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Fuel reduction and coarse woody debris dynamics with early season and late season prescribed fire in a Sierra Nevada mixed conifer forest[☆]

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Abstract

Fire exclusion has led to an unnatural accumulation and greater spatial continuity of organic material on the ground in many forests. This material serves both as potential fuel for forest fires and habitat for a large array of forest species. Managers must balance fuel reduction to reduce wildfire hazard with fuel retention targets to maintain other forest functions. This study reports fuel consumption and changes to coarse woody debris attributes with prescribed burns ignited under different fuel moisture conditions. Replicated early season burn, late season burn, and unburned control plots were established in old-growth mixed conifer forest in Sequoia National Park that had not experienced fire for more than 120 years. Early season burns were ignited during June 2002 when fuels were relatively moist, and late season burns were ignited during September/October 2001 when fuels were dry. Fuel loading and coarse woody debris abundance, cover, volume, and mass were evaluated prior to and after the burns. While both types of burns reduced fuel loading, early season burns consumed significantly less of the total dead and down organic matter than late season burns (67% versus 88%). This difference in fuel consumption between burning treatments was significant for most all woody fuel components evaluated, plus the litter and duff layers. Many logs were not entirely consumed – therefore the number of logs was not significantly changed by fire – but burning did reduce log length, cover, volume, and mass. Log cover, volume, and mass were reduced to a lesser extent by early season burns than late season burns, as a result of higher wood moisture levels. Early season burns also spread over less of the ground surface within the burn perimeter (73%) than late season burns (88%), and were significantly patchier. Organic material remaining after a fire can dam sediments and reduce erosion, while unburned patches may help mitigate the impact of fire on fire-sensitive species by creating refugia from which

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EXHIBIT 2

these species can recolonize burned areas. Early season burns may be an effective means of moderating potential ecosystem damage when treating heavy and/or continuous fuels resulting from long periods of fire exclusion, if burning during this season is not detrimental to other forest functions.

Keywords: Burning season; Conifer forest; Duff; Organic matter; Surface fuel; Woody fuel

1. Introduction

Fire exclusion in mixed conifer forests throughout western North America has led to an unnatural accumulation of twigs, branches, logs, litter, and duff, on the forest floor (Parsons and DeBenedetti, 1979; van Wagtendonk, 1985). Due to the lack of fire and increasing tree densities, the spatial continuity of these surface fuels is now also greater (Miller and Urban, 2000). In addition, more of the large downed logs are in a highly decayed state (Skinner, 2002). When ignited, heavy fuels can contribute to extreme wildfire behavior (Arno, 2000; Brown et al., 2003) with potentially detrimental ecosystem consequences (van Wagtendonk, 1985; Stephens, 1998). The heat released by consumption of heavy fuels may cause torching of nearby trees and the embers released by the torching of trees and burning of decayed snags can lead to long-distance spot fires. Rotten logs are readily ignited by embers and are therefore also important in propagating spot fires.

Besides acting as fuel and potentially influencing fire behavior, organic material on the forest floor provides habitat for a large number of forest species, including small mammals (Tallmon and Mills, 1994; Carey and Johnson, 1995; Ucitel et al., 2003; McCay and Komoroski, 2004), reptiles (James and M'Closkey, 2003), amphibians (Bunnell, 1995), and invertebrates (Harmon et al., 1986; Torgersen and Bull, 1995). The presence of organic matter also influences geomorphic processes. Litter and duff aids in water infiltration and reduces the potential for erosion (Agee, 1973). A strong correlation has been found between post-burn watershed sediment yield and the percentage of forest floor exposed by burning (Benevides-Solorio and MacDonald, 2001; Johansen et al., 2001). Logs and other woody debris can dam and retain sediments on slopes and plays an important role in stream channel dynamics (Harmon et al., 1986; Naiman et al., 2002).

With organic matter on the forest floor acting as fuel, habitat, and providing structural integrity to the forest ecosystem, managers are often faced with conflicting considerations (Brown and See, 1981; Brown et al., 2003; Ucitel et al., 2003). Prescription burning is a commonly used method to treat fuels, but fuel reduction targets to reduce wildfire hazard must be balanced with fuel retention targets to maintain habitat and other forest functions. If too much fuel is removed, the heat released may damage trees excessively and the loss of organic matter may lead to erosion and reduced abundance and diversity of fire-sensitive species (Kauffman and Martin, 1989). Conversely, prescribed fires that consume little of the available fuel may not adequately reduce fire hazard. Achieving such a balance can be particularly challenging when fuel loading is high.

