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Fuel buildup and potential fire behavior after stand-replacing fires, logging fire-killed trees and herbicide shrub removal in Sierra Nevada forests

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ABSTRACT

Typically, after large stand-replacing fires in mid-elevation Sierra Nevada forests, dense shrub fields occupy sites formerly occupied by mature conifers, until eventually conifers overtop and shade out shrubs. Attempting to reduce fuel loads and expedite forest regeneration in these areas, the USDA Forest Service often disrupts this cycle by the logging of fire-killed trees, replanting of conifers and killing of shrubs. We measured the effects of these treatments on live and dead fuel loads and alien species and modeled potential fire behavior and fire effects on regenerating forests. Sampling occurred in untreated, logged and herbicide-treated stands throughout the Sierra Nevada in four large fire areas 4–21 years after stand-replacing fires. Logging fire-killed trees significantly increased total available dead fuel loads in the short term but did not affect shrub cover, grass and forb cover, alien species cover or alien species richness. Despite the greater available dead fuel loads, fire behavior was not modeled to be different between logged and untreated stands, due to abundant shrub fuels in both logged and untreated stands. In contrast, the herbicide treatment directed at shrubs resulted in extremely low shrub cover, significantly greater alien species richness and significantly greater alien grass and forb cover. Grass and forb cover was strongly correlated with solar radiation on the ground, which may be the primary reason that grass and forb cover was higher in herbicide treated stands with low shrub and tree cover. Repeat burning exacerbated the alien grass problem in some stands. Although modeled surface fire flame lengths and rates of spread were found to be greater in stands dominated by shrubs, compared to low shrub cover conifer plantations, surface fire would still be intense enough to kill most trees, given their small size and low crown heights in the first two decades after planting.

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1. Introduction

Intense fires in Sierra Nevada forests of California sometimes kill large swaths of conifers and initiate secondary plant succession, dominated in early years by shrubs (i.e., *Ceanothus* spp., *Arctostaphylos* spp. and *Chamaebatia foliolosa*) (Kauffman and Martin, 1991; McKelvey et al., 1996; Miller et al., 2009). Shrub dominance may be as short as 35 years, if conifer seeds are present and the site does not reburn, or as long as a century or more, if the conifer seed sources are distant or frequent fires kill immature conifers (Cronemiller, 1959; Wilkin, 1967; Nagel and Taylor, 2005). In these areas, shrubs compete with small trees for soil moisture and light and thus slow forest recovery (Royce and Barbour, 2001). However, at the same time shrubs provide ecosystem benefits, such as habitat for wildlife, nitrogen fixation, soil stabilization, etc. (Delwiche et al., 1965; Heisey et al., 1980; Busse et al., 1996). After a long absence of fire, shade-tolerant firs and other species may eventually dominate (Conard and Radosevich, 1982; Helms and Tappeiner, 1996; Nagel and Taylor, 2005; Collins and Stephens, in press), but inevitably the forest burns again and the natural fire-shrub-conifer cycle continues.

In contrast to the long process of natural succession, in order to speed up coniferous forest replacement, the U.S. Forest Service, and to a greater extent, private industry, often intensively manages such high severity burns with various treatments. These include planting of conifer seedlings and related site preparation and maintenance methods that are designed to both reduce fuels for repeat fires as well as reduce competition for conifer seedlings, both of which potentially lead to a more rapid return of forests.

Logging large fire-killed trees is usually the first step in actively managing burned areas, primarily because timber sales can fund replanting. However, in many areas, logging is also used as a fuel reduction treatment. Removing the dead trees does not necessarily slow the spread of the fire front, however (most of their biomass is

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too large near the ground to ignite quickly, at least until the snags begin to fall), but does reduce potential fire brand production, smoldering fires and improves fire-fighter safety. Conceptually, logging fire-killed trees increases fine and medium surface fuels in the short term and decreases large diameter fuels in the long term (Peterson et al., 2009). Short-term empirical studies indicate that slash from post-fire logging operations may actually contribute to fire spread by significantly increasing fine, medium and coarse fuels on the ground (Donato et al., 2006; McIver and Ottmar, 2007; Monsanto and Agee, 2008). Although there are no long-term empirical studies on the net accumulation of fine and medium fuels after stand-replacing fires, models of accumulation and decay in logged and untreated stands have predicted that logged stands may continue to have substantially greater fine and medium sized fuel loads than untreated stands for 20 years (McIver and Ottmar, 2007).

After logging fire-killed trees on national forests, conifers are generally planted at high densities to reduce competition from emerging grasses and shrubs. However, this can set the stage for crown fire, as crown fuel spacing is highly important in its spread (Van Wagner, 1977). To minimize the initiation of crown fire, as well as damage from a surface fire, sufficient vertical space between surface fuels and tree canopies must be maintained; the greater the surface fuel load, the higher the crown must be (Van Wagner, 1977, Agee, 2007). Accordingly, surface fire damage to taller trees could be minimized by reducing surface fuels and removing lower branches (Scott and Reinhardt, 2001; Agee and Skinner, 2005; Raymond and Peterson, 2005; Scott, 2006).

Once canopies close, plantations may be thinned to stimulate growth and avoid mortality from competition with other trees. Thinning also has the benefit of reducing the probability of crown fire spread, but at the same time, increases the probability of more intense surface fire, as this allows for greater sunlight and air circulation near the ground, thus, greater fuel heating and drying before and during a fire (van Wagtendonk, 1996; Agee, 2007). Due to these tradeoffs, observations and modeling indicate that tree spacing has little to do with conifer survival after a fire in both even and uneven-aged young conifer stands (Raymond and Peterson, 2005; Stephens and Moghaddas, 2005).

Young conifers can be highly vulnerable to wildfire because their thinly barked stems and low branches are unprotected from scorching (Thompson et al., 2007; Kobziar et al., 2009). This risk may remain high for several decades if shrubs and other surface fuels are not frequently reduced (Zhang et al., in press). Even though maturing trees can withstand increasingly greater heat from a surface fire, in stands without fuel reductions, both litter loads and ladder fuels (live and dead tree and shrub branches) result in continued high vulnerability (Agee, 2007; Zhang et al., in press).

As with tree thinning there are also fuel tradeoffs in removing or leaving shrubs. Whereas shrubs can produce higher flame lengths than other surface fuels, they do not readily ignite until late in the fire season, when fuel moisture is low, especially if they have a high proportion of live braches. In contrast, litter and grass fuels produce lower flame lengths, but dry earlier in the year and ignite easily (Agee et al., 2002). Therefore, in the periods of time when spaces do exist between trees (i.e., in the first years after planting, if shrubs are removed, and after thinning), grasses and forbs may fill the gaps between trees (McDonald and Fiddler, 1999). Thus, in addition to the problems associated with greater air flow, fine grass and forb fuels may replace live woody shrub fuels and more readily ignite.

Significantly, annual alien grasses and forbs readily colonize disturbed, open, shrub-free pine forests and plantations (McDonald and Fiddler, 1999; Keeley and McGinnis, 2007; Gundale et al., 2008; McGlone et al., 2009). Among these, the alien grasses (i.e. cheatgrass, *Bromus tectorum*) are the most problematic surface fuels in many western ecosystems; they ignite easily, cause fire to spread quickly and may form a continuous fuel bed between woody plants (Brooks et al., 2004; Link et al., 2006). Young pine plantations are particularly vulnerable to grass fires (Weatherspoon and Skinner, 1995). The extremes in fire behavior would be infrequent high-intensity shrub fires or frequent lower intensity grass fires, both of which would endanger young conifer stands that are planted or establish naturally after stand replacing fire.

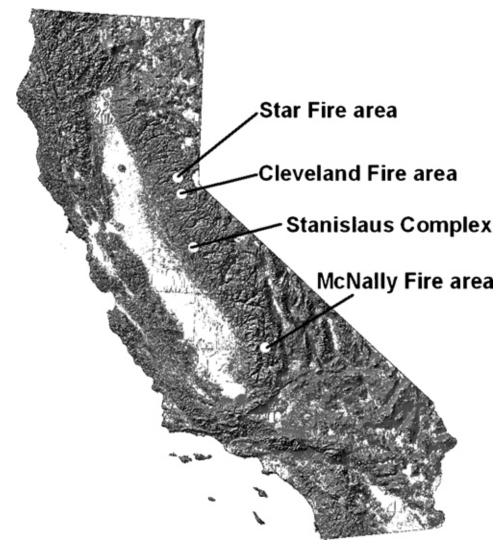

Fig. 1. Study areas: 2001 Star Fire area (elevation, 1280–2090 m), 1992 Cleveland Fire area (elevation, 1040–1850 m), 1987 Stanislaus Complex area (elevation, 910–1690 m) and 2002 McNally Fire area (elevation 1340–2700 m).

To look at these issues and seemingly endless tradeoffs, this study investigates how post fire treatments (no treatment, logging fire-killed trees, and using herbicides to kill competing shrubs) and secondary plant succession affect fuel loads, fuel distributions, potential fire behavior and potential young conifer mortality from fire on west slope Sierra Nevada forests. Here we examine four forests in the northern, central and southern Sierra Nevada that had burned in stand-replacing fires over the past two decades and make inferences about post fire treatments in the individual fire areas and across the entire Sierra Nevada west slope in the mid-elevational range of conifers.

