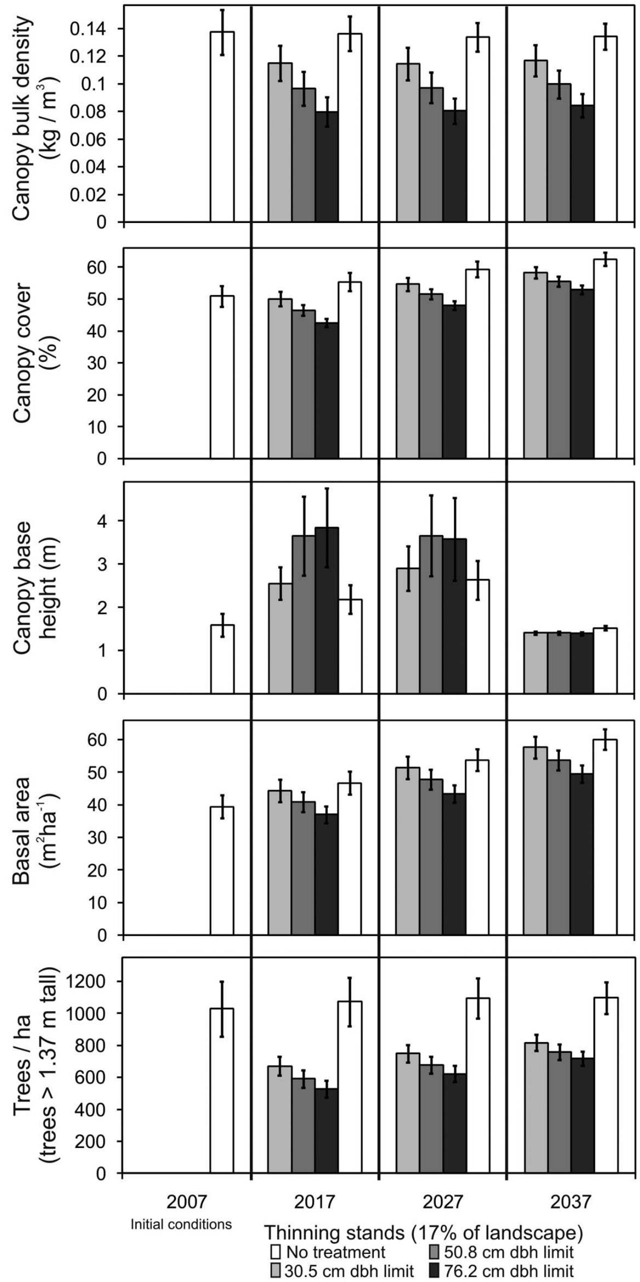

Figure 3. Average forest stand structural attributes for stands planned to undergo thinning. Thinned stands are simulated under three diameter-limited scenarios as well as a no treatment scenario for the same stands. Error bars represent 1 SEM. Attributes were derived from the Forest Vegetation Simulator, using tree lists for each stand based on our field inventory plots. The thinned stands represent 17% of the Last Chance landscape.

Tree density, basal area, canopy cover, and canopy bulk density decreased substantially for mastication and prescribed fire stands as well (Figure 4). The persistence of these effects, relative to the same stands modeled with no treatment, was evident for all three time periods and appeared generally stronger than that for the thinned stands. Initial canopy cover and canopy base height estimates in mastication stands were lower than those for all other