The net ecosystem effect of burning, whether by wildfire or prescribed fire, is often closely tied to the amount of heat released. Heat released is in turn proportional to the amount of available fuel (Alexander, 1982; Johnson and Miyanishi, 1995; Whelan, 1995), but fuel moisture, the physical structure of the fuel bed, weather conditions, and a myriad of other factors lead to a high degree of variability in patterns of consumption and subsequent fire effects (Alexander, 1982; Martin and Sapsis, 1992). The excessive litter, duff, and woody debris found in many areas of the Sierra Nevada where fire has been actively suppressed can result in long-duration heating when fire is returned to the system. In the mixed conifer forest, a significant proportion of the "fine fuel" – litter and smaller twigs and stems – is consumed at the flaming front (flaming combustion), leading to a pulse of heat release that has the greatest impact above ground (i.e. canopy scorch on affected trees). The duff layer is typically consumed through smoldering combustion after the flaming front has passed (Kauffman and Martin, 1989). In areas where the duff layer is thick, this smoldering combustion may be of long duration and generate substantially more heat than flaming combustion (Kauffman and Martin, 1989). Because a significant portion of the heat generated by smoldering combustion is transferred downward (Frandsen and Ryan, 1986; Hartford and Frandsen, 1992), soil and below ground processes are often most strongly impacted. Fire can also persist for long periods in large logs. Decayed logs are more likely to be completely consumed by fire than freshly fallen logs (Brown et al., 1985; Kauffman and Martin, 1989; Skinner, 2002), potentially producing a large amount of heat energy.

Even if extensive crown scorch is avoided with the first burn after a period of fire suppression, the heat produced can injure the cambium, kill roots and lead to the death of even large overstory trees (Ryan and Frandsen, 1991; Swezy and Agee, 1991; Stephens and Finney, 2002). In addition, the greater spatial continuity of fuels may cause fire to burn over a greater proportion of the ground surface. Historically, frequent fires are believed to have kept fuel loads relatively low and the lack of fuel continuity contributed to a highly patchy pattern of fire spread (Swetnam, 1993). The patchiness of fire spread under historical conditions may have been important in reducing the impact of fire on fire-sensitive species by creating abundant refugia from which these species could rapidly recolonize burned areas.

The amount of fuel consumed and percentage of the area burned can be controlled to some extent by varying the fuel moisture and weather conditions that prescription burns are conducted under. In similar mixed conifer forests, Kauffman and Martin (1989) reported that early season burns ignited one month after the last spring precipitation event consumed only 15% of the total available fuel, while early fall burns when fuel moisture was much lower consumed 92% of the total available fuel. Percentage consumption of the litter and duff in early and late season burns was significantly correlated with the moisture content of the lower duff layer. Fuel consumption can also vary by the tree species contributing most of the fuel. Agee et al. (1978) noted that pine litter could be effectively reduced by burning in spring, summer, or fall, but drier summer or fall conditions were required to reduce the more compact white fir (*Abies concolor*) and giant sequoia (*Sequoiadendron giganteum*) litter.

Prior to the policy of fire suppression, fires in the mixed conifer zone of the Sierra Nevada burned a given area approximately every 4–40 years (Kilgore and Taylor, 1979; Swetnam, 1993; Caprio and Swetnam, 1995; Skinner and Chang, 1996). In Sequoia and Kings Canyon National Parks, prescription burning has been used to reduce fuels and restore natural ecosystem processes since the late 1960s (Kilgore, 1973). Most of this burning has been done during the fall months, which is within or after the period when the majority of land area is likely to have burned prior to European settlement (mid-summer to early fall) (Caprio and Swetnam, 1995). Early season (late spring/early summer) burns were historically uncommon and usually associated with dry years. Fires in the fall are desirable from a fire management perspective because they are typically followed by the onset of seasonal rain and snow and therefore require less monitoring. However, fall fires potentially have more impact on air quality in the adjacent Central Valley (Cahill et al., 1996), due to stable atmospheric patterns common at this time of year. A greater proportion of the prescription burning in Sequoia and Kings Canyon National Parks has, in the past few years, been conducted earlier in the season under more favorable smoke dispersal conditions.

