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Western Ecological Research Center

Project Title (Primary): Fuel buildup and potential fire behavior after stand-replacing fires, logging fire-killed trees and herbicide shrub removal in Sierra Nevada forests

Additional Project[1]: Estimating aboveground biomass for broadleaf woody plants and young conifers in Sierra Nevada forests

Final Report: JFSP Project Number 06-3-4-10

Project Website: http://www.werc.usgs.gov/fire/seki/finefuels/finefuels.htm

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[1]**Additional Project:** More than 600 regression equations were developed to calculate fuel loads of Sierra Nevada shrubs and small conifers. The manuscript is in review. A subset of the equations are presented in our web page's *Woody Plant Biomass Calculator* (http://www.werc.usgs.gov/fire/seki/finefuels/regressions.html)

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For more information go to:
www.firescience.gov

I. Abstract

Typically, after large stand-replacing fires in the Sierra Nevada, dense shrub fields occupy sites formerly occupied by mature conifers, until eventually conifers overtop and shade out shrubs. Following large severe fires the US Forest Service often harvests dead trees. The Forest Service also commonly modifies secondary plant succession with herbicides in sites with good conifer growth potential in order to replace conifers in a fraction of the time. We analyzed the effects of logging fire-killed trees and herbicides on grass and forb cover, alien species cover and richness, shrub cover, fuel loads and potential fire behavior. 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 positively affected total available dead fuel loads in the 4-7 year-old fires, but not the older fires. Logging fire-killed trees was not found to affect shrub cover, grass and forb cover, alien species cover or alien species richness. The herbicide treatment resulted in extremely low shrub cover and significantly greater grass and forb cover, alien species cover and alien species richness. In areas that experience fires in the near future, conifer mortality is predicted to be extremely high in all treatments, based on fire behavior modeling. Logging fire-killed trees was not found to significantly affect predicted surface fire behavior. The herbicide treatment resulted in shorter predicted surface fire flame length and a slower predicted rate of surface fire spread in the two oldest fires, due to significant reductions of shrub fuels. However, herbicide-treated areas with very high grass and forb cover had the fastest predicted fire spread rate under extreme fire weather and fuel moisture conditions. Modeling indicated that most of the conifers that were planted or seeded in naturally would not survive a new fire in any of the study areas.

II. Background and purpose

On the west slope of the Sierra Nevada, fast moving high intensity and severity fires lasting a few days have generally replaced slowly advancing, low severity surface fires that lasted weeks or months (Skinner and Chang 1996, Millar et al. 2009). Many factors have contributed to the current fire regime, such as the mid 19th century decline of Native American burning (Anderson 2005) and the practices of Euro-Americans, such as unregulated grazing, which removed herbaceous fuels and effectively eliminated surface fires in some areas, and unmanaged logging which resulted in degraded forests with high levels of activity fuels (McKelvey et al. 1996). With the establishment of National Forests and the Bureau of Land Management, logging and grazing were regulated but continued at high levels, and for the first time systematic fire suppression began (Stephens and Ruth 2005). The legacy of these practices is overly dense young forests with continuous surface, canopy and ladder fuels (Parsons and Debenedetti 1979, Biswell 1989, McKelvey et al. 1996). Today, although most fires are suppressed before they become large, under extreme fire weather and fuel moisture conditions, over-abundant continuous fuels result in some fires that are unstoppable (Johnson et al. 1998). A few of these fast-moving fires have become extremely large, such as the Stanislaus Fire Complex of 1987 and the McNally Fire of 2002, both of which were over 60,000 ha. (150,000 acres).

In Sierra Nevada coniferous forests, post-fire plant succession generally involves a shrub stage composed primarily of *Ceanothus spp., Arctostaphylos spp.*, and *Chamaebatia foliolosa* (Kauffman and Martin 1991), especially when gaps of > 0.2 ha (0.5 acre) are created. Shrubs may dominate for 35 years or more if conifer seeds are present and the site does not reburn in this time period, but if frequent fires kill immature conifers, or conifer seed sources are far away, the shrub stage may last over a century (Cronemiller 1959, Wilkin 1967, Nagel and Taylor 2005). In the absence of fire and overtopping, some shrub species can live well over 100 years (i.e., *Arctostaphylos viscida*), while others die after ~35 years (i.e., *Ceanothus intergerrimus*). Pines and other conifers that become established soon after fire may eventually overtop and shade out shrubs, but the long-term dominance of shrubs may favor succession to shade-tolerant white fir (*Abies concolor*) (Conard and Radosevich 1982) and incense-cedar (*Calocedrus decurrens*), rather than pines and Douglas-fir (*Pseudotsuga menziesii*), the co-dominant species in many pre-settlement forests (Helms and Tappeiner 1996).

Typical native vegetation after a stand-replacing fire in the conifer belt of the Sierra Nevada. Often these communities are killed by the USFS with herbicides and heavy equipment in order to skip this stage of succession and rows of conifers are planted.

Many of the shrub species (i.e. *Ceanothus* and *Chamaebatia*) fix atmospheric nitrogen (Delwiche et al. 1965) and all of them stabilize soil in the post-fire environment, enhancing long-term soil health and therefore promoting forest growth in the long term, but they also compete vigorously with trees, especially pines. Researchers with the U.S. Forest Service have found that both survival and growth of ponderosa pine (*Pinus ponderosa*) in the post fire environment are enhanced by shrub removal (McDonald and Fiddler 1995, Zhang et al. 2008). The minimum area that must be cleared around trees is 1m (3 ft) and this may be accomplished by mechanical or chemical means. An unintended consequence of shrub removal, however, is the incursion of non-native annual grasses in some cases, which both compete with young trees, and more importantly, may change the local fire regime by adding a fine fuel component that would not otherwise exist. At mid-elevations of the Sierras, annual grasses provide continuous fine fuel that is typically available for five months each year. In the same way that disturbance from frequent fires ensures semi-permanent shrub fields, repeated shrub removal insures that annual grasses and forbs abound in gaps between conifers. Researchers have found that cheatgrass (*Bromus tectorum*) and other bromes increase exponentially after herbicide treatments targeting shrubs, but that within a few years, tree roots are long enough that competition with grass is no longer a problem (McDonald and Fiddler 1999).