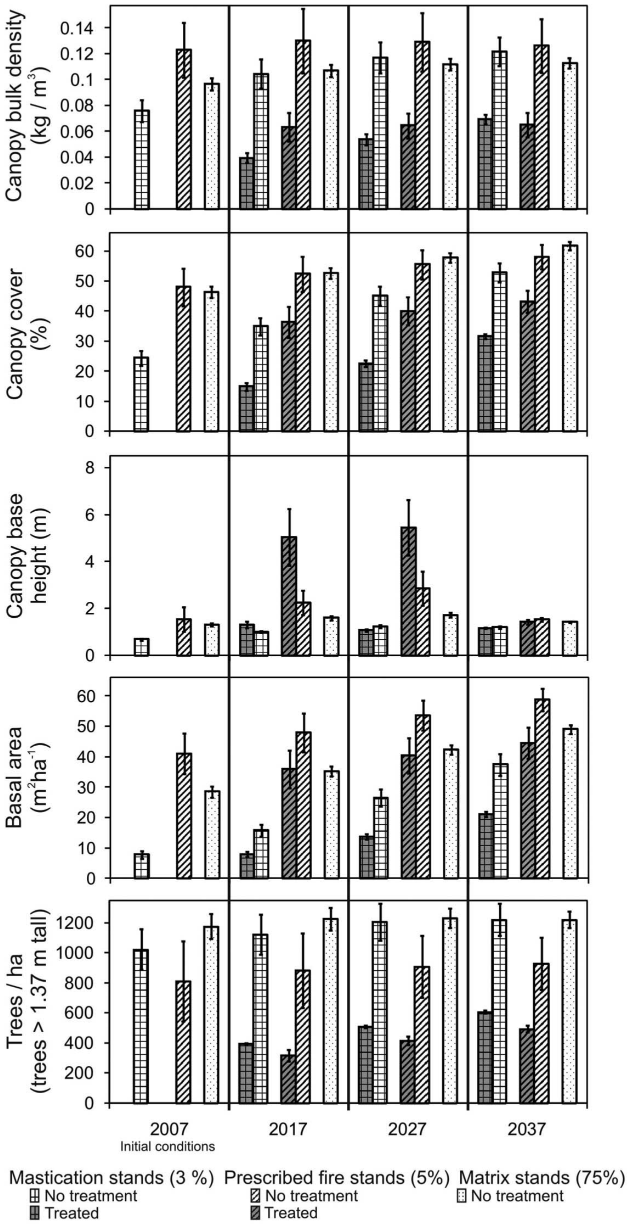

Figure 4. Average forest stand structural attributes for stands planned to undergo mastication treatment and prescribed fire treatment, as well as a no treatment scenario for the same stands. The stands planned for mastication and prescribed fire represent 3 and 5% of the Last Chance landscape, respectively. Structural attributes for stands within the study area that are not to be treated, referred to as matrix, are reported as well, representing 75% of the landscape. Error bars represent 1 SEM. Attributes were derived from the Forest Vegetation Simulator, using tree lists for each stand based on our field inventory plots.

stands, demonstrating differences in stand structure for the approximately 20- to 30-year-old plantations (2007 in Figures 3 and 4). In the first and second cycles after treatment implementation (2017 and 2027) canopy base height in prescribed fire stands increased dramatically (Figure 4). By the final time period, canopy base height in mastication and prescribed fire stands was similar to that in NoTrt and matrix stands (Figure 4).

Simulated Landscape-Level Fire Spread

The simulated treatments reduced conditional burn probabilities (flame lengths >2 m) not only within treatment areas, but also throughout the Last Chance study area (Figure 5). This reduction relative to the pretreatment scenario (2007) was evident across the Last Chance study area in both 2017 and 2027 (Figure 5). Analysis of burn probabilities in the three distance ranges outside the treated areas confirmed this reduction relative to the pretreatment condition and demonstrated only moderate increases in average conditional burn probability with increasing distance from treated areas (Figure 6). However, by 2037 the modeled burn probabilities exceeded those of the pretreatment scenario across the study area (Figures 5 and 6)

Mean conditional burn probabilities (flame lengths >2 m) for the NoTrt scenario declined slightly from 2007 to 2017 and from 2017 to 2027 but increased substantially in 2037 (Figure 7). Each of the three diameter-limited thinning scenarios resulted in considerable reductions in mean conditional burn probability for 2017 and 2027 and were all nearly indistinguishable from each other, regardless of simulation year. Although mean burn probabilities for the three treatment scenarios increased in 2037, all three scenarios were below that of the NoTrt scenario in 2037 (Figure 7).

Discussion

Simulated Stand-Level Treatments

All forest dynamics simulations were done in the absence of unplanned disturbances, namely wildland fire and insect outbreaks. Given the 30-year simulation period, this may or may not be a reasonable assumption; however this assumption was necessary to attain meaningful comparisons among treatment scenarios. The modeled stand structural changes for the first cycle after treatment implementation (i.e., reduced tree density, basal area, canopy cover, and canopy bulk density and increased canopy base height) were similar to those reported in studies of actual fuel reduction treatments (Stephens and Moghaddas 2005, Schmidt et al. 2008, Harrod et al. 2009, Stephens et al. 2009) and are consistent with reduced crown fire potential (Agee and Skinner 2005). With the exception of canopy base heights, the persistence of these structural changes relative to that for no treatment demonstrates a fairly long-lived effect associated with a single-entry fuel treatment (Figures 3 and 4).