The purpose of this study was to evaluate differences in surface fuel consumption, fire coverage (proportion of area burned), and coarse woody debris dynamics with early season and late season prescribed fires, to help managers refine burning prescriptions for this vegetation type. The findings are especially relevant to the first restoration burn after a long period of fire suppression.

2. Materials and methods

2.1. Study site description

Three replicate early season prescribed burn, late season prescribed burn, and unburned control units were established in a completely randomized design in Sequoia National Park (Fig. 1). The study site was located on a northwest-facing bench above the Marble Fork of the Kaweah River, adjacent to the Giant Forest sequoia grove, at elevations ranging from 1900 m to 2150 m above sea level. Each unit was 15–20 ha in

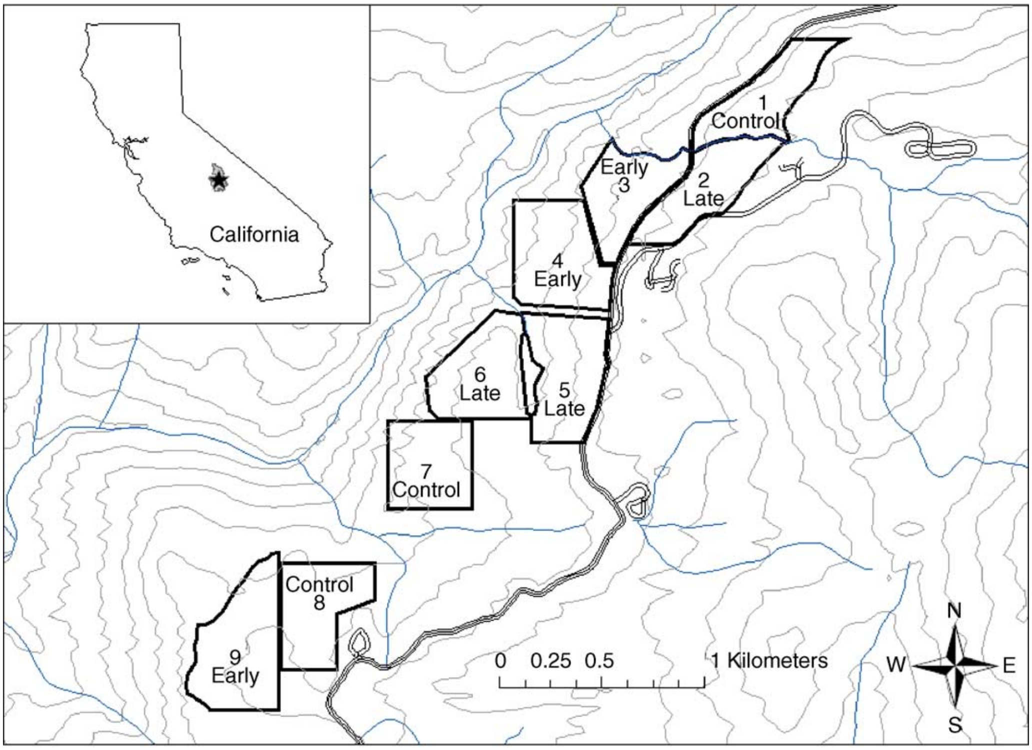

Fig. 1. Map showing location of the early and late season prescribed fire treatment areas in Sequoia National Park, California. The contour interval is 60 m.

size. Tree species in this old-growth mixed conifer forest were, in order of abundance, white fir, sugar pine (*Pinus lambertiana*), incense cedar (*Calocedrus decurrens*), red fir (*A. magnifica* ssp. *shastensis*), Jeffrey pine (*P. jeffreyi*), ponderosa pine (*P. ponderosa*), dogwood (*Cornus nuttallii*), and California black oak (*Quercus kelloggii*). Pre-treatment tree density and basal area averaged 714/ha and 66.5 m^2/ha, respectively. More than half of the trees (370/ha) had a diameter at breast height (dbh) $>$10 cm and numerous large trees were present (41 trees/ha with a dbh $>$80 cm). Cross-dating of wood sections containing fire scars collected from snags indicated that the pre-settlement fire return interval in the study area ranged between 15 and 40 years but the last major fire occurred in 1879 (Caprio and Knapp, unpublished data).