Logging fire-killed trees, though frequently justified as a fuel-reduction treatment on National Forests, has been shown to significantly increase fine, medium and coarse fuel loads in the short term (Donato et al. 2006, McIver and Ottmar 2007, Monsanto and Agee 2008). There is empirical evidence that post-fire logging reduces the long term accumulation of logs, but no empirical studies have been published on the net accumulation of fine and medium “activity” fuels. However, McIver and Ottmar (2007) modeled both the accumulation and decay of logs and activity fuels in logged and untreated stands after a relatively severe fire. This study predicted that logged stands would continue to have substantially greater fine-medium fuel loads than untreated stands for 20 years and that log fuels would continue to accumulate in untreated stands for 50 years.

After logging, conifers are frequently planted in large high severity fires in the Sierra Nevada using a standard grid pattern. The regular vegetation pattern that develops can produce high fire hazards (Weatherspoon and Skinner 1995, Stephens and Moghaddas 2005, Thompson et al. 2007). Biomass size, position, moisture content and live-to-dead ratio are potentially all affected by post fire treatments, and all of these factors affect fire behavior differently.

This study investigated how post fire treatments and plant succession affected fuel loads, fuel structure and potential fire behavior on west slope Sierra Nevada forests. This study took advantage of four extensive wildfires that occurred in the Sierra Nevada over the past two decades. These fires received a range of treatments, including logging, various forms of shrub removal, conifer planting, and other treatments, while a portion of each fire area was left untreated. We investigated how each of the treatments affected fuel loads by size class, and then used fire modeling to predict potential fire behavior and effects in these fuel complexes, using early-season and extreme weather and fuel moisture data collected near the sites. Due to the difficulty of replicating treatments in burns of the same age, we acknowledge that most of the conclusions in this study consisted of four case studies that lacked landscape-scale replication. However, comparisons of means from the individual fires enabled us to expand the scale of inference in some cases from the individual fire to the entire Sierra Nevada west slope.

III. Study description and location

Study areas and treatments

Fires included in this study were: a) the 2002 McNally Fire on the Sequoia National Forest, b) the 2001 Star Fire on the Tahoe and Eldorado National Forests, c) the 1992 Cleveland Fire on the Eldorado National Forest, and d) the 1987 Stanislaus Fire Complex (in the Hamm, Larson, and Paper fires, on the Stanislaus National Forest) (Fig. 1 and Table 1). The fires have detailed treatment histories, burn severity (dNBR), topography and vegetation data. Vegetation types include mixed conifer dry forest, mixed conifer mesic forest, red fir (*Abies magnifica*) forest and post-fire montane chaparral. Stand-replacing fires occurred in all sites.

Treatment and fire effects assessed

The following hypotheses were tested (Tables 2 and 3):

Logging fire-killed trees does not affect:

- *shrub cover*
- *grass and forb cover*
- *alien species cover*
- *alien species richness*
- *available dead surface fuel loads*

Post-fire herbicide directed at shrubs does not affect:

- *shrub cover*
- *grass and forb cover*
- *alien species cover*
- *alien species richness*
- *available dead surface fuel loads*

Examples of untreated and untreated areas in the 2002 McNally Fire. The area on the left was not treated. Fire-killed trees were logged in the stand on the right.