The initial increases in canopy base heights within thinning and prescribed fire stands are a product of removing trees from the understory and midcanopy layers either by thinning or burning. However, the finding that the most conservative thinning treatment (30.5 cm or 12 in. dbh limit) resulted in only a slight increase in canopy base height indicates that 7–10 years after treatment limiting thinning to this extent may not effectively reduce ladder fuels. North et al. (2009) argue that thinning trees above the 25 to 40.6 cm dbh (10 to 16 in.) class is not necessary for reducing ladder fuels. The modest increase in canopy base heights as the thinning dbh limit increases from 50.8 cm (20 in.) to 76.2 cm (30 in.) suggests there may be little justification for thinning trees larger than 50.8 cm (20 in.) dbh to

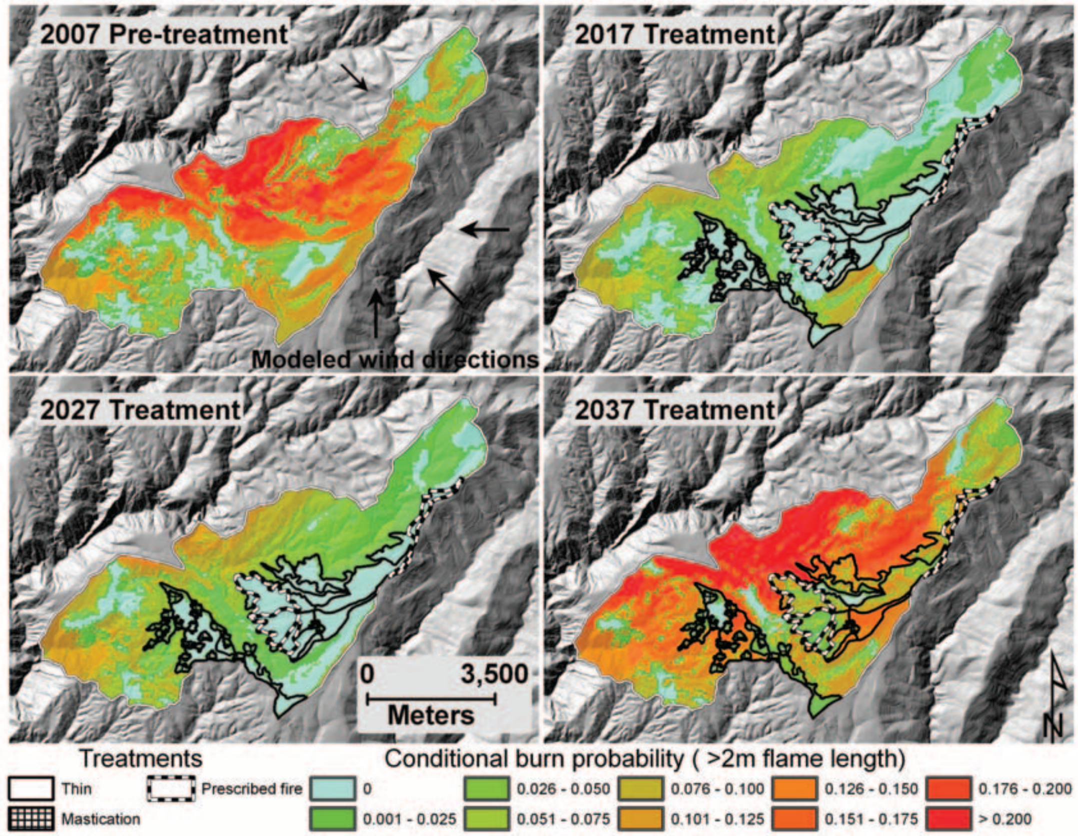

Figure 5. Conditional burn probabilities across the Last Chance landscape for which simulated flame lengths are greater than 2 m. Burn probabilities are reported for the pretreatment conditions (2007), as well as for the treated (76.2 dbh limit) scenarios modeled 30 years from pretreatment. Probabilities are based on 5000 randomly placed ignitions simulated using RANDIG (see Methods for explanation). Treatment types and boundaries along with modeled wind directions are also displayed.