2. Methods

2.1. Study areas and treatments

The study areas, located on the west side of the Sierra Nevada mountain range at 900–2700 m elevation, had detailed Forest Service post-fire treatment histories which were used to assign one of three treatments (untreated, logged or herbicide: Table 1). Vegetation types in this Mediterranean climate (wet snowy winters, mostly dry summers) include mixed conifer dry forest, mixed conifer mesic forest, red fir (*Abies magnifica*) forest and post-fire montane chaparral. A stand-replacing fire occurred in all study areas in 2002, 2001, 1992 or 1987. Study areas (Fig. 1; Table 1) include:

(A) 2002 McNally Fire area, Sequoia National Forest [Fire history from the California Fire and Resource Assessment Program (FRAP, http://frap.cdf.ca.gov/) indicated no other >20 ha wildfires have occurred since 1950 in the study locations].
(B) 2001 Star Fire area, Tahoe and Eldorado National Forests (FRAP indicated no other >20 ha wildfires have occurred since 1950 in the study locations).

Table 1
Sierra Nevada west side burned areas: study locations (2006–2008), treatments and sample size.

Fire area	Year of fire	Age when studied	Location (lat, long)	Treatment name	Post-fire treatments included	Slope (degrees)	Folded aspect	Conifer stump + snag basal area (m²/ha)	N_a	N_b
All areas	1987–2002	4–21	Sierra Nevada west slope	Untreated	None	18 (1)[a]	87 (8)[a]	55 (5)[a]	47	789
				Logged	Logging fire-killed trees	16 (1)[a]	83 (8)[a]	57 (5)[a]	59	720
				Herbicide	Logging fire-killed trees, herbicides targeting shrubs	15 (1)[a]	87 (7)[a]	38 (5)[b]	65	865
McNally	2002	4–6	36.1° N, 118.3° W	Untreated	None	20 (1)[a]	99 (14)[a]	76 (6)[a]	19	316
				Logged	Logging fire-killed trees[c]	18 (2)[a]	93 (13)[a]	60 (6)[a]	19	261
Star	2001	5–6	39.1° N, 120.5° W	Untreated	None	16 (2)[a]	68 (15)[a]	78 (9)[a]	13	269
				Logged	Logging fire-killed trees[d]	13 (2)[a]	83 (14)[a]	76 (9)[a]	12	158
				Herbicide[h1]	Logging fire-killed trees, herbicides targeting shrubs[e]	13 (3)[a]	69 (16)[a]	75 (9)[a]	14	214
Cleveland[*]	1992	14–16	38.7° N, 120.4° W	Untreated	None	9 (2)[a]	127 (40)[a]	1 (16)[a]	4	48
				Logged	Logging fire-killed trees[f]	15 (2)[a]	89 (15)[a]	53 (7)[b]	20	204
				Herbicide[h2]	Logging fire-killed trees, herbicides targeting shrubs[g]	16 (1)[a]	99 (12)[a]	41 (6)[ab]	31	392
Stanislaus[**]	1987	19–21	37.9° N, 120.0° W	Untreated	None	19 (3)[a]	74 (14)[a]	12 (4)[a]	11	156
				Logged	Logging fire-killed trees[h]	19 (2)[a]	50 (21)[a]	29 (5)[b]	8	97
				Herbicide[h3]	Logging fire-killed trees, herbicides targeting shrubs[i]	15 (2)[a]	82 (13)[a]	8 (3)[a]	20	259

Different letters in a column (blocked by individual fire areas and all areas) indicate significant difference at $\alpha = 0.05$. N_a: Sample size of all variables except grass and forb cover and foliage litter depth (includes slope, folded aspect, and basal area, left). N_b: Sample size of native and alien grass and forb cover and foliage litter depth.
[*] Includes areas that burned once (1992), twice (1959 and 1992), and three times (1959, 1992 and 2001).
[**] Includes the Hamm, Larson and Paper fires.
[h1] Glyphosate applied by hand sprayers.
[h2] Glyphosate/Triclopyr applied by hand sprayers.
[h3] Mostly hexazinone aerially applied before 1996–1998, then Glyphosate applied by hand.
[c] Logged and very few sites also planted with conifers in 2004–2005.
[d] Logged and half of the plots also planted with conifers in 2002–2005.
[e] Logged and planted with conifers in 2002–2005.
[f] Logged and most sites also planted with conifers in 1993–1996.
[g] Panted with conifers in 1993–1996 and most conifer plantations were thinned.
[h] Logged in 1988–1990 and few sites were also deep-tilled and then planted with conifers in 1990–1999.
[i] Most sites logged in 1988–1989, deep-tilled and then planted with conifers in 1990–1999.

(C) 1992 Cleveland Fire area, Eldorado National Forest [FRAP history of >20 ha wildfires since 1950 for all comprehensive fuel assessment stands (stands in which all variables were measured): 47% of the plots burned in 1992 only, 47% burned in both 1992 and 1959, and 5% burned in 2001, 1992 and 1959; fire history for rapid assessment plots (plots in which grass cover, forb cover and foliage litter depths were measured): 56% of the plots burned in 1992 only, 42% burned in both 1992 and 1959 (or 1954), and 3% burned three times, in 2001, 1992 and 1959].
(D) 1987 Stanislaus Fire Complex area, Stanislaus National Forest (FRAP history of >20 ha wildfires since 1950, with some earlier fires: includes the 1987 Hamm, Larson, and Paper fire areas, plus several study locations were inside the boundaries of one or more small fires in 1909–1959).

2.2. Treatment and fire effects assessed

Empirical field studies tested the effects of: (a) logging fire-killed trees and (b) post-fire herbicide treatment targeting shrub fields on: shrub cover, grass and forb cover, alien species cover, alien species richness and surface fuel loads. Fire behavior models predicted the effects of no treatment, logging fire-killed trees and herbicide use on potential surface and crown fire behavior and the probability of large conifer (<137 cm tall) mortality from fire.

2.2.1. Untreated stands

For several reasons (i.e., fiscal constraints, habitat protection, stream and hillside protection, the desire for natural regeneration, litigation, etc.) some areas were not treated after stand-replacing fire, however we carefully selected untreated sites that were forests before stand-replacing fire (with one exception, described in the comprehensive fuel assessment protocol, below, which had good site potential for conifers). In our analysis we considered untreated stands to be the controls for logged stands

2.2.2. Logged stands

Logging fire killed trees was a general treatment that included a wide variety of snag removal activities and related silvicultural activities, except for the broad-scale use of herbicides or mastication. Neither the intensity nor the methods were consistent across the study areas. Some logging methods and subsequent mechanical site preparations (i.e., tractor harvest and deep tilling) resulted in extensive soil disturbance, while others (i.e., helicopter-logging) did not. Also, the time since treatment varied, because both treatments and data collection for this study occurred over multiple years (Table 1). Additionally, some sites were replanted with conifers and others were not planted. Some sites had various forms of animal control to protect planted conifers and others did not. This study was designed to describe the average effects of logging fire-killed trees in the Sierra Nevada in areas managed in a variety of intensities. As such, all logging treatments were grouped by fire area and all areas combined for analysis. This paper does not address any specific logging prescription.

2.2.3. Herbicide-treated stands

The herbicide treatment targeting shrubs involved several broad-spectrum chemicals, from hexazinone, which was usually aerially applied (until 1999), to glyphosate, which was applied by hand (Table 1). In all cases, herbicides were used as a means of limiting competition with planted conifers. As a result, all of the herbicide-treated stands had very little shrub cover. In addition to the herbicide treatment, all of the herbicide-treated stands were also planted with conifers (*Pinus ponderosa, P. jeffreyi* and other species). Furthermore, these stands also had the same variety of treatments that occurred in the logged stands, above. For this reason, logged stands were the controls for the herbicide-treated stands. It is probably safe to assume that in general, the intensity of the other silvicultural treatments in herbicide-treated stands were more intensive than these treatments in the stands without herbicides, therefore, logged stands were not simply controls for the herbicide treatment itself, but also the other activities associated with intensively growing trees.

2.3. Site selection and field measurements

Two sampling protocols were used: a comprehensive fuel assessment protocol (Table 1, sample size = N_a) and a rapid assessment protocol (to increase the sample size of fine fuel loads, described below).

2.3.1. Comprehensive fuel assessment protocol

All stands were located in burned sites with suitable conditions for coniferous forests (i.e., conifer plantations, shrub fields with evidence of burned trees, or, in one case, the portion of a burned shrub field that was left untreated for wildlife, but surrounded by conifer plantations within the same pre-fire shrub field). The locations for the comprehensive assessment stands were not randomly selected, but were widely distributed throughout the four fire areas, near roads whenever possible. Here, we attempted to match up treated and untreated stands based on slope, aspect and elevation. In the two oldest fire areas, we surveyed all of the untreated remnants that we could find at the same elevation as treatment stands, including a few on private land near Forest Service plantations. Attempting to match slopes and aspects of treated and untreated stands, we sometimes placed more than one comprehensive assessment stand on separate slopes of the same Forest Service-designated stand. Areas were selected that were large enough, if available, to fit the sampling array of Fig. 2 in the center of the stand. The exact placement of the sampling array was systematically determined off site to protect against sampling bias. Some treatment types were rare and only occurred in narrow strips that would not fit the standard sampling array and so the array had to be modified to fit the stand. Mostly, this modified sampling array was used in the Cleveland Fire area, in narrow strips of upland vegetation inside Stream-side Management Zones (Forest Service-defined areas that were typically logged and planted with conifers, but herbicides were not broadly used to kill shrubs). Sampling in these areas occurred as far away from the ephemeral streams as possible and did not occur in areas with hydrophilic riparian species.

