LONG-TERM SURFACE FUEL ACCUMULATION IN BURNED AND UNBURNED MIXED-CONIFER FORESTS OF THE CENTRAL AND SOUTHERN SIERRA NEVADA, CA (USA)

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ABSTRACT

After nearly a century of fire exclusion in many central and southern Sierra Nevada mixed-conifer forests, dead and down surface fuels have reached high levels without the recurring fires that consume the accumulated organic matter. The effects of prescribed fires used to reduce fuel loads and restore fire have been monitored in Yosemite, Sequoia, and Kings Canyon National Parks for over 30 years. Ten years following prescribed fire treatments in Sequoia and Kings Canyon, mean total fuel loads accumulated to 84 percent of pre-fire levels in ponderosa pine forests, 83 percent in white fir-mixed conifer, and 66 percent in giant sequoia-mixed conifer forests. Thirty-one years after burning, mean fuel load of fine and sound woody fuels increased in ponderosa pine research plots in Yosemite. Most fuel accumulation appeared to occur within the first decade after fire, however the post-fire fuel complex was different than that pre-fire. In areas that have remained unburned, surface fuel accumulation appears to be relatively slow and may indicate that decay rates have approached accumulation rates for the mixed-conifer forest types. This long-term information has important implications for fire management planning, including scheduling fuel hazard reduction and subsequent maintenance treatments.

Keywords: *Fuel accumulation, prescribed burning, Sierra Nevada, mixed conifer, giant sequoia, ponderosa pine.*

INTRODUCTION

As a result of a long period of fire exclusion, heavy accumulations of fuels in many western forests are of concern to managers and the public (Leopold et al. 1963, Towell 1969, Kilgore 1972). These altered fuel conditions can promote uncharacteristically intense and/or extensive fires that may have undesirable effects (Hartesveldt 1964, Kilgore 1972, van Wagtendonk 1985). Intense fire can increase the risk of damage to life and property in wildland-urban interface areas and lead to severe fire effects on natural resources. Also, greater intensity may increase a fire’s resistance to control, which can in turn increase the costs of fire suppression.

Reducing the risk of these undesirable outcomes raises several management issues and questions. Because the altered fuel conditions are extensive, many areas need restoration but limited funds and resources are available. How do managers prioritize areas for treatment? How do managers know if it is more important to carry out restoration treatments or to maintain restored areas? To make the issue more complex, agency missions and political mandates may present managers with multiple goals such as reducing fuel hazards while at the same time restoring and maintaining natural processes. Understanding fuel dynamics in these systems is an important part of helping managers to answer some of these critical questions.

The rate at which fuels accumulate is one determinant of fire regimes, specifically fire return intervals, and of the natural range of variability in fuels loads (van Wagtendonk and Sydoriak 1987). For example, ponderosa pine, which has a high rate of flammable litter fuel accumulation, sustains frequent fires, while white fir, with a lower accumulation rate, burns less frequently. Given the same lightning ignition and fire weather patterns, the two species produce different fire regimes. Fire managers need to know when an area is ready to be re-burned with a prescribed fire in order to accomplish the task of simulating natural processes and managing wildlands consistent with ecological principles.

In conjunction with fuels treatments, land managers have collected fuels data before and after treatments to determine if immediate fuel reduction objectives were met. Post-fire fuel accumulation data, however, are not often collected, or only collected for a short time. Background fuel accumulation rates in untreated areas, where litterfall and decomposition of surface organic material occur in the absence of fire, are also largely unknown. As a consequence of this lack of long-term information, it is not known if fuels accumulate more quickly after treatment or eventually exceed pre-fire levels.

BACKGROUND

Throughout the forests of the central and southern Sierra Nevada, fire exclusion for many decades has resulted in heavy surface fuel accumulation and altered forest structure (Biswell et al. 1968, Kilgore 1972, Parsons 1978, Vankat and Major 1978). While these changes have long been recognized, efforts to restore fuel and forest conditions in the past have been intermittent and small scale compared to the extent of the affected area. Prescription burning has been used in the national parks in the Sierra Nevada since the late 1960s. In Sequoia and Kings Canyon National Parks, experimental fires were studied between 1964 and 1966, leading to a management program in 1969 (Parsons and van Wagtendonk 1996). In Yosemite National Park, the prescribed fire program began in 1970 concurrently with research on refined burning prescriptions (van Wagtendonk 1972). More recently, land management agencies including the National Park Service have increased efforts to use prescribed fire to reduce the fuel hazards and restore fuel and vegetation conditions.

Early work on fuels in the Sierra Nevada was done by Jenny et al. (1949) who determined decay constants for forest floors that had reached fuel depth equilibrium. Kittredge (1955) reported weight and depth measurements of forest floors for five conifers growing in the Sierra Nevada and found that trends with stand age were not evident after about 30 years. The first study on fuel accumulation rates for Sierra Nevada species was conducted by Biswell et al. (1966) just west of Sequoia and Kings Canyon National Parks with collection trays clustered at the bases of individual trees of giant sequoia (*Sequoiadendron giganteum* (Lindl.) Buchholz), ponderosa pine (*Pinus ponderosa* Laws.), sugar pine (*Pinus lambertiana* Dougl.), and white fir (*Abies concolor* (Gord. & Glend.) Lindl.). Unfortunately, fuels were only collected for two years and information about the trees was not recorded. Agee et al. (1977) randomly placed trays in pure stands of the same species but the stands had been previously manipulated, collection lasted only two years, and no tree information was collected. Stohlgren (1988) pointed out these deficiencies and conducted a four-year study in mixed stands of the same four species, as well as incense-cedar (*Calocedrus decurrens* (Torr.) Florin) and red fir (*Abies magnifica* A. Murr.). Basal area, stand density, and bole volume data were recorded. Longer term studies looked at accumulation rates up to seven years after prescribed burning in Sequoia and Kings Canyon National Parks (Parsons 1978) and six years in Yosemite National Park (van Wagtendonk and Sydoriak 1987). Although these studies showed decreases in accumulation rates over time for most fuel classes, the studies were too short to confirm asymptotic behavior.