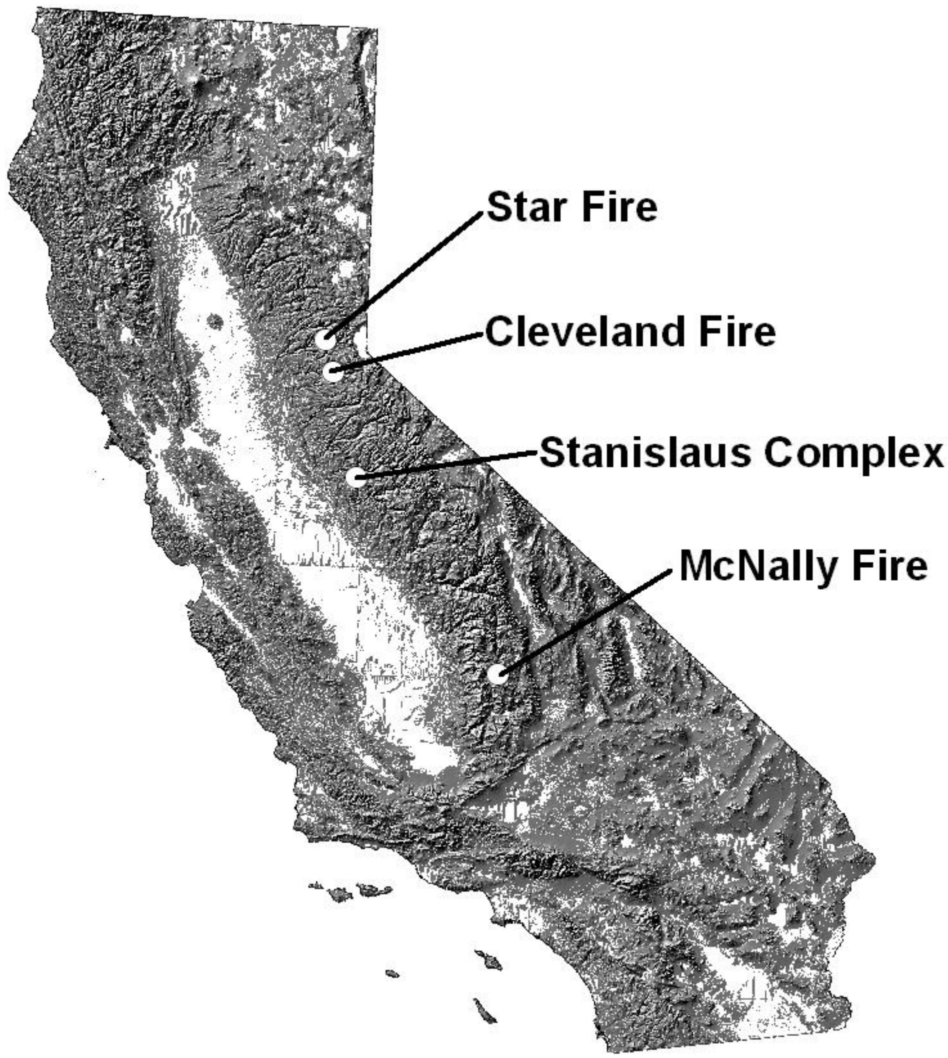

Fig. 1.

Table 1.
Sierra Nevada west side post-fire study locations (2006-2008), treatments and sample size

Fire	Year of fire	Location (lat, long)	Treatment name	Post-fire treatments included	N^a	N^b
McNally	2002	36.1° N, 118.3° W	Untreated	None[1]	145	19
			Logged	Logging fire-killed trees[1]	90	19
Star	2001	39.1° N, 120.5° W	Untreated	None	152	13
			Logged	Logging fire-killed trees[1]	50	12
			Herbicide	Logging fire-killed trees, herbicides targeting shrubs[2]	88	14
Cleveland*	1992	38.7° N, 120.4° W	Untreated	None	12	4
			Logged	Logging fire-killed trees[3]	24	20
			Herbicide	Logging fire-killed trees, herbicides targeting shrubs[4]	113	31
Stanislaus**	1987	37.9° N, 120.0° W	Untreated	None	57	6
			Logged	Logging fire-killed trees[5]	25	7
			Herbicide	Logging fire-killed trees, herbicides targeting shrubs[2, 6]	78	20
			Masticated	Shrubs shredded and scattered[2]	17	3

[1]Very few sites also planted with conifers.
[2]Also planted with conifers.
[3]Most sites also planted with conifers.
[4]Also planted with conifers and most conifer plantations were thinned.
[5]Few sites also deep-tilled and planted with conifers.
[6]Most sites also deep-tilled.
*Includes areas that burned once (1992), twice (1959 and 1992), and three times (1959, 1992 and 2001)
**Includes the Hamm, Larson and Paper fires.
N^a: Sample size of native and alien grass and forb cover and 1-h fuel load.
N^b: Sample size of other samples.

This study also assessed the effects of logging fire-killed trees, herbicide use and mastication on vegetation structure, fuel loads, potential surface and crown fire behavior and the probability of large conifer mortality from future fires.

Data collection

A 2 x 50 m (6.6 x 164 ft) belt transect at the center of the stand was used to assess crown diameter for aerial cover, height, and density of small trees [<1.37 m (<4.5 ft) tall and shrubs. Snags, stumps, and large trees [≥1.37 m (≥ 4.5 ft) tall] were measured in a 36 m diameter plot in the center of the stand. Stands were defined by uniform treatment history and topography and were highly variable in size. Snag and large tree measurements included diameter at stump height [0.2 m (0.7 ft) above the ground], diameter at breast height for conifers only [1.37 m (4.5 ft) above the ground], total height and density. Additionally, we measured height to live crown on large conifers and crown radius for aerial cover on large conifers and hardwood trees. Species were recorded for live trees and shrubs and, when recognizable, for snags and stumps. Dead and down fuels were sampled using Brown's planar transect method (Brown 1974). Five 25 m (82 ft) transects were regularly spaced, perpendicular to the belt transect. Along these transects, woody one-hour fuels [<0.64 cm (<0.25 inch) diameter] were assessed in a 2 m (6.6 ft) portion, ten-hour fuels [0.64-2.53 cm (0.25-1.00 inch) diameter] in a 10 m (33 ft) portion, and 100-1,000-hour fuels [2.53-7.62 cm (1.00-3.00 inch) diameter and greater] in the full 25 m (82 ft) of the transect. Thousand-hour fuel diameters were measured and noted as sound or rotten wood, and identified by species when discernable. Litter and duff depths were measured in two locations along the plane.

Understory species were surveyed in the spring to early summer using 1x1 m (3.3 x 3.3 ft) quadrats located 2 m (6.6 ft) past both ends of the five fuels transects, for a total of 10 quadrats per stand. In these quadrats, we identified plant species and determined the percentage of ground surface covered (aerial cover).

To increase the sample size of one-hour fuel, and both native and alien grasses and forbs, additional "rapid fuel assessment" plots were placed in stratified random locations in the four fire areas, outside of the areas with comprehensive fuel assessments. Mid-way through the project, power analysis indicated that one-hour fuel and grasses and forbs would not be adequately sampled in the comprehensive assessments, therefore we implemented rapid assessments that recorded apparent treatments, one-hour woody fuels [2 m (6.6 ft)-long one-hour fuel transects, four litter and duff depths, native and alien grass and forb cover].