In the comprehensive fuel assessment array, a 2 m × 50 m belt transect was oriented in a random direction; the middle of the belt pivoted from the stand center in a random direction (Fig. 2). This belt transect was used to assess crown diameter for aerial cover, height, and density of small trees (<1.37 m tall) and shrubs. Snags, stumps, and large trees (≥1.37 m tall) were measured in a 36 m diameter plot in the center of the stand (Fig. 2). Snag and large tree

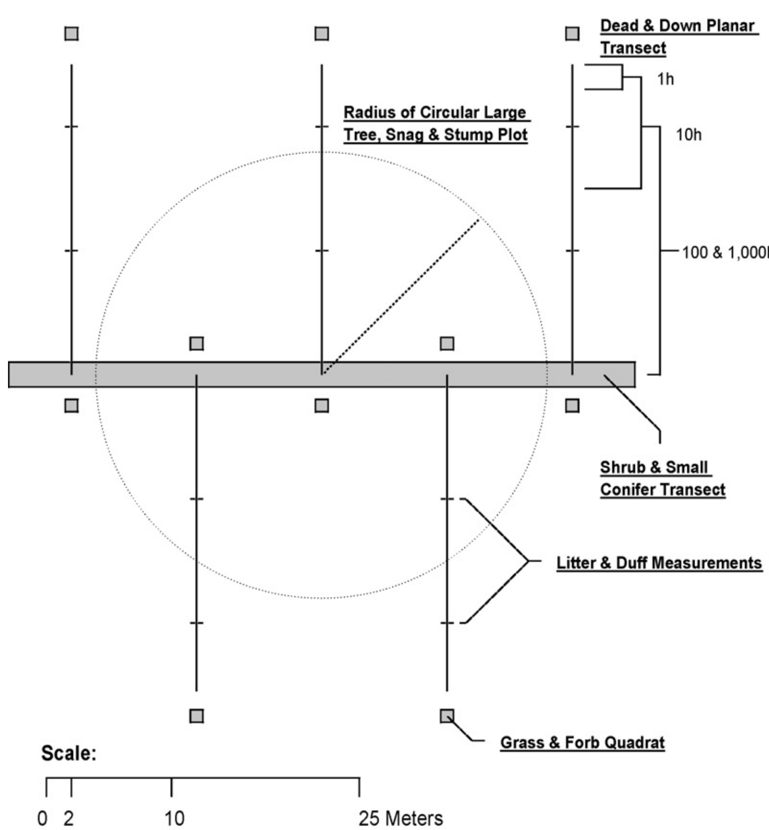

Fig. 2. Comprehensive fuel assessment array.

measurements included diameter at stump height (0.2 m above the ground), diameter at breast height for conifers only (1.37 m above the ground) and total height. Additionally, we measured height to live crown and crown radius of large conifers and hardwood trees. Species were recorded for live trees and shrubs and, when recognizable, for snags and stumps. Slope was determined at the stand center.

Dead and down fuels in the comprehensive fuel assessment stands were sampled using Brown's planar transecting method (Brown, 1974). Five 25 m transects were regularly spaced, perpendicular to the belt transect or at random angles from the belt (Fig. 2). Along these transects, woody 1-h fuels (<0.64 cm diameter) were assessed in a 2 m portion, 10-h fuels (0.64–<2.53 cm diameter) in a 10 m portion, and 100–1000-h fuels (2.53–7.62 cm diameter or greater) in the full 25 m of the transect. Thousand-hour fuel diameters were measured and noted as sound or rotten wood, and identified by species when discernable. Foliage litter depth was measured in two locations along the five transects.

Understory species in the comprehensive fuel assessment stands were surveyed in the spring or early summer using 1 m × 1 m quadrats located 2 m past both ends of the five fuels transects, for a total of 10 quadrats per stand (Fig. 2). In these quadrats, we identified plant species and determined the percentage of ground surface covered (aerial cover), using ocular estimates.

Solar radiation for each comprehensive fuel assessment stand was calculated using the formula in McCune and Keon (2002). Solar radiation on the ground was calculated by multiplying solar radiation by the percentage of ground surface area not covered by shrubs and trees.

Allometric equations were used to determine live and dead fuel loads by size class in the comprehensive fuel assessment stands. For shrubs and small conifers, we used regression equations reported in the Woody Plant Biomass Calculator (http://www.werc.usgs.gov/Project.aspx?ProjectID=177), which were from specimens collected in our study sites. Dead and down fuel loads were determined from the equations reported by Brown (1974) and updated with Sierra Nevada specific values from van Wagtendonk et al. (1996). Canopy fuels in large conifers were estimated from allometric equations in Carlton (2005). Live herbaceous fuel loads were estimated using a cover-to-biomass regression equation derived from data from a previous study (Keeley and McGinnis, 2007).

2.3.2. Rapid assessment protocol

In order to increase the sample size of foliage litter depths and aerial cover of native and alien grasses and forbs, we used rapid assessment plots, which were randomly located throughout the four fire areas and outside of comprehensive fuel assessment areas, without regard to Forest Service-designated stand boundaries. We mapped several hundred random points within each fire area using GIS and then surveyors were dropped off in different locations with a GPS and a map, where they walked from point to point, surveying all the mapped points that they came to. This resulted in sinuous patterns of rapid assessment plots because we intentionally mapped more random points than could be surveyed. Rapid assessment plots included two meter-long 1-h fuel transects (combined), four litter depth measurements (averaged) and a 1 m^2 native and alien grass and forb cover quadrat (Table 1, sample size = $N_b - 10 \times N_a$).

2.4. Fire behavior modeling

Three fire behavior modeling systems were used to predict different fire effects. All models used the mean slope of all the stands (29%), so that treatment effects on fuel-related fire behavior would not be confounded by slope effects. For surface fire behavior predictions (rate of spread and flame length), BehavePlus 4 (Andrews and Bevins, 2008) was used with surface fuel loads derived from field measurements (custom fuel models) and large conifers were not included. Other inputs, including, surface area-to-volume ratios for dead, live herbaceous and live woody fuels, dead fuel moisture of extinction, and dead and live heat content were from standard fire behavior fuel models (Scott and Burgan, 2005). For large conifer mortality predictions in the two oldest fire areas (Cleveland and Stanislaus fires), FMAPlus 3 (Carlton, 2005) was used with surface fuel loads from standard fuel models (Scott and Burgan, 2005) and individual large conifer field measurements. To determine which standard fuel model to use for each stand in FMAPlus, probable models derived from the key in Scott and Burgan (2005) were run in BehavePlus and flame lengths were compared with those of the custom models. We then selected the standard model with the closest predicted flame length to that of the custom model (GR4 for herbicide-treated stands in the Cleveland Fire that had burned three times, TL3 or TL8 for the remaining herbicide-treated stands and SH5 or SH7 for logged and untreated stands). For crown fire predictions in herbicide-treated stands of the two oldest fire areas, the Canadian Forest Fire Prediction System (Taylor et al., 1996) was used with model C6 (the conifer plantation model, the only fuel model specifically for this vegetation type).

For all the fire models, weather and fuel moisture were determined for both low danger early season (June 15–30 to represent average environmental conditions when live vegetation had high moisture content) and for extremely hazardous (98th percentile) conditions. Weather data dating back more than 20 years were used from Remote Automated Weather Stations (RAWS) near the four field sites. One, 10, 100-h and live fuel moistures were from calculations using FireFamily Plus 3 software (Brittain, 2004) [low danger early season conditions: 1-h fuel moisture content (fmc) = 3%, 10-h fmc = 4%, 100-h fmc = 8%, herbaceous fmc = 81–90%, wind speed = 2.7–4.9 m/s, wind adjustment factor = 0.2–0.5; extremely hazardous conditions: 1-h fmc = 2%, 10-h fmc = 2–3%, 100-h fmc = 5–6%, herbaceous fmc = 30%, live woody fmc = 50–62%, wind speed = 4.0–6.3 m/s, wind adjustment factor = 0.2–0.5]. For low danger early season live woody fuel moisture content (120%) we used the mean value from 23 years of field sampling by the Stanislaus National Forest at Mt. Provo, California, elevation 1341 m.

2.5. Data analysis

Three levels of analysis having three levels of inference comprised: (A) post fire treatment effects across all sites combined (the level of inference was the entire Sierra Nevada west side mid-elevation conifer zone in <22-year-old stand-replacing fire areas), (B) post fire treatment effects analyzed separately for each of the four stand-replacing fire areas (the level of inference was limited to each individual fire area), and (C) effects of multiple events of fires and post-fire treatments in the Cleveland Fire area with various combinations of fires and treatments. Fire history effects were not analyzed in the Stanislaus Complex which had several small fires between 1909 and 1959. Grass and forb cover (native grass, alien grass, native forb, alien forb and total grass and forb cover), and foliage litter depths were assessed using the combined data from both rapid assessment plots and individual plots in detailed assessments (sample size = N_b, Table 1). All other treatment effects, including fire behavior modeling effects, were assessed using the comprehensive fuel assessment array (sample size = N_a, Table 1).