Long-term fire monitoring began in 1978 in Yosemite National Park and in 1982 in Sequoia and Kings Canyon National Parks to determine if fuel reduction and other objectives of the prescribed fire programs were being met. In addition, the methods were designed to examine vegetation attributes of both the overstory and understory vegetation and to help detect unexpected consequences of prescribed burning. These monitoring programs have been active for over 20 years and the long-term data are being summarized and synthesized for use by park managers in planning and fire program evaluation.

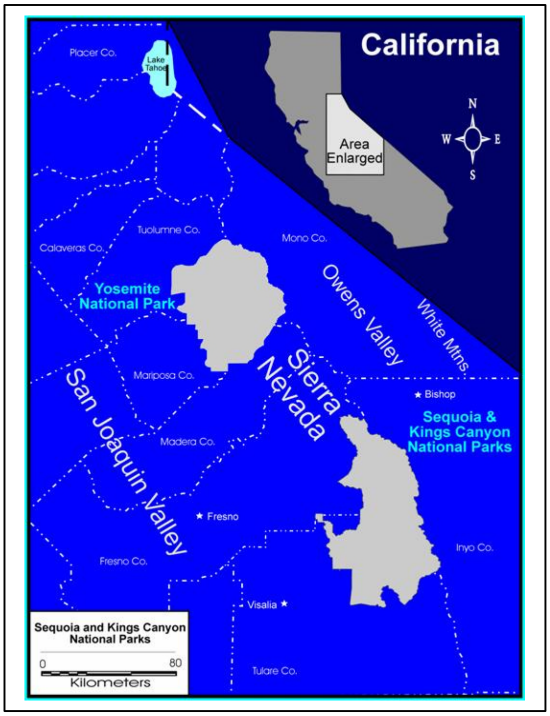
This study presents new data from long-term monitoring plots and re-sampled early research plots to determine fuel accumulation patterns in both burned and unburned areas. The study focuses on dead and down organic matter on the forest floor (surface fuels) including woody fuels, litter and duff. These fuels derive from the residual stand as well as those trees killed by fire in burned areas. The study does not address changes to standing understory vegetation, commonly referred to as “ladder” fuels. The amount of available surface fuel influences fire intensity and the continuity of those fuels affect fire spread. While ladder fuels are more commonly associated with the transfer of fire into the forest canopy, heavy surface fuels can also provide a mechanism for fire spread into the tree crowns, initiating a crown fire depending upon the environmental conditions (such as temperature, relative humidity, fuel moisture, and winds) at the time of the fire.

METHODS

The study sites are located in Yosemite National Park, in the central Sierra Nevada, and Sequoia and Kings Canyon National Parks in the southern Sierra Nevada, California (Figure 1). Topography is similar in each of the parks with steep mountains at the crest and gentle western slopes incised by steep canyons. In Sequoia and Kings Canyon, the crest is over 300 m higher than in Yosemite, and the foothills reach nearly 300 m lower. In addition, the Kern River creates a secondary crest west of the Sierra Nevada crest in Sequoia National Park. The vegetation communities are influenced by topography and latitude and range from foothill shrub and woodlands through montane and subalpine forests to alpine meadows. Boundaries between these communities are lower in elevation in Yosemite. The montane forests in this study include ponderosa pine forest, white fir-mixed conifer forest, and giant sequoia-mixed conifer forest.

The ponderosa pine forest ranges in elevation from 600 m on north-facing slopes and canyon bottoms to 2000 m on south-facing slopes (Figure 2). Soils are often but not always thin, and barren rock outcrops are common. The overstory consists of ponderosa pine, with sugar pine, incense-cedar, white fir, and black oak (*Quercus kelloggii* Newb.) or canyon live oak (*Quercus chrysolepis* Liebm.) present in varying degrees. The understory is usually comprised of incense-cedar, black oak and white fir. Shrubs such as manzanita (*Arctostaphylos spp.*), ceanothus (*Ceanothus*

Figure 1. Location of Yosemite and Sequoia and Kings Canyon National Parks (Map by Tony Caprio).



spp.), gooseberry (*Ribes spp.*), raspberry (*Rubus spp.*), wild cherry (*Prunus spp.*), or bear clover (*Chamaebatia foliolosa* Benth.) compose a larger portion of the understory than in higher elevation forests, and herbs are sparse to moderately common. In the ponderosa pine forest type, historic fire return intervals ranged from 1-15 years with a mean of 4 years (Wagener 1961, Kilgore and Taylor 1979, McBride and Jacobs 1980, Warner 1980, Caprio and Swetnam 1995). While specific environmental conditions under which each prescribed fire took place are not known, the general parameters for the prescriptions for all burns are listed in Table 1.

The giant sequoia-mixed conifer forest is located at elevations from 1590-2200 m, on all aspects, in drainage bottoms, broad upland basins, and occasionally on steep slopes and ridge tops. Soils are coarse textured and acidic and soil depth ranges from shallow to very deep. The community is dominated by mature white fir, red fir, and giant sequoia, but also includes sugar pine, ponderosa pine, Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.), and incense-cedar in small, varying amounts (Figure 3). Understory trees are primarily white fir and incense-cedar and the forest floor is typically sparse, with few herbs, and <20 percent shrub cover.

Figure 2. Ponderosa pine forest type.