Allometric equations were used to determine live and dead fuel loads by size class. For shrubs and small conifers, we used regression equations reported in http://www.werc.usgs.gov/fire/seki/finefuels/regressions.html, 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 from allometric equations in FMAPlus. Live herbaceous fuel loads were estimated using a cover-to-biomass regression equation derived from data from a previous study (Keeley and McGinnis 2007). Weather and fuel moisture were determined for early season (June 15-30 to represent average overall environmental conditions when overstory and understory vegetation had high moisture content) and for the 98th percentile extreme fire weather, using data from Remote Automated Weather Stations (RAWS) near the four field sites, dating back more than 20 years. One-hour, 10-hour, 100-hour and live fuel moistures were from calculations performed by FireFamily Plus software as percentile weather. For early season live woody fuel moisture, however, we used the mean value from 23 years of field sampling by the Stanislaus National Forest at Mt. Provo, California, elevation 1,341 m (4,398 ft).

Fire behavior modeling

Surface fire behavior predictions were calculated using the BehavePlus fire modeling program. Fuel loads derived from field observations were used as BehavePlus inputs. Fire behavior runs all used the mean slope of all the plots. Other inputs, including, surface area-to-volume ratios for one-hour, live herbaceous and live woody fuels, dead fuel moisture of extinction, and dead and live heat content were from standard fire behavior fuel models reported by Scott and Burgan (2005). Crown fire predictions and large conifer mortality were calculated using the FMAPlus fire modeling program, using standard fire behavior fuel models from Scott and Burgan (2005), rather than field derived (custom) models. To determine which standard fire behavior 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.

Data analysis

Plant characteristics, fuel characteristics and modeled fire behavior were compared between treatments with two sample *t*-tests and ANOVA, with Tukey post-hoc tests used to separate treatments if a significant difference ($P < 0.05$) was detected. Three levels of analysis having three levels of inference comprised: a) post fire treatment effects in each of the four fires (the level of inference was limited to the individual fire), b) effects of one, two or three fires in each post fire treatment in the Cleveland Fire (the level of inference was the post-Cleveland Fire treatment area), and c) post fire treatment effects throughout the Sierra Nevada west side using the mean from each treatment in each fire (the level of inference was the entire Sierra Nevada west side conifer belt in <22 year-old stand-replacing fires). All analyses except species richness were performed on natural log-transformed data. Grass and forb cover (native grass, alien grass, native forb, alien forb and total percentage of ground surface covered), and one-hour fuel loads were assessed using the combined data from rapid assessment plots and mean values from detailed assessments. Live woody fuel cover and fuel loads, canopy cover (from tree measurements), and basal area of large trees, snags and stumps were assessed using detailed assessment plots. Fuel data for BehavePlus and FMAPlus runs were from detailed assessment plots.

An herbicide-treated area six years after fire. During a 2007 Field trip to the Star Fire, the USGS project leader described the study to personnel from USDA Forest Service (Pacific Southwest Regional Office, Tahoe NF and Eldorado NF) and USGS Western Ecological Research Center.

IV. Key findings

Table 2.
Sierra Nevada west side post-fire hypothesis test results for logging fire-killed trees vs. untreated Sierra Nevada post-fire stands

Null hypothesis regarding post-fire treatments	Hypothesis acceptance or rejection and rationale	Scale of inference	Results
Logging does not affect shrub cover.	Accepted: Shrub cover was not found to be significantly different in logged and untreated stands.	Within each fire and throughout the Sierra Nevada	Table 4
Logging does not affect grass and forb cover	Accepted: Grass and forb cover was not found to be significantly different in logged and untreated stands	Within each fire and throughout the Sierra Nevada	Table 6
Logging does not affect alien species cover	Accepted: Alien grass and forb cover was not found to be significantly different in logged and untreated stands.	Within each fire and throughout the Sierra Nevada	Table 6
Logging does not affect alien species richness	Accepted: Alien grass and forb species richness was not found to be significantly different in logged and untreated stands.	Within each fire and throughout the Sierra Nevada	Table 6
Logging does not affect available dead surface fuel loads.	Rejected: Total available dead fuel loads were significantly greater in logged sites than untreated sites of the two youngest fires (McNally and Star fires).	Within the McNally and Star fires only	Table 5

Table 3.
Sierra Nevada west side post-fire hypothesis test results for the herbicide treatment vs. logging fire-killed trees and no treatment in post-fire Sierra Nevada stands

Null hypothesis regarding post-fire treatments	Hypothesis acceptance or rejection and rationale	Scale of inference	Results
Herbicide use does not affect shrub cover.	Rejected: Shrub cover was significantly reduced by herbicide treatments.	Within each fire and throughout the Sierra Nevada	Table 4
Herbicide use does not affect grass and forb cover	Rejected: Grass and forb cover was significantly greater in herbicide-treated stands.	Within each fire and throughout the Sierra Nevada	Table 6
Herbicide use does not affect alien species cover	Rejected: Alien grass cover was significantly greater in the herbicide-treated stands in the two oldest fires (Cleveland and Stanislaus fires). Alien forb cover was greater in herbicide-treated areas in all fires.	Within each fire, but not significant in all sites combined	Table 6
Herbicide use does not affect alien species richness	Rejected: Alien grass and forb species richness in the second oldest fire (Cleveland Fire) was 12X greater in the herbicide than the logging treatment. Alien grass and forb species richness in the oldest fire (Stanislaus Complex) was 5X greater in the herbicide than the logging treatment.	Within the two oldest fires (Cleveland and Stanislaus) and significantly different in all sites combined	Table 6
Herbicide use does not affect available dead surface fuel loads.	Rejected: Total available dead fuel loads were significantly lower in the herbicide treatment than the logging treatment (control for herbicide) in the oldest fire (Stanislaus Complex) only.	Within the Stanislaus Complex only	Table 5