To compare the effects of treatment type across all Sierra Nevada sites, mixed effects models were used, with fire, plot nested in fire, and the interaction of fire and treatment type as random effects. Within individual fire areas, treatment effects were also analyzed with mixed models, using plot as the random effect. Mixed models

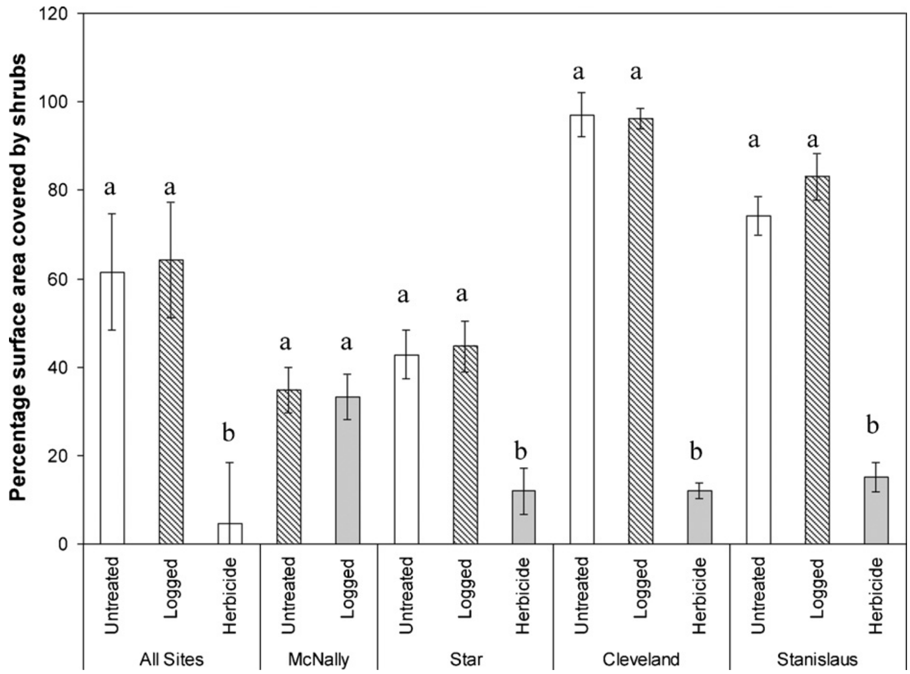

Fig. 3. Sierra Nevada post-fire percentage of ground surface area covered by shrubs. Different letters above bars (blocked by individual fire areas and all sites) indicate significant difference at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions.

for the Cleveland Fire area also had the number of fires, the number of herbicide applications, and the interaction of treatment and numbers of fires as additional fixed effects. For grasses, forbs and litter depth, including plot as a random effect controlled for plot variation among groups of plots. In the fuel analyses, which applied only to the comprehensive arrays, multiple transects for measuring fuel loads within each array were combined to provide a single value per stand (i.e. average 10, 100 and 1000-h fuel loads over the five individual transects per comprehensive fuel assessment array were combined). The mixed models were followed by Fisher's LSD tests to compare effects of treatment types. Comparisons within the Cleveland Fire area stands that burned different numbers of times were analyzed the same way except that the effects of numbers of fires and numbers of herbicide treatments were evaluated as continuous effects. However, ANOVA with Tukey post hoc tests were used to analyze the effects of a specific number of fires combined with a specific treatment using comprehensive stand data. Natural-log, logit, square-root and arcsin square-root transformations were used, when necessary, to correct normality and homoscedasticity. All mixed models were fitted using restricted maximum likelihood and denominator degrees of freedom were computed using the Satterthwaite approximation (SAS Institute, 2007; Littell et al., 1996). $P < 0.05$ was considered significant for all analyses.

Linear regression was used to explore the relationship between solar radiation on the ground and (a) total grass and forb cover, (b) alien grass and forb cover and (c) alien grass and forb species richness in the comprehensive fuel assessment stands. Linear regression was also used to explore the relationship between aspect (folded, as per McCune and Keon, 2002) and total grass and forb cover in the comprehensive fuel assessment stands.

3. Results

3.1. Logging fire-killed trees

Stand structure: Analysis of snag + stump basal area in logged and untreated stands indicated that in the two youngest fire areas (McNally and Star), prefire stand structure was not significantly different in the two treatment types (Table 1). However, snag + stump basal area was significantly different in logged and untreated stands of the two oldest fire areas (Cleveland and Stanislaus). Snag + stump basal area in these stands indicate that logging probably occurred in the areas with greater prefire basal area

3.1.1. Logging effects on shrub cover

Shrub cover was not found to be significantly different between logged and untreated stands in all areas combined or in any of the individual fire areas (Fig. 3). Shrub aerial cover (percentage of the ground surface area covered by shrubs) was approximately equal in logged and in untreated stands within the individual fire areas, ranging from ~33% in logged and untreated stands of the young southern fire area (McNally Fire) to nearly 100% in logged and untreated stands in the second oldest fire area (Cleveland Fire) (Fig. 3). Also, in the Cleveland Fire area, shrub cover was not significantly different between logged and untreated stands that had burned twice (1959 and 1992). Nor was there a different between logged stands that had burned once versus twice (Cleveland Fire area). Small conifer cover was low in all four fire areas and was not significantly different based on treatment (Table 2). Available live woody fuel loads were closely related to shrub and small conifer cover and were not significantly different between logged and untreated stands (Table 3).

3.1.2. Logging effects on total and alien grass and forb cover

Total grass and forb cover was not significantly different between logged and untreated stands in all areas combined or in the four individual fire areas (Fig. 4). Also, total grass and forb cover was not significantly different between logged and untreated stands that had burned twice (Cleveland Fire area). Alien grass and forb cover was not significantly different between logged and untreated stands in all areas combined or within the individual fire areas (Table 4).

3.1.3. Logging effects on alien species richness

Alien grass and forb species richness was not found to be significantly different between logged and untreated stands

Table 2
Sierra Nevada west side burned areas: percentage of aerial cover of small conifers (<1.37 m tall), large conifers (≥1.37 m tall) and hardwood trees, and large conifer density [mean (standard error)].

Fire area	Treatment	Small conifer percentage aerial cover	Large conifer percentage aerial cover	Hardwood tree percentage aerial cover	Large conifer density (trees/ha)	Large conifer height to live crown (m)	Large conifer height (m)	Large conifer dbh (cm)
All areas	Untreated	0.5 (0.7)[a]	1.5 (6.0)[a]	3.0 (4.4)[a]	57 (108)[a]	–	–	–
	Logged	0.9 (0.6)[a]	3.1 (5.9)[a]	7.4 (4.3)[a]	81 (106)[a]	–	–	–
	Herbicide	1.1 (0.6)[a]	21.7 (6.6)[b]	4.1 (4.4)[a]	362 (115)[b]	–	–	–
McNally	Untreated	0.1 (0.1)[a]	0[a]	0.1 (0.1)[a]	0[a]	–	–	–
	Logged	0.0 (0.1)[a]	0[a]	0.0 (0.0)[a]	0[a]	–	–	–
Star	Untreated	1.4 (0.9)[a]	0[a]	2.1 (1.2)[a]	0[a]	–	–	–
	Logged	3.3 (0.9)[a]	0[a]	1.7 (1.3)[a]	0[a]	0*	1.5*	4*
	Herbicide	3.3 (0.8)[a]	0.1 (0.0)[a]	1.1 (1.2)[a]	1 (1)[a]*	0.02 (0.02)*	1.7 (1.7)*	2 (2)*
Cleveland	Untreated	0.0 (0.0)[a]	0.1 (6.7)[a]	0.2 (2.1)[a]	10 (112)[a]	1.0**	2**	4**
	Logged	0.2 (0.2)[a]	4.9 (3.0)[a]	2.6 (0.9)[a]	137 (50)[b]	0.6 (0.1)[a]	3 (0.2)[a]	6 (1)[a]
	Herbicide	0.4 (0.1)[a]	20.4 (2.4)[b]	2.3 (0.7)[a]	342 (40)[c]	0.5 (0.1)[a]	5 (0.2)[b]	11 (1)[b]
Stanislaus	Untreated	0.6 (0.5)[a]	5.6 (5.3)[a]	9.4 (6.3)[a]	203 (129)[a]	0.6 (0.1)[a]	3 (0.6)[a]	6 (2)[a]
	Logged	0.2 (0.4)[a]	7.6 (6.1)[a]	27.9 (7.3)[a]	177 (151)[a]	0.6 (0.1)[a]	3 (0.5)[a]	5 (1)[a]
	Herbicide	0.4 (0.4)[a]	45.3 (3.9)[b]	12.9 (4.6)[a]	770 (96)[b]	1.2 (0.1)[b]	5 (0.3)[b]	11 (1)[b]

Different letters in a column (blocked by individual fire areas and all areas) indicate significant difference at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions.
* Most trees were small in the Star Fire area; only one logged and two herbicide comprehensive fuel assessment plots contained large conifers.
** Untreated stands of the Cleveland Fire area had almost no large conifers; only one untreated comprehensive fuel assessment plot contained large conifers.