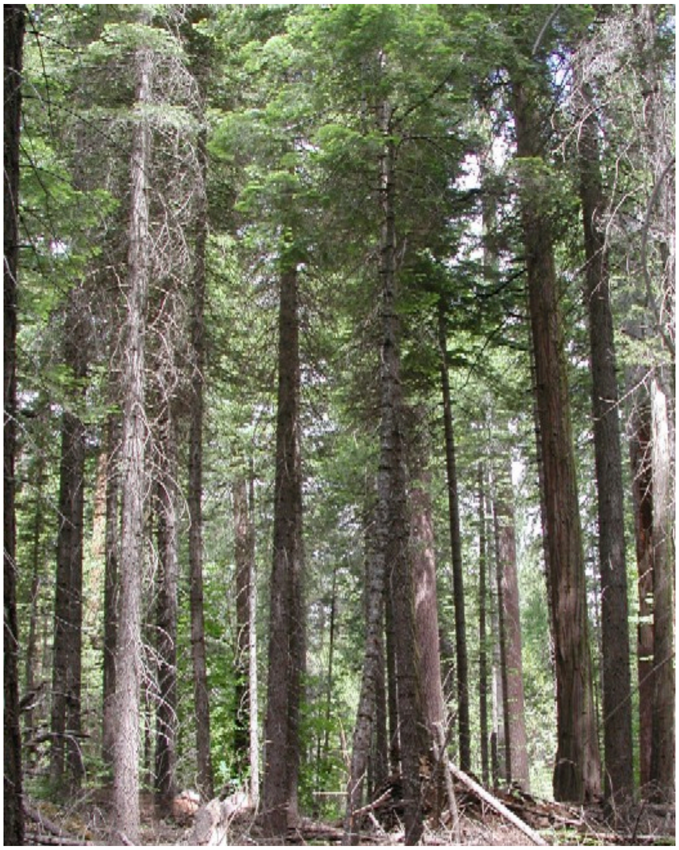
Figure 3. Giant sequoia-mixed conifer forest type.

The white fir-mixed conifer forest is generally found at an elevation of 1800-2200 m, predominately on north and west aspects. The overstory consists of mature white fir, sugar pine, ponderosa pine, and incense-cedar (Figure 4). Understory trees include incense-cedar and white fir with occasional black oak. The shrub and herbaceous vegetation layer and soils are similar to those found in the giant sequoia-mixed conifer forest. Historic fire return intervals in the giant sequoia- and white fir-mixed conifer forests ranged from 2-30 years, with a mean of ten years (Kilgore and Taylor 1979, Swetnam 1993). Environmental conditions for prescribed fires were similar to those for the ponderosa pine forest, but with slightly lower fuel moistures and higher wind speeds in the mixed-conifer forest types (Table 1).

Table 1. Environmental and fire behavior parameters for prescribed fire in ponderosa pine and mixed-conifer forest types.

Prescription Parameter	Yosemite	Sequoia and Kings Canyon
Air Temperature (^{0}C)	4-24	4-29
Relative Humidity (%)	20-65	20-60
Mid-flame Wind Speed (km hr^{-1})	0-10	0-13
1-hr Timelag Fuel Moisture (%)	4-10	3-12
10-hr Timelag Fuel Moisture (%)	6-16	4-13
100-hr Fuel Timelag Moisture (%)	7-20	5-14
1000-hr Timelag Fuel Moisture (%)	10-20	10-20
Flame Length (m)	0.2-0.8	0-0.8
Rate of Spread (m min^{-1})	0.1-7.0	0-5.4
Fireline Intensity (Kw m^{-1})	3-588	14-415

Figure 4. White fir-mixed conifer forest type.



Early research in Yosemite focused on refining prescriptions for that park's prescribed fire program (van Wagtendonk 1972). Twenty-four representative 10 m x 10 m plots were established in 1971, eight each in ponderosa pine, ponderosa pine with bear clover, and ponderosa pine with incense-cedar. Burn treatments in 1971 were randomly assigned to plots and included burning direction and a range of fuel moisture conditions to help refine burn prescriptions. For each plot, ten randomly placed litter and duff samples, including woody fuels less than 2.54 cm diameter, were measured for depth, collected in bulk, and then separated, dried and weighed in the laboratory. Woody fuels were measured using techniques described by Van Wagner (1968) using two transects 14.14 m in length. Diameter and height for all trees in the plots were also recorded. Immediate post-fire fuels and vegetation data were collected following the burn treatments in 1971.

All research plots were re-burned in 1972 in a 26-ha prescribed fire but fuels and vegetation were not re-measured following the prescribed fire. The research plots were re-measured in 2003 using a modified planar intercept method following Brown (1974, 1982) for woody fuels and depth measurements for litter and duff (National Park Service 2003). Litter and duff depths recorded 31 years post-fire were converted into fuel loads using relationships established by van Wagtendonk et al. (1998). Rotten logs were not sampled in 1971, and therefore, were separated from the other fuel components in the 2003 data to allow for more direct comparison with the earlier data.

For the monitoring programs in Sequoia, Kings Canyon, and Yosemite National Parks, plot locations were first stratified by vegetation type and then selected randomly within areas scheduled for prescribed burning. Monitoring plots were established over a five to ten year period and burned in a number of different prescribed fires, therefore, data collected at each post-fire interval does not necessarily occur in the same calendar year. Fuel load and tree data were included from Sequoia and Kings Canyon National Parks for 3 ponderosa pine plots, 9 white fir-mixed conifer plots, and 26 giant sequoia-mixed conifer plots for burned areas, and 9 unburned giant sequoia-mixed conifer plots. Data were combined from Yosemite, Sequoia, and Kings Canyon National Parks for a total of 10 unburned ponderosa pine plots and 8 unburned white fir-mixed conifer forest plots.

All fuel inventories in the monitoring plots were conducted using a modified planar intercept method (Brown 1974, 1982) where woody fuels were tallied and 5-10 litter and duff depths per transect were sampled along four 15.24 m transects (National Park Service 2003). As with the Yosemite research plots, litter and duff depths were converted into fuel loads using relationships established by van Wagtendonk et al. (1998). Diameters for all trees greater than 1.4 m in height were recorded. Data were collected pre-fire, immediately post-fire, and then one, two, five, and ten years post-fire, although not all post-fire data are presented here.