Table 4

Sierra Nevada west side post-fire percentage aerial cover of shrubs, small conifers [<1.37 m (<4.5 ft.) tall], large conifers [>1.37 m (>4.5 ft.) tall] and hardwood trees, and large conifer density [mean (standard error)]

Fire	Treatment	Shrub aerial cover	Small conifer aerial cover	Large conifer aerial cover	Hardwood tree aerial cover	Large conifer density {trees/ha} [trees/ac]
McNally	Untreated	34.9 (5.4)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0
	Logged	33.3 (4.8)	0.0 (0.0)	0.1 (0.1)	0.1 (0.1)	0
Star	Untreated	42.8 (5.3)^{a1}	1.4 (0.5)	0.0 (0.0)	2.1 (1.5)	0
	Logged	44.7 (8.1)^{a1}	3.3 (1.2)	0.0 (0.0)	1.7 (1.0)	0
	Herbicide	11.9 (2.7)^{b2}	3.3 (0.9)	0.1 (0.1)	1.1 (1.1)	{1 (1)} [2 (2)]
Cleveland	Untreated	97.0 (2.9)^{a}	0.0 (0.0)	0.1 (0.1)^{a}	0.2 (0.2)	{10 (10)} [25 (25)]
	Logged	95.1 (2.0)^{a}	0.2 (0.1)	4.9 (1.6)^{b}	2.6 (0.9)	{137 (46)} [338 (114)]
	Herbicide	12.0 (1.8)^{b}	0.4 (0.2)	20.4 (3.0)^{c}	2.3 (0.8)	{342 (44)} [845 (109)]
Stanislaus	Untreated	74.2 (6.2)^{a}	0.6 (0.5)	5.6 (4.5)^{a}	9.4 (5.2)	{203 (166)} [501 (410)]
	Logged	67.5 (10.6)^{a}	0.3 (0.1)	11.6 (5.3)^{a}	24.9 (10.0)	{311 (152)} [768 (375)]
	Herbicide	18.1 (3.6)^{b}	0.4 (0.1)	45.3 (4.5)^{b}	12.9 (4.0)	{770 (91)} [1902 (225)]
	Masticated	11.0 (2.8)^{b}	1.3 (0.5)	4.2 (2.4)^{a}	4.5 (2.9)	{242 (159)} [598 (393)]

Different letters in a column (blocked by fire) indicate significant difference at α = 0.05. Different superscript numbers (in the Star Fire block) indicate significant inter-fire treatment effect at α = 0.05. See Table 1 for locations, dates and treatment descriptions.

Table 5
Sierra Nevada west side post-fire individual and total available fuel loads [mean Mg/ha (standard error)]. Values in English units are approximately ½ of metric units (1 Mg/ha = 0.45 short tons/acre)

Fire	Treatment	*1-hour (<0.64 cm diam.)	10-hour (0.64-2.54 cm diam.)	100-hour (2.55-7.62 cm diam.)	1000-hour (>7.62 cm diam.)	Shrub foliage	Shrub fine live branches (<0.64 cm diam.)	**Available dead fuels (<7.63 cm diam.)	***Available live woody fuels (shrubs and trees)
McNally	Untreated	3.9 (0.3)	2.3 (0.2)	3.8 (0.3)^{a}	17.7 (3.8)^{a}	0.4 (0.1)	1.4 (0.3)	10.2 (0.6)^{a}	1.1 (0.2)
	Logged	2.7 (0.2)	2.0 (0.2)	7.8 (0.9)^{b}	35.3 (7.7)^{b}	0.4 (0.1)	1.3 (0.2)	13.7 (1.3)^{b}	1.1 (0.2)
Star	Untreated	4.2 (0.3)	3.0 (0.5)	7.0 (1.6)^{a}	45.9 (10.0)	0.5 (0.1)^{a}	1.3 (0.2)^{a1}	16.4 (2.6)^{a}	1.2 (0.1)^{a}
	Logged	5.0 (0.5)	4.0 (0.4)	14.7 (1.2)^{b}	66.8 (11.1)	0.4 (0.1)^{a}	1.6 (0.3)^{a1}	25.6 (1.4)^{b}	1.5 (0.3)^{a}
	Herbicide	4.9 (0.4)	3.3 (0.3)	11.0 (1.2)^{b}	44.1 (5.9)	0.1 (0.0)^{b}	0.2 (0.1)^{b2}	19.4 (1.6)	0.5 (0.1)^{b}
Cleveland	Untreated	5.7 (0.5)	1.2 (0.3)	4.5 (1.4)	28.2 (12.5)^{a}	6.1 (2.2)^{a}	4.3 (1.2)^{a}	12.5 (2.0)	8.2 (2.2)^{a}
	Logged	8.7 (0.8)^{a}	1.8 (0.2)	6.0 (0.7)	72.8 (14.7)^{b}	3.0 (0.7)^{a}	3.5 (0.4)^{a}	17.6 (1.6)	5.5 (0.7)^{a}
	Herbicide	4.4 (0.3)^{b}	2.1 (0.2)	5.7 (0.6)	36.3 (5.6)^{b}	0.2 (0.0)^{b}	0.3 (0.1)^{b}	14.9 (1.1)	3.3 (0.5)^{b}
Stanislaus	Untreated	6.8 (0.7)	1.7 (0.3)^{ac}	5.4 (1.2)	50.4 (14.7)^{a}	1.6 (0.3)^{a}	2.1 (0.2)^{a}	19.2 (2.1)	4.2 (0.7)^{ac}
	Logged	7.1 (1.1)	2.3 (0.3)^{ab}	8.6 (1.2)^{a}	44.8 (7.2)^{ab}	1.5 (0.3)^{a}	2.5 (0.2)^{a}	23.0 (2.7)^{a}	6.0 (1.3)^{ab}
	Herbicide	6.5 (0.6)	1.2 (0.2)^{c}	4.8 (1.2)^{b}	10.3 (1.6)^{c}	0.3 (0.1)^{b}	0.4 (0.1)^{b}	15.0 (1.4)^{b}	7.9 (0.7)^{b}
	Masticated	5.9 (0.6)	7.3 (1.0)^{b}	5.5 (1.3)	2.4 (1.4)^{bc}	0.4 (0.2)	0.3 (0.1)^{b}	22.2 (3.4)	1.8 (0.1)^{c}