Table 3
Sierra Nevada west side burned areas: foliage litter depth and individual and total available fuel loads [mean Mg/ha (standard error)].

Fire area	Treatment	*Foliage litter depth (cm)	10-h (0.64–<2.54 cm diameter)	100-h (2.54–<7.62 cm diameter)	1000-h (≥7.62 cm diameter)	**Available live woody fuels (shrubs and trees)
All areas	Untreated	1.9 (0.5)[a]	2.1 (0.5)[a]	5.0 (1.5)[a]	37.8 (9.4)[a]	3.9 (2.4)[a]
	Logged	2.0 (0.5)[a]	2.6 (0.5)[a]	9.3 (1.5)[b]	55.9 (9.1)[a]	4.4 (2.4)[a]
	Herbicide	1.6 (0.5)[a]	2.2 (0.5)[a]	6.8 (1.5)[ab]	24.3 (9.3)[a]	6.5 (2.6)[a]
McNally	Untreated	1.0 (0.1)[a]	2.3 (0.2)[a]	3.8 (0.7)[a]	17.7 (6.1)[a]	1.2 (0.2)[a]
	Logged	0.9 (0.1)[b]	2.0 (0.2)[a]	7.8 (0.7)[b]	35.3 (6.1)[b]	1.1 (0.2)[a]
Star	Untreated	1.3 (0.1)[a]	3.0 (0.4)[a]	7.0 (1.4)[a]	45.9 (9.0)[a]	1.2 (0.2)[a]
	Logged	1.5 (0.2)[a]	4.0 (0.4)[a]	14.7 (1.4)[a]	66.8 (9.4)[a]	1.5 (0.2)[a]
	Herbicide	1.2 (0.1)[a]	3.3 (0.4)[a]	11.0 (1.3)[a]	44.1 (8.7)[a]	0.5 (0.2)[b]
Cleveland	Untreated	1.7 (0.4)[ab]	1.3 (0.5)[a]	4.5 (1.6)[a]	28.2 (23.3)[ab]	8.3 (2.2)[a]
	Logged	2.6 (0.2)[a]	1.8 (0.2)[a]	6.0 (0.7)[a]	72.8 (10.4)[a]	6.2 (1.0)[a]
	Herbicide	1.8 (0.2)[b]	2.1 (0.2)[a]	5.7 (0.6)[a]	36.3 (8.4)[b]	6.1 (0.8)[a]
Stanislaus	Untreated	3.1 (0.3)[a]	1.7 (0.3)[ab]	5.4 (1.4)[ab]	50.4 (8.4)[a]	5.7 (2.0)[a]
	Logged	3.0 (0.4)[a]	2.7 (0.4)[b]	9.1 (1.7)[a]	45.6 (9.9)[a]	9.0 (2.3)[a]
	Herbicide	2.7 (0.2)[a]	1.2 (0.2)[a]	4.8 (1.1)[b]	10.3 (6.3)[b]	15.2 (1.4)[b]

Hour ratings refer to dead time lag surface fuels. Different letters in a column (blocked by individual fire areas and all areas) indicate significant difference at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions.
* Combined with rapid assessment plots for greater sample size.
** Live biomass that is thought to be available in the surface and crown fire front is live foliage and 50% of live branches <0.64 cm diameter.

Table 4
Sierra Nevada west side burned areas: percentage of aerial cover of native and alien grasses and forbs and native species richness [mean (standard error)].

Fire area	Treatment	Native grass aerial cover	Alien grass aerial cover	Native forb aerial cover	Alien forb aerial cover	Native species richness
All areas*	Untreated	3.8 (3.1)[a]	1.7 (1.4)[a]	6.2 (2.2)[a]	0.2 (0.2)[a]	29.1 (2.5)[a]
	Logged	3.4 (3.1)[a]	1.4 (1.4)[a]	6.7 (2.2)[a]	0.5 (0.2)[a]	30.0 (2.3)[a]
	Herbicide	12.9 (3.5)[a]	6.3 (1.5)[b]	8.5 (2.2)[a]	1.5 (0.2)[b]	31.5 (2.6)[a]
McNally	Untreated	3.1 (0.8)[a]	2.0 (0.6)[a]	11.4 (1.3)[a]	0.07 (0.03)[a]	32.6 (1.7)[a]
	Logged	2.5 (1.0)[a]	0.6 (0.8)[a]	11.0 (1.6)[a]	0.05 (0.03)[a]	28.9 (1.7)[a]
Star	Untreated	3.9 (1.1)[a]	0.2 (0.4)[a]	5.6 (0.9)[a]	0.2 (0.3)[a]	27.2 (3.2)[a]
	Logged	0.2 (1.7)[b]	0.01 (0.7)[a]	9.1 (1.4)[ab]	1.1 (0.4)[ab]	33.0 (3.3)[a]
	Herbicide	5.3 (1.4)[a]	1.2 (0.5)[a]	9.4 (1.1)[b]	1.4 (0.3)[b]	36.1 (3.1)[a]
Cleveland*	Untreated	4.5 (6.7)[a]	0.3 (3.1)[a]	7.2 (3.0)[a]	1.3 (0.7)[ab]	28.5 (4.4)[ab]
	Logged	3.3 (4.5)[a]	1.2 (1.8)[a]	3.5 (1.8)[b]	0.4 (0.4)[a]	28.0 (2.0)[a]
	Herbicide	25.7 (2.2)[b]	7.1 (1.1)[b]	8.7 (1.0)[a]	1.9 (0.3)[b]	35.5 (1.7)[b]
Stanislaus	Untreated	3.8 (1.8)[a]	3.3 (1.5)[a]	1.8 (0.7)[a]	0.1 (0.3)[a]	27.3 (3.0)[a]
	Logged	8.1 (2.7)[a]	2.2 (2.1)[a]	2.4 (1.0)[a]	0.3 (0.4)[a]	30.8 (3.6)[a]
	Herbicide	7.9 (1.5)[a]	10.6 (1.2)[b]	3.0 (0.6)[a]	1.2 (0.2)[b]	23.0 (2.3)[a]

Different letters in a column (blocked by individual fire areas and all areas) indicate significant difference at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions.
* Not including plots from the Cleveland Fire area that burned three times (grass and forb cover was greater in the excluded plots).

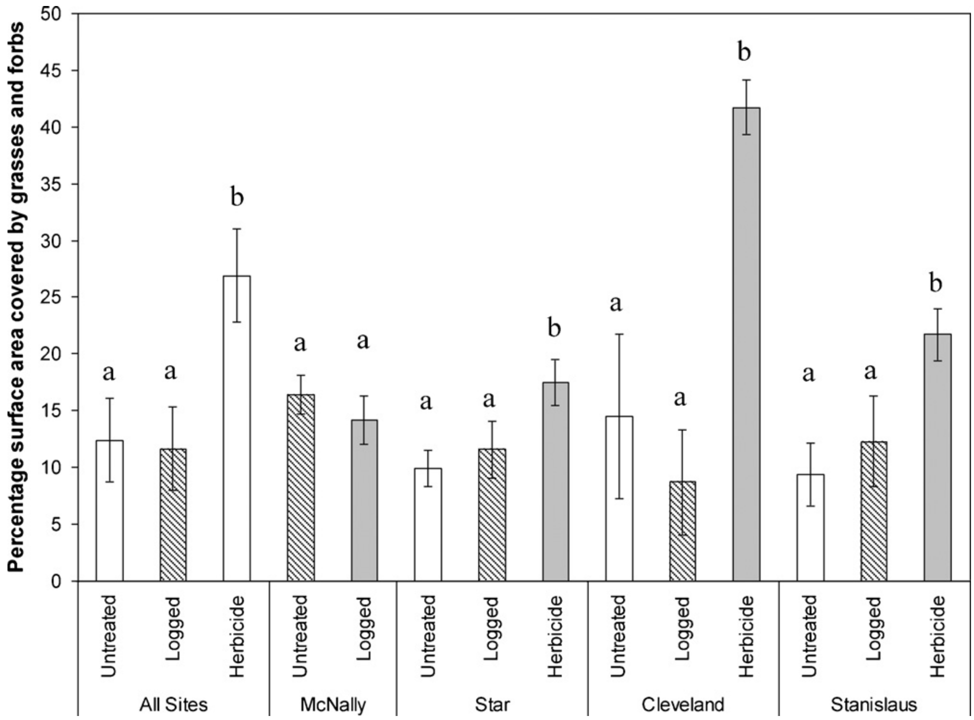

Fig. 4. Sierra Nevada post-fire percentage of ground surface area covered by grasses and forbs, excluding plots from the Cleveland Fire area that burned three times and had greater grass and forb cover. Different letters above bars (blocked by individual fire areas and all sites) indicate significant difference at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions.

(Fig. 5). Likewise, alien grass and forb species richness was not found to be significantly different between logged and untreated stands of the Cleveland Fire area that had burned twice. On average, there were fewer than two alien species in logged and untreated stands in the three youngest fire areas, whereas, logged and untreated stands in the oldest fire area (Stanislaus Complex) had an average of two or three alien species.