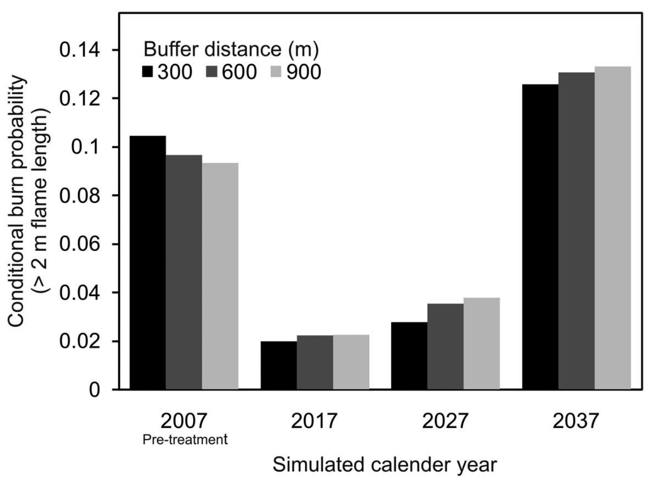

Figure 6. Mean conditional burn probabilities (simulated flame lengths >2 m) within concentric, nonoverlapping buffers immediately surrounding treated areas in the Last Chance core study area. Means are reported for the pretreatment conditions (2007), as well as for the treated (76.2 dbh limit) scenarios modeled 30 years from pretreatment. Probabilities are based on 5,000 randomly placed ignitions simulated using RANDIG (see Methods for explanation).

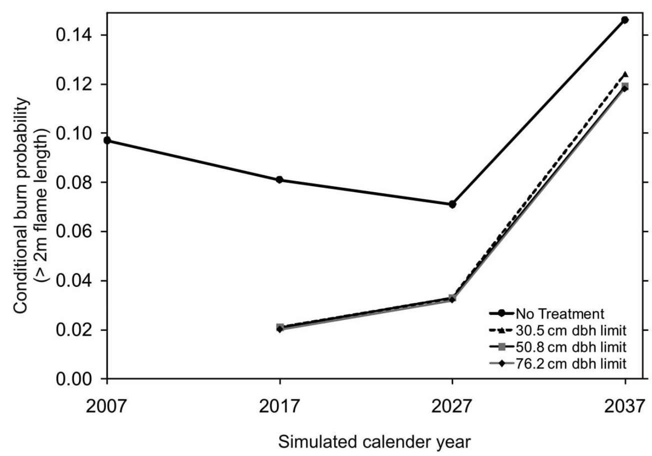

Figure 7. Mean conditional burn probabilities across the Last Chance landscape for which simulated flame lengths are >2 m. Three diameter-limited thinning scenarios along with a no treatment scenario are reported. Each scenario was modeled into the future based on output from the Forest Vegetation Simulator, using our 2007 field inventory plot data as a baseline. Probabilities are based on 5,000 randomly placed ignitions simulated using RANDIG (see Methods for explanation). Note that the three thinning scenarios are nearly indistinguishable, with the exception of a slight departure for the 30.5-cm scenario in 2037.

reduce potential fire behavior in forests similar to those studied here.

As regeneration after treatment disturbances takes place, the established trees begin to grow into the understory canopy layer, resulting in decreased canopy base heights over time (2027 and 2037 in Figures 3 and 4). In 2027 only prescribed fire stands exhibited higher canopy base heights relative to no treatment. This is probably due to a substantial pruning effect (i.e., high scorch heights) brought about by a fairly aggressive burning prescription and is evident from the almost 6-m average canopy base heights and substantial reductions in tree density within burned stands for 2017 and 2027. The much lower canopy base height for the 76.2 cm (30 in.) dbh thinning scenario in 2027 is likely due to the regeneration response to increased growing space created by the more intensive disturbance, i.e., lower residual canopy cover and tree density.

As with most modeling exercises, results are inherently subject to a certain number of assumptions and ideas put forth by the modeler (Collins et al. 2010). This is especially the case for canopy base height estimates over time from FVS, namely in 2027 and 2037 (Figures 3 and 4). In the absence of pertinent local data we made assumptions in modeling seedling establishment based on local expert knowledge and on our own familiarity with the study site. The modeled number of established trees varied by species and involved stochasticity among stands and among FVS cycles. Although these assumptions are somewhat subjective, we believe our modeled forest stand dynamics reflect reasonable progressions of treated and untreated stands.