Hour ratings refer to dead time lag surface fuels. Different letters in a column (blocked by fire) indicate significant difference at $\alpha = 0.05$. Different superscript numbers (in the Star Fire block) indicate significant inter-fire treatment effect at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions. *Used values from rapid assessment plots for greater sample size (not for other fuel components). **Includes grass, forbs, 1-h, 10-h, 100-h and dead shrubs. ***Includes live foliage and 50% of live branches <0.64 cm (<0.25 inch) diameter.

Table 6
Sierra Nevada west side post-fire percentage aerial cover and species richness of grasses and forbs [mean (standard error)]

Fire	Treatment	Total grass and forb aerial cover	Native grass aerial cover	Alien grass aerial cover	Native forb aerial cover	Alien forb aerial cover	Native species richness	Alien species richness
McNally	Untreated	16.5 (1.9)	3.2 (0.9)	2.1 (0.8)	11.2 (1.4)	0.05 (0.04)	32.6 (1.7)	1.5 (0.5)
	Logged	14.5 (2.0)	2.6 (0.8)	0.7 (0.2)	11.1 (1.7)	0.1 (0.1)	28.9 (1.8)	0.7 (0.2)
Star	Untreated	9.8 (1.3)[a1]	3.8 (1.0)	0.2 (0.1)	5.7 (0.7)[a]	0.2 (0.1)[a]	27.2 (2.3)	0.6 (0.2)[1]
	Logged	13.1 (3.2)[1]	0.2 (0.1)[a]	0.02 (0.02)	11.6 (2.8)	1.3 (0.8)	33.0 (4.1)	1.8 (0.8)[1]
	Herbicide	18.3 (2.6)[b2]	5.3 (1.9)[b]	1.2 (0.9)	10.3 (1.6)[b]	1.5 (0.5)[b]	36.1 (3.1)	3.5 (1.4)[2]
Cleveland	Untreated	16.4 (6.3)	4.8 (2.2)[a]	0.4 (0.4)[a]	9.5 (3.6)	1.7 (0.9)	28.5 (1.8)	1.8 (0.8)
	Logged	10.8 (4.3)[a]	3.7 (2.9)[a]	1.7 (0.9)[a]	4.7 (3.5)	0.6 (0.3)[a]	28.0 (2.1)[a]	1.0 (0.4)[a]
	Herbicide	44.6 (2.7)[b]	25.6 (2.5)[b]	8.5 (1.2)[b]	9.0 (1.1)	2.5 (0.4)[b]	34.4 (1.6)[b]	12.3 (2.0)[b]
Stanislaus	Untreated	10.0 (2.7)[a]	3.9 (1.4)	3.8 (1.7)[a]	2.1 (0.8)	0.1 (0.04)[a]	27.3 (2.4)	3.3 (1.7)[a]
	Logged	14.5 (5.0)	8.8 (3.7)	3.5 (1.6)[a]	1.7 (0.4)	0.5 (0.4)	30.6 (2.2)	2.3 (1.0)[a]
	Herbicide	22.6 (2.8)[b]	8.3 (1.7)	11.0 (1.9)[b]	1.9 (0.4)	1.3 (0.4)[b]	23.0 (2.7)	12.3 (2.1)[b]
	Masticated	19.3 (5.7)	8.4 (4.2)	6.5 (3.5)	3.6 (1.6)	0.8 (0.6)	29.3 (3.3)	11.0 (3.5)

Different letters in a column (blocked by fire) indicate significant difference at $\alpha = 0.05$. Different superscript numbers (in the Star Fire block) indicate significant inter-fire treatment effect at $\alpha = 0.05$. See Table 1 for locations, dates and treatment descriptions.

Table 7
Sierra Nevada west side post-fire mean surface fire behavior (standard error) in early season (late June) and 98th percentile weather and fuel moisture. Values in English units are 3 x metric units (1.00 m/s = 2.98 chains/hour) (1.0 m = 3.3 feet).

Fire	Treatment	Predicted early season rate of spread (m/s)	Predicted 98th percentile rate of spread (m/s)	Predicted early season flame length (m)	Predicted 98th percentile flame length (m)
McNally	Untreated	0.07 (0.007)	0.14 (0.012)	1.6 (0.1)	2.4 (0.1)
	Logged	0.05 (0.006)	0.11 (0.011)	1.5 (0.1)	2.2 (0.2)
Star	Untreated	0.08 (0.013)	0.15 (0.026)[1]	1.9 (0.2)	2.8 (0.3)[1]
	Logged	0.09 (0.007)	0.18 (0.013)[a1]	2.4 (0.2)	3.5 (0.2)[a1]
	Herbicide	0.06 (0.008)	0.10 (0.012)[b2]	1.7 (0.2)	2.3 (0.2)[b2]
Cleveland	Untreated	0.13 (0.024)[a]	0.50 (0.034)[a]	2.6 (0.4)[a]	5.7 (0.4)[a]
	Logged	0.18 (0.021)[a]	0.51 (0.049)[a]	3.4 (0.3)[a]	6.0 (0.4)[a]
	Herbicide	0.02 (0.007)[b]	0.04 (0.014)[b]	0.7 (0.1)[b]	0.9 (0.1)[b]
Stanislaus	Untreated	0.43 (0.075)[a]	0.86 (0.136)[a]	5.1 (0.5)[a]	7.4 (0.6)[a]
	Logged	0.30 (0.054)[a]	0.61 (0.107)[a]	4.6 (0.6)[a]	6.7 (0.8)[a]
	Herbicide	0.02 (0.003)[b]	0.03 (0.004)[b]	0.7 (0.1)[b]	0.9 (0.1)[b]
	Masticated	0.01 (0.006)[b]	0.02 (0.008)[b]	0.4 (0.2)[b]	0.5 (0.3)[b]