RESULTS

Ponderosa Pine Forest

After many decades without fire, the mean total fuel load for three ponderosa pine plots in Sequoia and Kings Canyon National Parks was 19.1 kg m^{-2} (standard error (SE) = 0.6; Figure 5). Immediately following initial treatment with prescribed fire, total fuel load was reduced by 99 percent. By ten years post-fire, mean total fuel load reached 16.0 kg m^{-2} (SE = 3.7), 84 percent of pre-fire levels. The post-fire fuel complex differed from the pre-fire complex with a larger proportion of woody fuels than duff post-fire (Figure 5). The density of understory trees was greatly reduced post-fire with 77 percent mortality of trees less than 30 cm in diameter (Table 2). Note that by five-years post-fire, the mean total fuel load was 4.4 kg m^{-2} (SE = 0.5), only 23 percent of the pre-fire levels indicating that many of the trees killed by the fire did not start falling to the forest floor until five years after the fire. While the sample size is small (3 plots), the trend is consistent with data from other plots that have only reached the five-year post-fire stage.

In ten unburned plots in Sequoia, Kings Canyon, and Yosemite National Parks, the initial mean total fuel load was 13.6 kg m^{-2} (SE = 1.9) and increased to 18.1 kg m^{-2} (SE = 2.6) after ten years (Figure 5). The mean increase was 4.5 kg m^{-2} (or 33 percent), and a one-tailed, paired t-test indicated a significant increase in total fuel load over a ten year time period (P=0.044, n=10).

In the re-sampled Yosemite National Park research plots (Figure 6), total fuel load increased over the 31-year time period from 6.3 to 9.9 kg m^{-2} in the ponderosa pine forest type (57 percent increase), 5.5 to 9.9 kg m^{-2}

Figure 5. Fuel load in the ponderosa pine forest type after ten years in burned (Sequoia and Kings Canyon National Parks) and unburned areas (Sequoia, Kings Canyon, and Yosemite National Parks combined), and seven years after a second burn (Yosemite National Park). Error bars indicate ± one standard error.

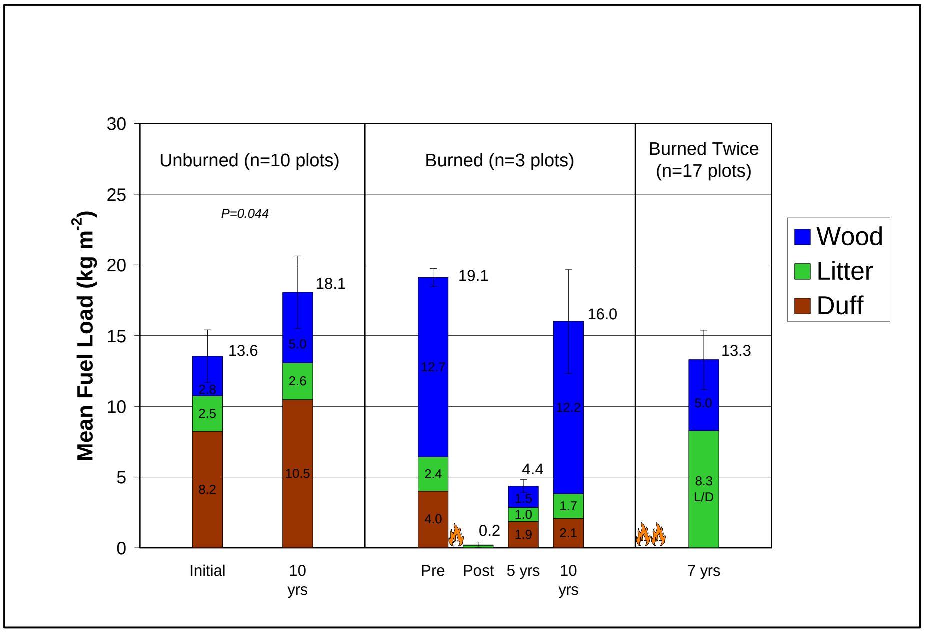


Figure 6. Fuel load in three different ponderosa pine forest sub-types 31 years after burning in Yosemite National Park research plots. Fine fuels include litter, duff, and woody fuels less than 2.54 cm in diameter. Note that large rotten logs were not measured prior to burning in 1971 but are included as an error bar in the 31-year post-fire data (total with rotten logs included in parentheses).

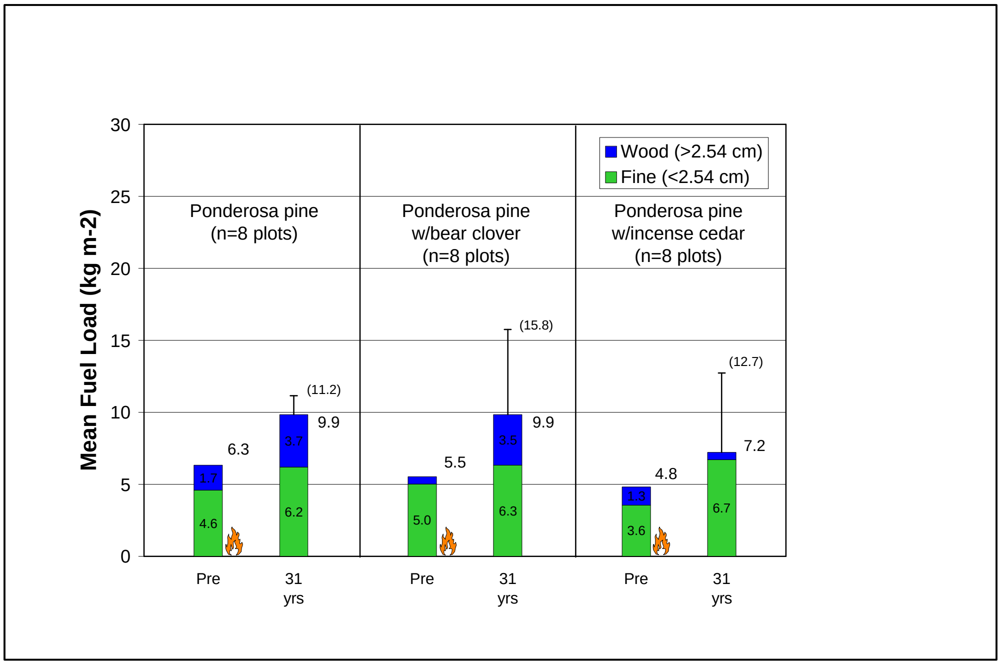


Table 2. Density and basal area for understory (0-30 cm in diameter) and overstory (>30 cm in diameter) trees in Sequoia and Kings Canyon National Parks monitoring plots and Yosemite National Park research plots. Mean values are reported with standard error (SE) below in parentheses. Monitoring plots only include trees >1.4 m in height. Note that post-fire tree data was not collected following the 1972 prescribed fire in the research plots.