The annual grass, *Bromus tectorum*, was the most common alien species encountered in the study—it occurred in 30% of the untreated stands and 18% of the logged stands. *Bromus* species (including *B. tectorum* and other species) were in 34% of the untreated stands and 27% of the logged stands. The alien grass, *Vulpia myuros,* was in approximately two-thirds as many stands as cheatgrass. *Lactuca* sp., was the most common alien forb (same frequency as *V. myuros*), followed by *Tragopogon* and *Torilis arven-*

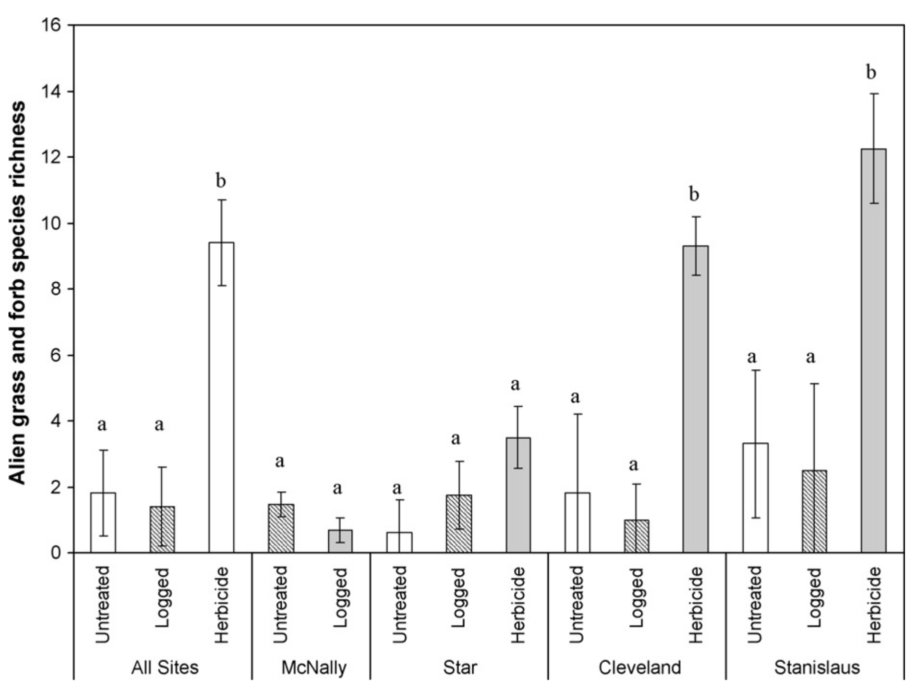

Fig. 5. Sierra Nevada post-fire alien grass and forb species richness, excluding plots from the Cleveland Fire area that burned three times and had greater alien richness. Different letters above bars (blocked by individual fire areas and all sites) indicate significant difference at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions.

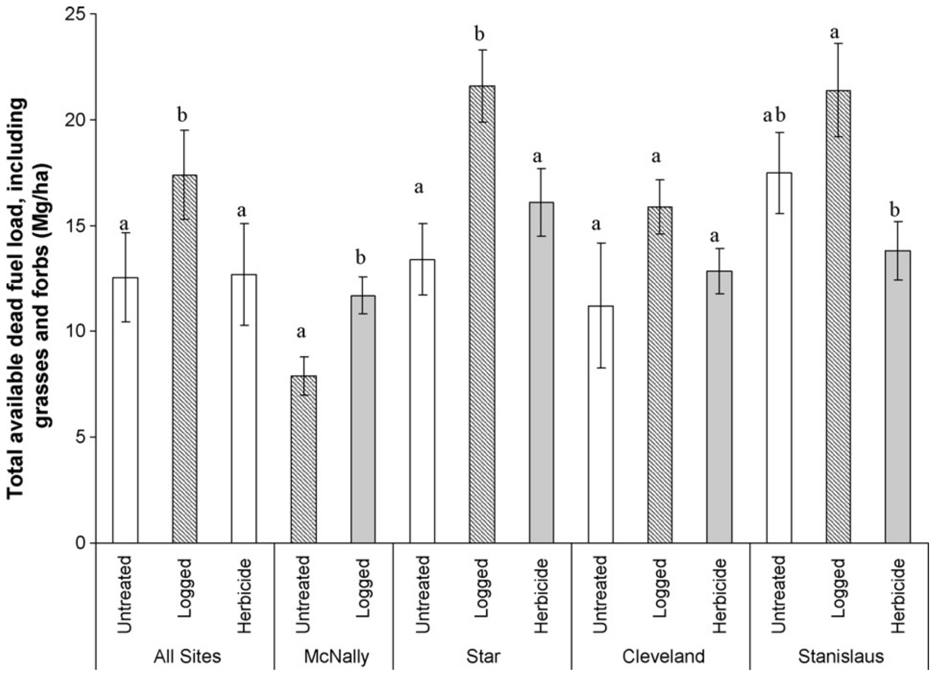

Fig. 6. Sierra Nevada post-fire total available dead surface fuel load, including grasses and forbs. Different letters above bars (blocked by individual fire areas and all sites) indicate significant difference at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions.

sis. *Lactuca sp*. occurred at approximately the same frequency in logged (in 14% of the stands) and untreated stands (in 16% of the stands).

3.1.4. Logging effects on surface fuel loads

Total available dead fuel loads were significantly greater in logged stands than untreated stands in all areas combined and in the two youngest fire areas (McNally and Star fires) (Fig. 6). They were not different in the two oldest fire areas (Cleveland and Stanislaus fires), even though pre-fire basal area may have been greater in logged areas (Table 1). Few of the individual dead fuel components were significantly different between logged and untreated stands (Table 3).

3.2. Post fire herbicide treatment targeting shrubs

3.2.1. Stand structure

Analysis of snag + stump basal area in herbicide-treated and logged stands indicated that stand structure was not significantly different in the youngest fire area with the herbicide treatment (Star; Table 1). Snag + stump basal area was not significantly different between herbicide-treated and logged stands of the second oldest fire area (Cleveland), but was significantly different between stands of the oldest fire area (Stanislaus). However, due to extensive ground disturbance, decay, and stumps from plantation thinning, we could not use stumps and snags to determine pre-fire stand structure in these older areas.

3.2.2. Herbicide effects on shrub cover

The herbicide treatment was effective at significantly reducing shrub cover; herbicide-treated stands had significantly lower shrub cover than logged stands in all areas combined and in all three individual fire areas with this treatment (Fig. 3). Shrub cover in herbicide treated stands was not significantly different in the multiple burns of the Cleveland Fire area.

3.2.3. Herbicide effects on conifers

Conifer cover, density, height and stem diameter were significantly greater in herbicide-treated stands than logged stands (Table 2); however, this does not indicate whether or not survival and growth were greater in herbicide-treated stands, as not all logged areas were planted and we did not have data on planting density in logged stands.

3.2.4. Herbicide effects on grass and forb cover

Herbicide-treated stands had significantly greater grass and forb cover than logged stands (Fig. 4). Also, herbicide-treated stands that burned three times had significantly greater grass and forb cover than those that burned twice, and those that burned twice had greater cover than those that burned once (Cleveland Fire area). The results reported in Fig. 4 and Table 4 did not include plots that burned three times (and the number of fires remained a fixed effect).

Having found that grass and forb cover was greatest in herbicide treated stands, where shrub cover was the lowest, some of the factors that could have accounted for the differences were tested. It was found that grass and forb cover was strongly correlated with the amount of solar radiation on the ground (calculated from latitude, slope, aspect and woody vegetation cover) in the two oldest fire areas combined (Fig. 8). Solar radiation on the ground explained 60% of the variation, whereas aspect alone only explained 7% of the variation.

3.2.5. Herbicide effects on alien species cover

Alien grass and forb cover was significantly greater in herbicide-treated stands than logged stands in all areas combined and in the two oldest fire areas (Cleveland and Stanislaus fires) (Table 4). Combined alien grass and forb cover was correlated with the amount of solar radiation on the ground in the two oldest fire areas combined; solar radiation explained 36% of the variation of alien cover (Fig. 8).

3.2.6. Herbicide effects on alien species richness

Alien grass and forb species richness was significantly greater in herbicide-treated stands than logged stands in all areas com-

Fig. 7. Observations after an escaped late-season prescribed fire that had burned through a highly-maintained herbicide-treated stand on the Stanislaus NF provide an example of the low probability for young conifer survival after a fire, except when fuel moisture is high, as it is in most stands only in the springtime. In this example (both photos), all the trees were the same age (<17 years old, planted after the 1990 A-Rock Fire), limbed to the same height (2 m), uniformly thinned (~5 m spacing) and were on the same gentle slope. The trees in this herbicide-treated stand that died had surface fuels consisting of short drought-resistant vegetation and litter, whereas, the trees that survived had a scorched bracken fern and litter surface fuel layer (none of our study stands had extensive bracken fern). The presence of bracken fern, which was still green outside the fire perimeter, indicates that this area has unusually high fuel moisture and is analogous to an herbicide-treated stand with grass and forb understory in the late spring only. Scorched needles at the bottom of the canopy of the surviving trees indicate that limbing may have prevented torching and that perhaps limbing could be used to protect trees from late spring prescribed fires in plantations.

bined and in the two oldest fire areas (Cleveland and Stanislaus fires) (Fig. 5). Alien species richness was also significantly greater in herbicide-treated stands than logged stands of the Cleveland Fire area that had burned once or twice. *Bromus tectorum*, the most common alien species in both herbicide-treated and logged stands, occurred in 47% of the herbicide-treated stands and 18% of the logged stands. *Bromus* species (including *B. tectorum* and other species) occurred in 65% of the herbicide-treated stands and 27% of the logged stands. The most common alien forb, *Lactuca* sp., was twice as frequent in herbicide-treated stands (31% frequency) as logged stands (14% frequency). Alien grass and forb species richness was correlated with the amount of solar radiation on the ground in the two oldest fire areas combined; solar radiation explained 34% of the variation of alien species richness.