Different letters in a column for an individual fire indicate significant difference at α = 0.05. Different superscript numbers (in the Star Fire block) indicate significant inter-fire treatment effect at α = 0.05. See Table 1 for locations, dates and treatment descriptions.

Table 8

Sierra Nevada west side post-fire mean probability of large conifer [>1.37 m (>4.5 ft.) tall] mortality (standard error) in a fire with early season (late June) and 98th percentile weather and fuel moisture

Fire	Treatment	Predicted early season large conifer mortality	Predicted 98th percentile large conifer mortality
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)
	Masticated	98.0 (1.5)	99.7 (0.3)

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

Discussion

Surface fire behavior predictions indicate that, in general, hand crews could have safely planned for direct attack of fires during early season burning in all but the heaviest shrubs in the McNally and Star Fires, 4-7 years after the initial stand-replacing fires, as mean flame lengths would be <2 m (<6.5 ft). However, under 98th percentile fire weather and fuel moisture conditions, flanking attack would have been necessary in these stands, due to flame lengths > 2m (>6.5 ft). The portion of the Cleveland Fire that burned three times (1959, 1992 and 2001) was predicted to have more extreme surface fire behavior than other herbicide-treated areas that burned once or twice, due to the extensive annual grasses and forbs there. Also in the Cleveland Fire, in sites that were treated without herbicides, those that burned twice (1959 and 1992) were predicted to have more extreme surface fire behavior than those that burned just once (1992). In the Cleveland Fire and Stanislaus Complex, which were assessed 14-21 years after stand-replacing fires, surface fire behavior would have been too intense in untreated stands and logged stands for direct attack in both early season and 98th percentile weather and fuel moisture conditions. Average flame lengths would be predicted to be 3-8 m (10-26 ft) in these shrub fields. In herbicide-treated areas, although surface fire flame lengths would not generally prevent hand crews from safely executing direct attack, passive crown fire predicted for most stands would increase the danger to fire crews and hamper firefighting efforts because of spot fire production. As a result, direct attack in conifer stands would not be an option in most stands. Many of the herbicide-treated areas, especially in the Stanislaus Complex, were so dense that they would likely burn like tall shrubs fields.

Shrub fires are modeled as surface fires, even though fire spreads from shrub crown to shrub crown, and not through the surface layer only. In our study sites, only herbicide-treated areas had dense conifer canopies. Native vegetation in the older fires consisted of dense shrub fields with widely scattered large trees. In either case, most large trees died in passive crown fires under both early season and extreme fire weather and fuel conditions. There was simply more "crown" to burn in dense herbicide-treated areas than native vegetation. Passive crown fires were predicted for almost all of the stands containing large conifers. The only exceptions were the stands with standard fuel model TL3, and then only during the less severe (early season) fire weather and fuel moisture conditions.

Herbicide use resulted in significantly greater grass and forb cover. As growing space was opened by the application of herbicide, more grass and forb fuels were produced. Within this enhanced grass and forb cover was significantly enhanced alien species cover, as found by McDonald and Fiddler (1999). There were also 2-12 times more alien species in herbicide areas than logged areas. Unlike the herbicide treatment, logging fire-killed trees did not prevent shrubs from occupying the post-fire landscape and therefore did not enhance grass and forb development.

V. Management implications

Although logging fire-killed trees in the Sierra Nevada west side significantly increased the total available dead fuel load compared to no treatment in the most recently burned stands, it did not significantly affect the modeled surface fire behavior. This was because approximately half of the available dead fuel, the only significantly different individual component of this available fuel, was the largest, least important diameter class that the model considered (100-hour fuel). Fine dead fuels drive the Rothermel (1972) surface fire spread model, and in our study, fine fuels were not high in logged or untreated areas.

Herbicide use significantly altered the plant community. Along with the intended reduction of shrubs, this treatment significantly increased grass and forb cover, a potential driver of rapid fire spread. Of particular concern were the alien grasses which were most prevalent on the Cleveland Fire, but were also abundant along the edges of the Star Fire herbicide treatment areas. Based on the abundance of alien annual grasses, especially bromes, throughout the Cleveland Fire and near roads in herbicide treated areas of the Star Fire, these fuels are expected to spread throughout the shrub-free areas of the younger Star Fire. In addition, herbicide use on shrubs caused a dramatic increase in the number of alien grass and forb species.

Native plant communities in the conifer belt of the Eldorado NF (Star and Cleveland fires) and Stanislaus NF (Stanislaus Complex) were removed by herbicide (and deep tilling). Today these areas have very healthy young conifers that are highly vulnerable to fire, as demonstrated by multiple fires in the Cleveland Fire area and fire behavior modeling. Whether the Forest Service removes the native post-fire plant community to facilitate rows of pine or it allows natural succession to take place in severely burned forests, nearly all of the post fire conifers would be expected to die in a reburn within, at least, the first two decades.