Simulated Landscape-Level Fire Spread

One of the primary objectives of a landscape fuel treatment project is to reduce the potential for exacerbated fire effects, not only within treated areas but also across the landscape (Weatherspoon and Skinner 1996, Finney 2001). Inasmuch as the modeled burn probabilities we present (>2-m flame lengths) can serve as a proxy for more damaging or problematic fire occurrence, the reduced conditional burn probabilities across the Last Chance study area after simulated treatments indicate an effective landscape fuel treatment project (Figure 5). This reduction in burn probabilities was evident well outside of treatment boundaries and persisted for almost 20 years after simulated treatments (Figure 6). Limiting our analyses to only those probabilities in which flame lengths were >2 m was an attempt to separating out higher intensity modeled fire behavior, which presumably is associated with exacerbated fire effects (fires with flame lengths <2 m would be mostly beneficial to this ecosystem). Furthermore, when fires are modeled for a fixed period of time, increased burn probabilities are indicative of faster spread rates (Finney et al. 2007, Seli et al. 2008). Faster spread rates in many forested fuel types are related to higher fireline intensities (Albini 1976), which can lead to increased fire effects. This assumption would not necessarily be valid when surface fuels are dominated by grasses (van Wagtendonk 1996). However, because we did not have grass or timber-grass fuel models in the Last Chance study area either pre- or post-treatment we believe that burn probabilities are reasonable indicators of potential fire effects.

The treatment effectiveness across the entire Last Chance landscape exists in the absence of a dispersed or regular arrangement of treated stands. We hypothesize that a few factors related to the position and size of the individual treatment units contributed to the modeled reductions in burn probabilities. Although there are several individual treated stands with, in some cases, differing prescriptions, the Last Chance treatments primarily consist of two large blocks (Figure 5). These treatment blocks are centered about the long axis of the study area (Figure 5). We suggest that because of the approximate centralized position of the treatments, many of the modeled fires intersected one or both of the treatment blocks. In addition, the large size of the treatment blocks may have increased the potential to slow fire spread. The centralized location may have also been a safeguard against fires becoming too large, given that the simulated fires burned under multiple wind directions using RANDIG (Table 2). If treatments were positioned toward one end of the study area or more dispersed throughout the study area the varying wind directions among simulated fires may have had led to more fires either avoiding treated areas or overwhelming treatments. Addressing these hypotheses more directly would involve substantial theoretical modeling that exceeds our intent of analyzing an actual landscape fuel treatment project.

The lack of clear differences among diameter-limited thinning scenarios for landscape-level burn probabilities (Figure 7) bears some attention. It is possible that the generally open forest structure pretreatment (2007 in Figures 3 and 4) has some impact. Because initial canopy cover estimates averaged near 50%, there may not have been much difference among the thinning scenarios, which aimed to reduce canopy cover to between 40 and 60%, depending on the scenario. The low canopy cover for the Last Chance study area is due in part to the history of extensive timber operations in the area (K. Jones, Tahoe National Forest, pers. comm., Jul. 29, 2008).

Another likely explanation for lack of differences among diameter-limited thinning scenarios lies in our surface fuel assumptions for the thinning treatments. In our modeling, treatment of surface fuels after thinning (i.e., pile and burn) did not change among diameter-limited scenarios, and thus surface fuel model assignments were unchanged among thinning scenarios for the first two cycles after thinning (2017 and 2027) (Table 1). As a result, the similarity in landscape-level conditional burn probabilities among the three scenarios is not too surprising, at least in the first two FVS cycles. We submit that our supposition that residual surface fuels would not vary much among diameter-limited thinning scenarios is reasonable, assuming that funding treatment of activity fuels and natural surface fuels after thinning is independent of the revenues from the thinning. One potential difference, however, is that the most conservative diameter-limited scenario (30.5 cm or 12 in.), which leaves more trees (Figure 3), may result in more restricted access throughout the stand. If activity fuels and natural surface fuels are piled mechanically, then this restricted access could limit the amount of woody fuel actually removed from the stand, which could result in increased potential for higher intensity surface fire and reduced treatment effectiveness.

Stand development within both treated and untreated stands probably drove the observed increases in conditional burn probabilities across the Last Chance study area over time (Figures 5–7). However, these increases in burn probabilities (>2-m flame lengths) were not constant over our simulation duration. The increase in mean conditional burn probability from 2017 to 2027 was well below that from 2027 to 2037 for the treatment scenario (Figure 7). This result suggests landscape-level treatment longevity of approximately 20 years based on a single-entry treatment. Although we do not model it, maintenance treatments (e.g., prescribed fire) would probably extend this longevity across the landscape. Recall that we simulated thinning, burning, and mastication treatments in the 1st year of the first FVS cycle (2007). Results from Finney et al. (2007) indicating reductions in mean burn probabilities at treatment rates of 1% per year (20% of the landscape every 20 years) support our findings. (Last Chance treatments covered 25% of the study area.)