Plot Type	n	Diameter Class	Pre-fire		1-year Post-fire	
			Density (trees ha^{-1})	Basal Area (m^2 ha^{-1})	Density (trees ha^{-1})	Basal Area (m^2 ha^{-1})
			Mean *(SE)*	Mean *(SE)*	Mean *(SE)*	Mean *(SE)*
Ponderosa pine (research)	8	0-30 cm	388 *(113)*	8.4 *(1.9)*	-	-
		>30 cm	113 *(41)*	21.2 *(7.3)*	-	-
Ponderosa pine w/ bear clover (research)	8	0-30 cm	171 *(170)*	2.1 *(1.6)*	-	-
		>30 cm	50 *(22)*	32.1 *(15.8)*	-	-
Ponderosa pine w/ incense-cedar (research)	8	0-30 cm	7,992 *(2,260)*	17.3 *(4.4)*	-	-
		>30 cm	54 *(42)*	9.4 *(6.6)*	-	-
Ponderosa pine (monitoring)	3	0-30 cm	310 *(91)*	6.6 *(2.9)*	70 *(12)*	2.7 *(0.6)*
		>30 cm	177 *(61)*	38.5 *(13.2)*	130 *(46)*	30.9 *(11.3)*
White fir-mixed conifer (monitoring)	9	0-30 cm	562 *(135)*	6.5 *(0.8)*	200 *(31)*	4.5 *(0.8)*
		>30 cm	181 *(17)*	67.8 *(4.7)*	171 *(16)*	66.7 *(5.1)*
Giant sequoia-mixed conifer	26	0-30 cm	486 *(87)*	6.2 *(0.9)*	187 *(44)*	3.9 *(0.7)*
		>30 cm	156 *(13)*	167.3 *(38.7)*	146 *(13)*	147.5 *(30.9)*

in ponderosa pine with bear clover (80 percent increase), and 4.8 to 7.2 kg m^{-2} in ponderosa pine with incense-cedar (50 percent increase). Both fine fuels (which included litter, duff, and woody fuels less than 2.54 cm in diameter) and sound woody fuels (greater than 2.54 cm in diameter) increased over the 31-year time period compared to the pre-fire levels, except for the ponderosa pine plots with incense-cedar where woody fuels decreased by 58 percent (Figure 6).

An additional 17 monitoring plots were installed in 1992 in areas that had already burned twice in the last 22 years (1970 and 1985) in Yosemite National Park. These plots experienced a recent fire frequency more similar to the historic fire regime and had a mean total fuel load of 13.3 kg m^{-2} (SE = 2.1) seven years after the second fire (Figure 5). This fuel load was similar to that found initially in the unburned monitoring plots but less than that both in the pre-fire plots and the unburned plots after ten years (Figure 5).

White fir-mixed conifer forest

The pre-fire mean total fuel load was 16.3 kg m^{-2} (SE = 3.1) for the white fir-mixed conifer forest type in nine plots from Sequoia and Kings Canyon National Parks. Mean total fuel load was reduced by 85 percent immediately following treatment with prescribed fire. Within ten years post-fire, the mean total fuel load reached 13.6 kg m^{-2} (SE = 1.9), 83 percent of the pre-fire level (Figure 7). Similar to the ponderosa pine type, understory tree mortality was high (64 percent) (Table 2), and the post-fire fuel complex differed from pre-fire with a larger proportion of woody fuels than duff post-fire. Total fuel load did not increase significantly in unburned areas over a ten-year time period in combined white fir-mixed conifer plots from Sequoia and Kings Canyon and Yosemite National Parks (Figure 7; one-tailed, paired t-test: P=0.661, n=8).

Giant sequoia-mixed conifer forest

Prior to prescribed fire application, the mean total fuel load was 20.4 kg m^{-2} (SE = 1.5) for the giant sequoia-mixed conifer forest type in Sequoia and Kings Canyon National Parks. Immediately after treatment with prescribed fire, mean total fuel load was reduced by 75 percent. Within ten years following fire, mean total fuel load reached 13.4 kg m^{-2} (SE = 1.2), 66 percent of pre-fire levels (Figure 8). Again, a larger proportion of woody fuels than duff found post-fire illustrates that the post-fire fuel complex differed from that pre-fire. Mortality of understory trees was high (62 percent), while post-fire overstory density and basal area changed little (Table 2). Like the white fir-mixed conifer forest type, mean total fuel load in unburned areas did not increase significantly over ten years (Figure 8; one-tailed, paired t-test: P=0.250, n=9).

Most of the treated areas are either scheduled for a second treatment with prescribed fire after about ten years or they have not yet reached the next monitoring phase (20-years post-fire), therefore it is difficult to determine how fuel accumulation rates continue to change over a longer post-fire time period. Several plots in Sequoia and Kings Canyon National Parks have, however, been burned twice and have reached the 20-year post-fire stage. Although the sample size is small (3 plots), total fuel accumulation was minimal between 10 and 20 years after the second prescribed fire (Figure 9). The total fuel load 20 years after the second fire was slightly less than that in unburned areas but the fuel complex is similar (a high proportion of litter and duff), while the fuel complex ten years post-fire has a larger proportion of woody fuels (Figures 8 and 9).