Example of likely fuel moisture effects on fire severity in an herbicide-treated area on the Stanislaus NF (outside our study area). Trees on the left were completely scorched and killed, while those on the right with a fern understory were only lightly scorched and are expected to survive. Both areas had been uniformly thinned and limbed and were located on the same slope and aspect. The area was planted after the 1990 A-Rock Fire, adjacent to Yosemite NP, and then burned in the 2009 Big Meadow Fire. Firefighting activities may have also contributed to fire severity in these stands.

VI. Relationship to other recent findings and ongoing work on this topic

Over the past decade there has been great demand for scientific information on the effects of logging fire-killed trees (McIver and Starr 2000, Beschta et al. 2004). One of the many important questions is: In what ways are fuels and fire behavior affected by post fire logging and for how long? Studies in the Pacific Northwest showed that small, medium and large diameter dead woody surface fuel loads were greater in logged areas than untreated areas in the short term (Donato et al. 2006, McIver and Ottmar 2007, Monsanto and Agee 2008). In the Sierra Nevada, we found that total available dead fuel loads (which included grasses and forbs, 1-hour, 10-hour, 100-hour and dead shrubs) and 100-hour fuel loads were significantly greater in logged areas than untreated areas in the short term (field data collected in the youngest two fires 2-5 years after logging). In the long term, McIver and Ottmar (2007) predicted that small-medium fuels would remain higher in logged areas for 20 years. Our study in the Sierra Nevada did not detect a significant difference in fine-medium fuel loads in logged and untreated stands in the fires that were sampled 13-21 years after logging. Thousand-hour fuel loads in the Pacific Northwest were greater in untreated areas than logged areas, following the initial pulse from logging slash (McIver and Ottmar 2007, Monsanto and Agee 2008). In the Sierra Nevada, we found that 1,000-hour fuel loads were twice as high in logged areas than untreated areas 2-3 and 13-15 years after logging. The mean 1,000-hour fuel load in the second-youngest fire (sampled 4-5 years after logging) was also higher in logged areas than untreated areas, but this difference was not statistically significant. Thousand-hour fuel loads in logged areas sampled 19-21 years after logging were similar to untreated areas.

VII. Future work needed

More studies are needed to track the longevity of post-fire logging slash, taking into account decay rates based on physical properties of wood and biotic and abiotic site conditions. Standard fire behavior fuel models need to be developed for young closely-spaced conifers in the western US. There are no analogs to the Canadian Forest Fire Behavior Prediction System (model C-6) for dense conifer stands in the US system (see Scott and Burgan 2005 and Albini 1976). Physics-based crown fire spread models need to be developed for shrubs, small conifers, large conifers and mixtures of shrubs and trees. Currently it is impossible to compare the fire intensity of a passive crown fire in young conifers and a “surface” fire in shrubs, based on fire behavior models.

VIII. The deliverables crosswalk table

Deliverable	Description	Status
Report	Progress report submitted to the Joint Fire Science Program using English units and metric equivalents	Complete.
Report	Progress report submitted to the U.S. Forest Service representatives associated with this study	Complete.
Meeting	PI will attend 3 day Joint Fire Science workshop	Complete.
Report	Progress report submitted to the Joint Fire Science Program using English units and metric equivalents	Complete.
Report	Progress report submitted to the U.S. Forest Service representatives associated with this study	Complete.
Web page	Construct a web site with project description and early results, contact all USFS units in the region and make them aware of the site	Complete.

Report	Progress report submitted to the Joint Fire Science Program using English units and metric equivalents	Complete.
Report	Progress report submitted to the U.S. Forest Service representatives associated with this study	Complete.
Publication	Submit a scientific manuscript presenting these results in a scientific journal	Two manuscripts in review.
Meeting	PI will attend 3 day Joint Fire Science workshop	Instead delivered an oral presentation at the Fire in the Southwest: Integrating Fire into Management of Changing Ecosystems, Tucson, AZ (2008).
Presentation	Oral or poster presentation by project manager at 7th North American Forest Ecology Workshop	Presented two posters instead at the Southern Sierra Science Symposium, Visalia, CA (2008). Will also deliver an oral presentation and present a poster at the 4th International Fire Ecology and Management Congress: Fire as a Global Process, Savannah, GA (2009).
Presentation	Oral presentation by project manager at Ecological Society of America Annual Meeting	An oral presentation was instead delivered at the Yosemite Fire Symposium, Yosemite NP, CA (2008). Also delivered an oral presentation at Sequoia and Kings Canyon National Parks Noon Lecture Series (2008).

Field tour	Field tours of study sites on Tahoe, Eldorado and Stanislaus National Forests for U.S. Forest Service line officers, foresters and botanists	First tour conducted to the Star Fire and attended by USFS representatives from the Pacific Southwest Regional Office, Tahoe NF, Eldorado NF and USGS Western Ecological Research Center (2007). More tours will be conducted in 2009-2010 to describe peer-reviewed results.
Report	Final report written and submitted to the Joint Fire Science Program using English units and metric equivalents	Complete
Report	Final report written and submitted to the U.S. Forest Service representatives associated with this study	Pending peer review
Presentation	Present official results at U.S. Forest Service management meetings	Pending peer review

IX. Additional Deliverable

Estimating aboveground biomass for broadleaf woody plants and young conifers in Sierra Nevada forests—over 600 regression equations for estimating weights of individual plant parts for fuel models and other biomass needs (in review). A subset of the equations are presented in our web page's *Woody Plant Biomass Calculator* (http://www.werc.usgs.gov/fire/seki/finefuels/regressions.html).

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