Modeling Limitations

One of the obvious limitations to our analysis is the lack of consistency in vegetation and fuel layers between the core study area and the buffer area (Figure 1). Both the different sources of the data and the static nature of the buffer layer may have led to anomalous fire behavior near the edges of the core area. However, there is little evidence for such abnormality when burn probabilities are displayed geographically (Figure 5). Because the vegetation and fuel layers for the core study area were derived from an intensive inventory consisting of almost 200 field plots, increasing the field sampling to include data collection for a buffered area would have required substantial additional effort. Given limited budgets, a better strategy may have been to sample a larger buffered area less intensively and forego the detail gained by more closely spaced inventory plots.

It is likely that the fuel model selection logic we developed (Figure 2; Table 1) had an impact on conditional burn probability outputs over the simulated duration. Our assumptions that thin/pile and burn stands progressed from moderate-load conifer litter to high-load conifer litter surface fuel models and, by the final cycle, entered into the untreated selection logic may or may not represent realistic fuel recovery. Little work has been done in the area of fuel model succession. Miller and Davis (2009) developed a dynamic model of fuel succession after fire, in which transitions from one fuel model to the next were based on both fire severity and time since fire. These transitions and rates were based on expert opinion and follow logic similar to ours with respect to time since disturbance. More empirical studies of fuel recovery after disturbance are needed to form robust methodologies for dynamically assigning fuel models in long-term simulation studies.

Another limitation of our analysis is that the conditional burn probabilities we report are different from actual burn probabilities for our study area. The probabilities we report are "conditional" on the occurrence of an ignition within the larger buffered study area, under the modeled moisture and wind conditions. Based on analysis of actual fires within and around the larger buffered study area, fire rotations were between 214 and 227 years, depending on the length of the reporting period (1950–2008 or 1900–2008, respectively), which translates to an approximately 0.004 annual probability of the entire study area being burned, substantially less than our average conditional burn probability (>2 m flame lengths) for the NoTrt scenario in 2007 of 0.097. Despite this discrepancy, the probabilities we report are a robust and useful measure of fuel treatment effects across landscapes (Ager et al. 2010).

Ultimately there is no substitute for learning from actual wildland fires affecting completed fuel treatments. Although there is a suite of case studies demonstrating stand-level fuel treatment performance in wildland fires (e.g., Martinson and Omi 2002, Finney et al. 2003, 2005, Raymond and Peterson 2005, Skinner et al. 2005, Moghaddas and Craggs 2007, Ritchie et al. 2007, Strom and Fulé 2007, Safford et al. 2009), there are very few studies that have analyzed performance of coordinated landscape fuel treatments in an actual wildland fire (see Finney et al. 2005). The probability of such an opportunity occurring is low given the current rarity of implemented landscape fuel treatments (Collins et al. 2010). As a result, much of the analysis of landscape fuel treatments is largely based on modeling, which is subject to the limitations we have discussed throughout.

Conclusions

It is clear from our findings that although the Last Chance project does not use the dispersed, regular arrangement of treatments (see Finney 2001) or a more intensive modeling effort to spatially locate treatment (see Finney 2007), the landscape fuel treatment effort demonstrates effective reduction in modeled burn probabilities. Because our analysis incorporates variable wind directions and speeds, one of the dominant drivers of fire spread, we believe these results reflect a realistic assessment of treatment effectiveness and not simply results driven by a few key modeling assumptions. These winds represent actual conditions that are associated with large fire potential within the Last Chance study area. Furthermore, we used detailed and extensive forest stand structure data as inputs for our fire and forest dynamics modeling. These factors, along with the modeling adaptations we incorporated (modified fuel model selection and stochastic regeneration) contribute to a robust analysis, despite the limitations we discussed.

Although there were differences in residual forest structure among diameter-limited thinning scenarios at the stand level, the lack of clear differences in >2 m flame length burn probabilities among thinning scenarios suggests that at the landscape scale effective fuel reduction treatments rely more on treating surface fuels and thinning ladder fuels than on thinning diameter limits. However, it is worth noting that our modeling may under represent crown fire propagation and spotting and thus may not be able to capture differences in reduction of crown fire potential among thinning scenarios. As Safford et al. (2009) demonstrated, fuel treatments in actual wildland fire areas thinned at lower intensities (e.g., hand-thinning) resulted in little to no reduction in fire severity, whereas in areas more intensively thinned fire severity was substantially reduced within 50 m of treatment boundaries. Capturing these changes in fire intensity and subsequent effects via modeling (e.g., a probabilistic reduction of propagating crown fire, spotting) after landscape fuel treatment implementation would improve our ability to evaluate whether or not a landscape fuel treatment achieved such objectives.

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