Figure 7. Fuel load in the white fir-mixed conifer forest type after ten years in burned (Sequoia and Kings Canyon National Parks) and unburned areas (Sequoia, Kings Canyon, and Yosemite National Parks combined). Error bars indicate ± one standard error.

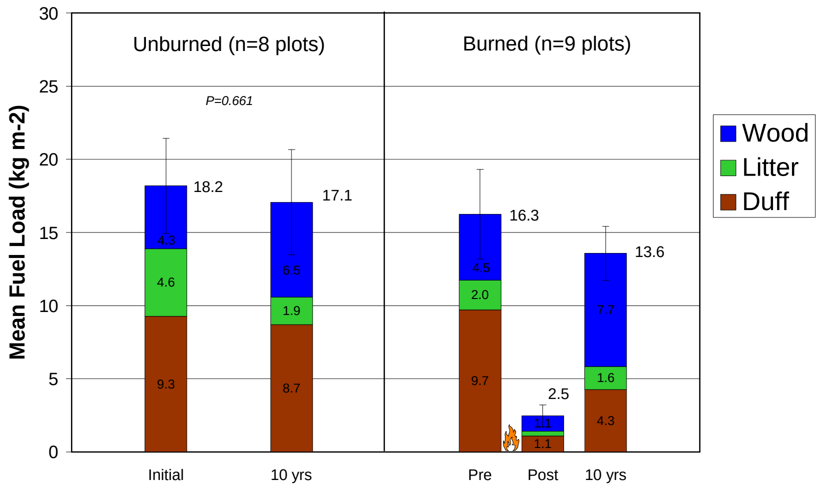


Figure 8. Fuel load in the giant sequoia-mixed conifer forest after ten years in burned and unburned areas in Sequoia and Kings Canyon National Parks. Error bars indicate ± one standard error.

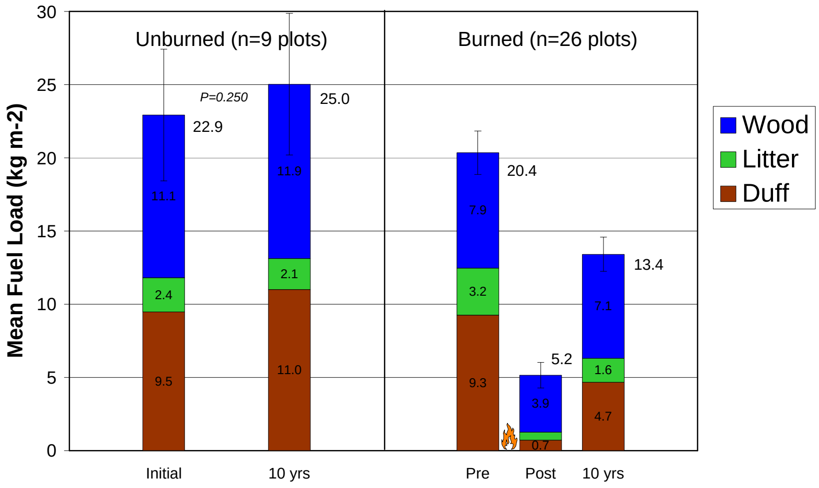
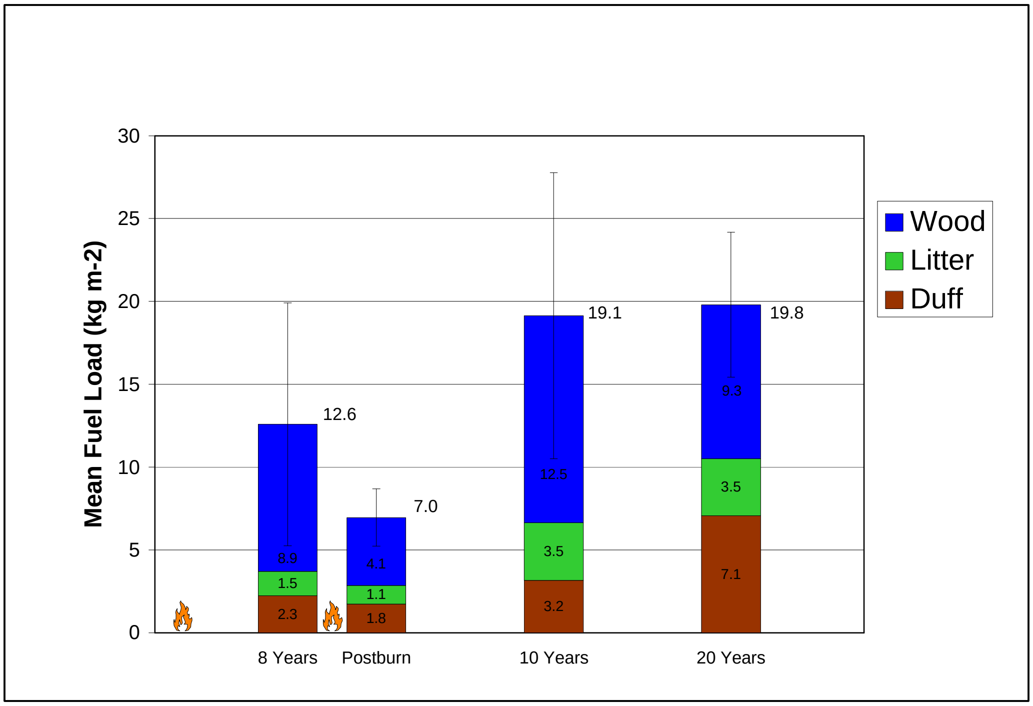


Figure 9. Fuel load in the sequoia-mixed conifer forest 10 and 20 years after a second prescribed fire in Sequoia and Kings Canyon National Parks (n=3 plots). Error bars indicate ± one standard error.