3.2.7. *Herbicide effects on surface and canopy fuel loads*

The herbicide treatment resulted in a significant reduction of available live woody fuel loads in the Star Fire area (Table 3). In the Cleveland Fire area, available live woody fuel loads were not significantly different between logged stands, which had high shrub cover and low conifer cover, and herbicide treated stands, which had low shrub cover and high conifer cover. In the oldest fire area (Stanislaus Complex), however, where trees were older, total available live woody fuel loads were significantly greater in herbicide-treated stands than logged stands (Table 3), due to the size and spacing of the conifers in these stands (Table 2).

Total available dead fuel loads were significantly lower in herbicide-treated stands than logged stands in all areas combined and in the Star and Stanislaus fire areas (Fig. 6). In the second oldest fire area (Cleveland), foliage litter depth was lower in herbicide-treated stands, and in the oldest fire area (Stanislaus), 10 and 100-h loads were lower (Table 3). Thousand-hour fuel loads were also lower in the herbicide-treated stands of two oldest fire areas (Cleveland and Stanislaus; Table 3).

In the young northern fire area (Star Fire), only a few of the herbicide-treated areas had conifers >1.37 m tall and no large post-fire conifers were in the untreated areas (Table 2). However, large conifer cover was significantly greater in herbicide-treated stands than logged stands in the two oldest fire areas. Hardwood tree aerial cover was not significantly different in any of the fire areas based on treatment (Table 2).

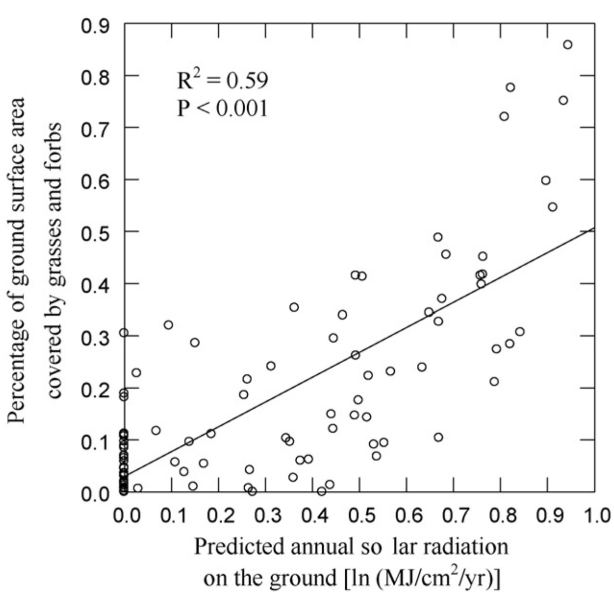

Fig. 8. The relationship between solar radiation reaching the ground (calculated from latitude, slope, aspect and woody vegetation cover) and ground surface area covered by grasses and forbs in Sierra Nevada fire areas (Cleveland and Stanislaus fires). See Table 1 for locations and post-fire treatments.

3.2.8. *Comparison of herbicide-treated conifer plantations to shrub-dominated stands*

To summarize the effects of herbicides directed at shrubs, in this section we again look at the three fire areas with the herbicide treatment (Star, Cleveland, and Stanislaus), but this time, combine logged and untreated stands as a single treatment (no-herbicide) and compare these stands to herbicide-treated stands, minus those that burned three times. First, we found that grasses and forbs responded positively to the reduced shrub cover. Herbicide-treated plantations had greater total grass/forb cover and alien forb cover. The two oldest fire areas (Cleveland and Stanislaus) also had greater alien grass cover in the herbicide-treated stands. Also, the herbicide-treated stands in the two oldest fire areas had significantly greater alien species richness than no-herbicide stands

Next, we explore fuel loads. We found no clear pattern for dead surface fuel loads. Whereas, the herbicide-treated stands in the Cleveland Fire area had significantly greater foliage litter depths than the no-herbicide stands, herbicide-treated stands of the Stanislaus Complex had lower 10-h fuel loads than no-herbicide stands. There was a clear pattern for live fuel loads. In the youngest

Table 5
Sierra Nevada west side burned areas: predicted mean surface fire behavior (standard error) during low danger early season (June 15–30) and extremely hazardous (98th percentile) weather and fuel moisture conditions modeled from custom fuel models (using BehavePlus). For consistancy with standard fuel models, our custom models included shrubs as surface fuels, but did not include large conifer branches as surface fuels, even when they were in the shrub layer.

Fire area	Treatment	Predicted low danger early season rate of spread (m/s)	Predicted extremely hazardous rate of spread (m/s)	Predicted low danger early season flame length (m)	Predicted extremely hazardous flame length (m)
All areas	Untreated	0.2 (0.1)[a]	0.4 (0.2)[a]	2.8 (0.7)[a]	4.5 (1.1)[a]
	Logged	0.2 (0.1)[a]	0.4 (0.1)[a]	3.1 (0.7)[a]	4.7 (1.1)[a]
	Herbicide	0.01 (0.1)[b]	0.1 (0.1)[b]	0.8 (0.8)[b]	0.9 (1.2)[b]
McNally	Untreated	0.1 (0.01)[a]	0.14 (0.01)[a]	1.6 (0.1)[a]	2.4 (0.2)[a]
	Logged	0.1 (0.01)[a]	0.11 (0.01)[b]	1.5 (0.1)[a]	2.2 (0.2)[a]
Star	Untreated	0.1 (0.01)[a]	0.2 (0.02)[ab]	1.9 (0.2)[a]	2.8 (0.2)[a]
	Logged	0.1 (0.01)[a]	0.2 (0.02)[a]	2.4 (0.2)[b]	3.5 (0.3)[b]
	Herbicide	0.1 (0.01)[a]	0.1 (0.02)[b]	1.7 (0.2)[a]	2.3 (0.2)[a]
Cleveland	Untreated	0.1 (0.03)[a]	0.5 (0.1)[a]	2.6 (0.4)[a]	5.7 (0.6)[a]
	Logged	0.2 (0.01)[a]	0.5 (0.03)[a]	3.4 (0.2)[a]	6.0 (0.3)[a]
	Herbicide	0.02 (0.01)[b]	0.04 (0.03)[b]	0.7 (0.1)[b]	0.9 (0.2)[b]
Stanislaus	Untreated	0.4 (0.04)[a]	0.9 (0.1)[a]	5.1 (0.3)[a]	7.4 (0.4)[a]
	Logged	0.3 (0.05)[a]	0.7 (0.1)[a]	5.0 (0.4)[a]	7.3 (0.5)[a]
	Herbicide	0.02 (0.03)[b]	0.03 (0.1)[b]	0.7 (0.2)[b]	0.9 (0.3)[b]

Different letters in a column (blocked by individual fire areas and all areas) indicate significant difference at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions.

of the three fire areas in this analysis (Star), herbicide-treated stands had lower live woody fuel loads than no-herbicide stands. In the next older fire area (Cleveland), live woody fuel loads of conifers and sparse shrubs in herbicide-treated stands weighed the same as shrub fuels in no-herbicide stands. The difference was how they were distributed; conifer fuels were higher, with space between canopies and shrub fuels were continuous. Finally, in the oldest fire area (Stanislaus), available live woody fuels of conifers in herbicide-treated stands significantly outweighed those of shrubs in no-herbicide stands.

3.3. Predicted fire behavior

Logging had very little effect on predicted surface fire behavior. Modeled surface fire behavior was only significantly different between logged and untreated stands of the Star Fire area, where predicted flame lengths were higher in logged stands in both low danger early season and extremely hazardous fire weather, and the McNally Fire area during extreme conditions, where rate of spread was lower in logged stands (Table 5). Modeled rate of spread and flame length increased as stands aged (Table 5).

The herbicide treatment significantly affected modeled surface fire behavior. Herbicide-treated stands were predicted to have slower surface fire rate of spread (except for the Star Fire area in low danger early season) and lower flame lengths than logged stands in all sites combined and in the individual fire areas (Table 5). Differences in surface fire behavior between herbicide-treated and logged stands were predicted to increase with stand age (Table 5). Comparing herbicide-treated stands that had burned once, versus twice or three times (in the Cleveland Fire area), those that had burned three times had significantly greater grass and forb fuel loads and were modeled to have significantly greater surface fire rate of spread and flame length than those that had burned fewer times. This was predicted for both low danger early season and extreme conditions.

In the herbicide-treated stands of the two oldest fire areas (Cleveland and Stanislaus fires), the Canadian Forest Fire Prediction System, using model C-6 (the only published fire behavior model specifically for North American conifer plantations), predicted continuous crown fire (the most extreme fire behavior classification) for extremely hazardous weather and fuel moisture conditions. Using this model with low danger early season conditions, surface fire was predicted, but this fire classification may be an underestimate, as the canopy base height for this model is 2 m and most of the trees in our study areas had a height to live crown that was much lower than 2m (Table 2). FMAPlus, using standard fuel models TL3 (moderate load conifer litter) and TL8 (long-needle litter) and individual field measurements of conifer crown base height, predicted that most large conifers would die in a fire whether it occurred in the early or extreme weather and fuel moisture conditions (Table 6). The only survivors would be a small percentage of trees in certain herbicide treated stands having the shortest flame lengths and highest canopy base height.