DISCUSSION

In the ponderosa pine monitoring plots, total fuel load reached 84 percent of pre-fire levels ten years following prescribed fire. These results continue the trend in earlier work by van Wagtendonk and Sydoriak (1987) who found that fuel loads reached 55 percent of pre-fire levels six years after burning in the ponderosa pine forest type. High mortality of understory trees supports the relatively high rate of accumulation of post-fire woody fuels (Table 2). The largely intact post-fire overstory continued to contribute litterfall to surface fuels in this relatively productive forest type. In untreated areas, results indicate that total fuel accumulation may be occurring slightly faster than decomposition in areas last burned 50-90 years ago. These continued rates of fuel accumulation would be sufficient to support the frequent fires found historically in the ponderosa pine forest types.

Park fire records, which date back to 1930, indicate that the Yosemite research plots had not burned during 41 years prior to the pre-fire sample in 1971. Fire scars from a tree within the study area showed that the last fire to burn through the area prior to 1971 was in 1895 (Swetnam et al. 1998). Based on Kittredge's (1955) earlier results, fire-free periods of 41 or 76 years would have been more than enough for fuels to reach equilibrium by 1971. Similarly, in 2003, after 31 years of accumulation, the fuels would have again approached the equilibrium amount.

The slight increase in fine fuels (<2.54 cm in diameter) over the 31-year post-fire time period in the research plots (Figure 6) may be attributed to several possibilities. Although data were not collected after the prescribed fire in 1972, observation of the area indicated that many of the understory trees were killed and that about half of the woody and fine fuels were consumed. The increase in fine fuels may be due to post-fire woody fuels from trees killed by the 1972 prescribed fire or from subsequent tree damage or mortality due to non-fire causes. Also, litterfall from the residual stands that may exceed decomposition rates in these relatively productive sites could contribute to the increase in fine fuels. Alternatively, the increase in fine fuels could be attributed to the difference in sampling methods used between the two time periods. In 1971, fine fuels were collected from paired sub-plots and weighed before and after burning, while in 2003, depth measurements were made in the field and converted to fuel load using depth/weight relationships (van Wagtendonk et al. 1998).

The increase in sound (not decayed) woody fuels (>2.54 cm in diameter) in two of the Yosemite research ponderosa pine forest types (Figure 6) may be due to tree mortality caused by insects and/or disease occurring well after the prescribed fire in 1972. Although most fuel accumulation has been attributed to fire exclusion, tree mortality from causes other than fire is known to contribute to the fuel load. For example, Thomas and Agee (1986) found that bark beetles were a significant source of large tree mortality after prescribed burning in mixed conifer forests at Crater Lake National Park, and Agee (2003) concluded that extended drought had killed many large trees inside and outside of a burned area in the park. Similarly, in Yosemite, Guarin and Taylor (2005) found that drought triggered mortality was an important process causing forest structural and compositional change. In the ponderosa pine with incense-cedar sub-type, where pre-fire understory tree density was the highest (Table 2), sound woody fuels decreased over the 31-year period indicating that small trees killed by the fire may have been consumed or fell and decayed during that time period. Differences in sampling transect length may also explain the difference in sound woody fuels between the pre-fire and 31-year post-fire results.

The mean fuel loads for the research plots both pre-fire and 31-years after fire (Figure 6) are much less than those in both the burned and unburned monitoring plots (Figure 5). These differences may be due to the fact that large rotten woody fuels were not sampled on the transect lines in the earlier research study. Including the rotten logs with the other fuels measured during the 31-year post-fire sample makes the 2003 mean total fuel loads more similar to the monitoring plot results (11.2 kg m^{-2} for ponderosa pine, 15.8 kg m^{-2} for ponderosa pine with bear clover, and 12.7 kg m^{-2} for ponderosa pine with incense-cedar) (Figures 5 and 6).

If the fuel loads in the 1971 pre-fire research plots are anomalously low due to a different sampling method (fine fuels) or transect length used (woody fuels), then the 31-year post-fire fuel loads may not have actually increased over pre-fire levels, but are rather, an artifact of the sampling method. In any case, when all fuels are included, the 31-year post-fire fuel loads are similar to, or slightly less than, those in untreated areas. These results could indicate that decomposition may be approaching fuel accumulation rates after about 30 years without treatment, consistent with the findings of Kittredge (1955). Although total fuel load increased somewhat in the unburned ponderosa pine monitoring plots after 50-90 years without fire, basal area was much higher (59.9 m^2 ha^{-1}) than that for the research plots or burned monitoring plots. A difference in basal area may account for the variation in fuel accumulation patterns among the different ponderosa pine forest sampling sites. Continued monitoring of these unburned areas is necessary to confirm whether the fine fuels and the larger woody fuel components continue to increase or whether accumulation has stabilized.

As fuels may continue to slowly accumulate in untreated ponderosa pine forests, treatment to reduce fuel hazard and stand densities that contribute to surface fuel accumulation is increasingly important. In addition to reducing fuel accumulations, fire serves many other ecosystem functions such as selectively removing understory vegetation, recycling nutrients, and maintaining wildlife habitat, to name just a few examples. Without fire, these ecosystems will not function as they did naturally. Even if fuel accumulation is minimal in these untreated areas, the need still exists to restore stand structure and decrease ladder fuels that could contribute to undesirable fire behavior and effects. Additional long-term fuel accumulation data are needed to determine whether surface fuels continue to build up in areas left untreated for many decades in this forest type.

In pre-fire and unburned plots in the white fir-mixed conifer forest, the total fuel load range of 16.3 to 18.2 kg m^{-2} is twice the 8.5 kg m^{-2} reported by Stohlgren (1988) for a 1.1 ha study area in Sequoia National Park that had not burned in about 40 years. Woody fuels >15.1 cm in diameter were not included in that study, which may account for some of the difference. The total fuel load is less than the 23.0 kg m^{-2} found at another white fir-mixed conifer forest site in Sequoia National Park that had not burned in over 90 years (Stephens and Finney 2002). Since the woody fuel loads are very similar between studies, the different method they used to measure the duff and litter depth (duff pins) may account for the greater litter and duff load (18.0 kg m^{-2} compared to 10.6-13.9 kg m^{-2} in this study).