4. Discussion

Over the past decade there has been great demand for scientific information on the effects of logging fire-killed trees on fuels and

Table 6
Sierra Nevada west side burned areas: mean probability of large conifer (>1.37 m tall) mortality (standard error) in a fire during low danger early season (June 15–30) and exteremely hazardous (98th percentile) weather and fuel moisture conditions (predicted from standard fuel models using FMAPlus).

Fire area	Treatment	Predicted large conifer mortality during low danger early season fire weather and fuel moisture	Predicted large conifer mortality during extremely hazardous fire weather and fuel moisture
Cleveland	Untreated	100 (0.0)*	100 (0.0)*
	Logged	99.9 (0.1)	99.9 (0.1)
	Herbicide	94.8 (2.0)	96.5 (1.4)
Stanislaus	Untreated	100 (0.0)	100 (0.0)
	Logged	100 (0.0)	100 (0.0)
	Herbicide	87.3 (3.9)	91.8 (3.0)

No significant difference was detected between treatment effects at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions.

* Untreated stands of the Cleveland Fire area had almost no large conifers; only one untreated comprehensive fuel assessment plot contained large conifers.

fire behavior (McIver and Starr, 2000; Beschta et al., 2004). Beginning to address this demand, studies in the Pacific Northwest have shown that small and medium diameter dead woody surface fuels, which actively burn at the fire front and contribute most to fireline intensity, were greater in logged areas than untreated areas in the short term (Donato et al., 2006; McIver and Ottmar, 2007) and were predicted to remain higher in these areas for approximately 20 years (McIver and Ottmar, 2007). In the Sierra Nevada, we found that total available dead fuel loads were significantly greater in logged areas than untreated areas in the first 5 years after logging, however; greater fuel loads in logged areas were in the largest fuel sizes and did not equate to greater fire risk. These fuel loads were not significantly different 13–20 years after logging. How much of each fuel component remained in each stand was a result of individual site treatments prescribed by the Forest Service to meet multiple objectives, such as fuel management, timber extraction, wildlife habitat, erosion control, etc. For example, in the McNally Fire area, much of the post-fire logging occurred primarily to reduce fuels and where trees were not sold as timber, a feller-buncher cut and stacked logs in burn piles, while braches were intentionally left to protect against excessive erosion. Ultimately, the amount of fuel remaining in any given stand after logging was under the control of individual Forest Service managers, within the framework of regional and national forest management rules and environmental laws.

Looking at individual dead-down fuel components, we found that only the largest fuel size class that burns in the initial fire front (100-h) is significantly greater in logged than untreated stands in one of the two youngest fire areas (McNally) and all fire areas combined. How does this translate to potential fire behavior? Surface fire behavior modeling indicated few significant differences (flame lengths were predicted to be higher in the logged stands of the Star Fire area, compared to untreated stands) in either low danger early season or extremely hazardous fuel moisture and weather conditions, possibly because logging did not generally increase fine fuel loads. Also, live woody fuels (shrubs) dominate the overall surface fuel complex a short time after stand-replacing fire and are not significantly different between logged and untreated stands. Furthermore, because logging fire-killed trees does not significantly impact shrub cover, it does not significantly impact grass and forb fuels. Grasses and forbs are suppressed by dense shrub fields.

Logs (1000-h fuels) theoretically do not affect fire behavior at the flaming front (they are too large to ignite instantly); however, they do affect fire intensity and severity and have long burning periods (Monsanto and Agee, 2008). Also, fireline construction is slowed when large-diameter fuels are abundant. In the Pacific Northwest, these heavy fuels were greater in untreated areas than logged areas, following the short-term increase from logging slash (McIver and Ottmar, 2007; Monsanto and Agee, 2008). In the Sierra Nevada, we find a significant short-term increase of 1000-h fuel loads from logging fire-killed trees—they are significantly greater in the young southern fire area (McNally, 2–3 years after logging). The means are also higher (not significantly) in logged areas of the second and third oldest fire areas. Thousand-hour fuel loads are not significantly different between untreated stands and logged stands sampled 19–21 years after logging. However, in herbicide-treated stands, where post-fire site preparation treatments were more intense, 1000-h fuel loads are significantly lower.

After logging fire-killed trees, the Forest Service sometimes kills the native post fire vegetation with herbicides in the Sierra Nevada in order to enhance conifer growth. Today many of these areas have very healthy young conifers that are highly vulnerable to fire, as this and other studies have found (Stephens and Moghaddas, 2005; Thompson et al., 2007; Kobziar et al., 2009). While herbicide-treated stands may become somewhat fire resistant after two decades (modeled morality was 40–50% in the southern Cascade range; Zhang et al., in press), our models, using standard fuel models, indicate that nearly all conifers would die if a reburn occurred two decades after stand-replacing fire; therefore, additional treatments may be needed to protect existing conifer plantations. Canadian model C-6 indicates that limbing to 2 m would be insufficient to protect these conifers from a late season fire. Observations after an escaped late-season prescribed fire that had burned through a highly maintained herbicide-treated stand on the Stanislaus NF, provide an example of the low probability for young conifer survival after a fire, except during the springtime in most stands, when fuel moisture content is high (Fig. 7).

Theoretically, conifer plantations could be better protected from surface and crown fires by reducing surface fuels (i.e. shrubs and litter), increasing tree spacing and increasing crown heights (Graham et al., 2004; Kobziar et al., 2009), but achieving sufficiently low surface fuels would be difficult in these plantations if grasses and forbs increase as a result; treatments that increase the amount of sunlight reaching the ground also increase grass and forb cover (Fig. 8). This ecological response helps explain why herbicide-treated stands of the Cleveland Fire area have the greatest grass and forb cover; the trees are widely spaced and there are few shrubs. Young conifer plantations are not protected from surface fires if grasses increase due to other fuel manipulations, as grass fuels also produce sufficient heat to cause severe scorching in young conifers (Weatherspoon and Skinner, 1995). Illustrating the hazard, the alien grass-fueled St. Pauli Fire (a portion of the Cleveland Fire area that burned three times) killed approximately 70,000 planted trees in 2001 (Fig. 9). The area has been replanted three times after fires and is now best described by a grass standard fuel model (GR4). This area is particularly vulnerable because it is directly uphill of a major highway, a potential source of frequent ignitions and alien seeds.

The average fire return interval for cheatgrass in other western ecosystems is 3–5 years (Whisenant, 1990). The fire return interval for cheatgrass in pine plantations is not yet known, but it is likely to be much shorter than 28 years, the average fire return interval for Sierra Nevada montane shrub fields (Nagel and Taylor, 2005). In shrub ecosystems, frequent fires sometimes lead to type conversion from shrubs to grass, especially in areas with lower productivity that are close to anthropogenic ignition sources. Perhaps in the most extreme cases, type conversion could also occur in

Fig. 9. Photo of the 2001 St. Pauli Fire area, Eldorado National Forest, California, two years after the most recent fire. This area has burned and been replanted three times since 1959. Also shrubs have been sprayed with herbicides multiple times since 1995 to limit competition with conifers. Today, the standard fuel model for moderate-load dry-climate grass (GR4; Scott and Burgan, 2005) best describes the fuels in this area.

Sierra Nevada forests where shrubs are unable to produce seeds, due to herbicides and frequent fires.

5. Conclusions

Both untreated and logged areas in Sierra Nevada forests two decades after stand-replacing fire generally have dense shrub cover, low conifer cover and extremely low alien cover and alien species richness. In this fire-adapted ecosystem the transition from shrubs to forests may last decades or longer.

While logging fire-killed trees on Sierra Nevada national forests may significantly increase total available dead fuel loads in the short term, and may also significantly increase predicted flame lengths in some young burned areas, it does not affect the modeled surface fire behavior in the longer term. Predicted fire behavior from the light logging slash that we encountered in national forests, is probably outweighed by the effects of shrub fuels in these stands. For this reason, logging neither increased nor decreased modeled fire hazards over the long term.

In contrast, modeled surface fire flame lengths and rates of spread were found to be greater in shrub fields than low shrub cover conifer plantations treated with herbicides. However, modeled surface fire intensity would still be great enough to kill most trees, given their small size and low crown heights in the first two decades after planting. Also, dense conifer plantations may burn like shrub fields, in continuous crown fires, as indicated by the Canadian fire behavior model that is specifically for conifer plantations.

Lastly, some herbicide-treated areas may be in danger of recurrent grass fires, especially in areas with frequent anthropogenic ignitions. This is because alien grasses and forbs are stimulated to grow when shrubs are killed; creating highly flammable fuel beds that may burn more frequently, though less intensely, than the native vegetation. Furthermore, reburning herbicide-treated areas increases grasses and forbs; therefore, subsequent fires may increase the probability of a reburn intense enough to kill young conifers. Also, herbicide-treated areas have more alien grass and forb species than areas with high shrub cover.

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