Fuel load differences among studies might also be due to stand structure and/or composition differences among the sites. Stand density and basal area for the white fir-mixed conifer forest are comparable to those reported for the other study sites (density: 743 trees ha^{-1}, 679 trees ha^{-1}, and 707 trees ha^{-1}, this study, Stohlgren 1988, and Stephens and Finney 2002, respectively; basal area: 74.3 m^2 ha^{-1}, 65.9 m^2 ha^{-1}, and 83 m^2 ha^{-1}, this study, Stohlgren 1988, and Stephens and Finney 2002, respectively). In another study from the Giant Forest area of Sequoia National Park, the density of four 1-ha white fir-mixed conifer forest stands was much lower, ranging from 353 to 469 trees ha^{-1}, while basal area was more similar, ranging from 53.9 to 80.0 m^2 ha^{-1} when the study was initiated in 1985 (Mutch and Parsons 1998).

In the giant sequoia-mixed conifer forest, the fuel load range for the litter and duff components (no woody fuel) for pre-fire and unburned plots is 11.8 to 13.1 kg m^{-2}. These results are consistent with early research by Kilgore (1973) that reported 11.2 kg m^{-2} of litter and duff in the Redwood Mountain area of Kings Canyon National Park, and similar reduction of litter and duff in burned plots (90 percent this study, 85 percent in the earlier study). The total fuel load range of 20.4 to 25.0 kg m^{-2} for pre-fire and unburned plots in this forest type is also similar to a later study by Parsons (1978) that reported a total fuel load of 19.1 kg m^{-2} at the Kilgore study area, however, the percent fuel reduction in burned plots was lower (75 percent this study, 89 percent in the earlier study). Litter and duff consumption was the same, therefore, this difference can be attributed to much greater woody fuel reduction in the earlier study (88 percent) compared to this study (51 percent).

In the white fir- and giant sequoia-mixed conifer forest monitoring plots treated once with prescribed fire, total fuel load reached 83 percent and 66 percent of pre-fire levels, respectively, ten years post-fire. This trend is similar to the earlier work by Parsons (1978) in the giant sequoia-mixed conifer forest at Redwood Mountain that showed total fuel load was 53 percent greater in areas seven years after prescribed fire compared to similar areas that had just burned. The fuel accumulation results are also similar to earlier results with a smaller subset of the same giant sequoia-mixed conifer forest monitoring plot data which showed the ten-year post-fire mean total fuel load reached 75 percent of pre-fire levels for 7 plots (Keifer 1998) and 63 percent of pre-fire levels for 12 plots (Keifer and Manley 2002).

The relatively high woody fuel component ten years post-fire is likely due to the large number of understory trees killed by fire in the white-fir and giant sequoia-mixed conifer forests (64 percent and 62 percent, respectively; Table 2) that fell to the forest floor during the ten year period following fire. In Mutch and Parsons' (1998) study in Giant Forest, two stands that were burned experienced a large reduction in total density (62 to 67 percent, compared to 50 percent in this study), with 75 percent of trees less than 50 cm in diameter and 25 percent of trees greater than 50 cm in diameter killed by four years post-fire (Mutch and Parsons 1998). Post-fire reduction in basal area was much greater (23 to 31 percent, compared to only 4 percent in this study), which may be due to greater mortality of large diameter trees and/or delayed mortality of small diameter trees that occurred between one and four years after the fire (Mutch and Parsons 1998).

These stand structure changes are also consistent with earlier results reported with smaller subsets of the giant sequoia-mixed conifer forest monitoring plot data that showed most of the 40-50 percent density reduction resulting from prescribed fire generally occurred in trees less than 40 cm in diameter (Keifer 1998, Keifer et al. 2000). Twenty years after a second prescribed fire treatment, in three giant sequoia-mixed conifer plots, woody fuels, as well as litter and duff, were somewhat less than that in unburned areas. As densities are further reduced following repeated fires and stand structures more closely approach those prior to fire exclusion, branch and tree mortality is not expected to contribute as much to the future surface fuel load (Parsons 1978, Keifer and Manley 2002).

In the longer fire return interval white fir- and giant sequoia-mixed conifer forests, surface fuel accumulation may have slowed in untreated areas. In both of these mixed conifer forest types, the analysis indicates no significant difference between accumulation and decomposition rates in areas left untreated for about 40-90 years. This result supports the findings of Stohlgren (1988) who, using mass balance equations (with forest floor mass and litterfall), estimated that fuel loads would reach a steady state after about 62 years without fire in the white fir-mixed conifer forest. These sites had not burned for about 40-80 years prior to the study initiation. Treatment of these unburned areas, therefore, may not be urgent with respect to increasing surface fuels because the existing surface fuel hazard, while currently high, may not get worse with time.

If the goal is to maintain surface fuels below pre-treatment levels, managers may need to treat mixed conifer areas again in about ten years. Waiting longer, however, may not mean that surface fuels will accumulate greatly over pre-fire levels (Figures 7 and 8). Continued monitoring of fuels will help to inform managers about the most favorable time to re-burn these areas. In addition to reducing surface fuel loads, burning to maintain ecosystem functions is also important, therefore, waiting too long between treatments could have consequences for other aspects of the ecosystems.

This information also may be useful for prioritizing areas for fuels treatment. For example, if managers must choose between burning untreated areas of either ponderosa pine forest or white fir-mixed conifer forest, it might be prudent to treat the ponderosa pine forest type first as surface fuels may still be accumulating. It is critical to note that treatment to reduce current fuel hazard and restore altered stand structure (ladder fuels) is still important in all of these forest types.

This study demonstrates the usefulness of long-term fuel accumulation data for fuels treatment planning and evaluation, and illustrates the need to continue long-term monitoring and research studies. In addition, more repeated prescribed burns are needed to document fuel accumulation patterns over time following multiple treatments. This study also highlights that data from unburned areas are valuable as a reference to determine background fuel accumulation and fuel dynamics in the absence of fire.

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