Early season burns were conducted 20 and 27 June 2002 and late season burns were conducted 28 September, 17 and 28 October 2001. Weather data (ambient air temperature, relative humidity, wind speed, and wind direction) were taken hourly immediately prior to and during the burns using a belt weather kit. Conditions were similar during burns within burning season treatment. Ambient air temperature was somewhat higher during the early season burns (range = 16–22 °C) than during the late season burns (range = 13–18 °C). Relative humidity and wind speed ranged from 44 to 68% and 0 to 8 km/h, respectively, during the early season burns and 20 to 63% and 0 to 7 km/h, respectively, during the late season burns. The period of relative humidity $<$40% during the late season burns was confined to the morning of one burn (17 October) and occurred as a temperature inversion dissipated. Relative humidity for much of this burn was within the range experienced during the others.

Ignition was accomplished using drip torches and was initiated at the highest elevation within each burn unit. Three and sometimes four ignition specialists spaced 10–15 m apart walked perpendicular to the slope from higher to lower elevations igniting strips and spot-igniting fuel “jackpots”. Burns were mainly strip head fires of low to moderate intensity. With the exception of occasional single small trees that torched, fire was predominantly on the surface.

2.2. Fuel moisture

Fuel moisture measurements were made at the time of ignition for each burn. Woody fuels of different size classes, in addition to litter and duff, were collected in different microenvironments within the burn unit and separately placed into air-tight plastic bags or nalgene bottles. The larger woody fuels were obtained by cutting 1–2 cm wide cross sections out of logs with a chain saw. Samples were returned to the lab, weighed wet, dried in a mechanical convection oven at 85 °C for 48 h, and weighed again. Because several of the duff samples collected prior to one of the early season burns contained a significant amount of mineral soil, separate duff samples were re-collected shortly after the burn in an adjacent unburned forest area with similar aspect, species composition, and canopy cover.

2.3. Surface fuel loading

Mass of surface fuel (dead and down woody fuels plus litter and duff) was estimated both prior to treatment and following treatment using Brown’s planar intercept method (Brown, 1974). Two 20 m transects were installed at each of 36 spatially referenced points located on a 50 m grid within each unit. The direction of the first transect was based on a random bearing (n), and the second transect was placed $n + 120^\circ$ from the first. The proximal end of each transect was offset 2 m from the gridpoint to avoid disturbance in the area of the grid point. Number of intercepts of 1-h (hour) (0–6 mm) and 10-h (>6–25 mm) fuels were counted along the first 2 m of the transect, while 100-h (>25–76 mm) fuels were counted along the first 4 m of the transect. The 1000-h fuels (>76 mm) were counted along the entire length of the transect. Diameter, species, and decay class (sound or rotten) of each 1000-h log was noted. A log was considered rotten if it could be dented or broken up with a kick. The maximum height above the ground of elevated dead woody fuel was measured in three adjacent 33 cm long sections in the center of the transect. Litter and duff depth measurements were also taken at three spots along the transect (5 m, 10 m, and 15 m). Depth measurements were made 50 cm to the right of the transect prior to treatment and 50 cm to the left of the transect post-treatment. Because so little of the forest floor was composed of freshly cast leaf and needle material at the time of sampling, we defined litter as both the freshly cast and fermentation layers (fermentation layer = cemented together by fungal growth but the shape and structure of needles, etc. still visible). The duff layer was anything below the fermentation layer down to mineral soil. Fuel loads were calculated using formulas of Brown (1974) with individual tree species constants for bulk density, squared quadratic mean diameter, and non-horizontal correction from van Wagtendonk et al. (1996, 1998). The individual species constants were weighted by the proportional basal area of tree species in the study area. Total litter and duff fuel mass was estimated using fuel depth to weight relationships developed for the study area (described below).

At the time of the second census (post-burn), the total transect length covering areas that burned, did not burn, or were composed of rock were mapped along each Brown’s transect. Patchiness of the burn pattern was estimated by calculating the average number and average size of unburned patches. Brown’s transects in the early season burn units were surveyed shortly after the burns and in the same growing season, while the late season burns were followed by snowfall and could not be evaluated until the following spring. The fuel reduction estimates for the late season burns were therefore corrected for the amount presumed to have been added over the winter and prior to the fuel survey. Because late season burns consumed nearly the entire litter and duff layers where fire passed over the surface (see duff pin methods, next paragraph), all litter, duff, and small woody fuels on burned ground were assumed to have fallen since the burns and were not considered in the calculation of post-burn fuel estimates. Large woody fuel pieces that obviously fell post-burn (i.e. lying in a burned area but showing no visual evidence of combustion) were also not considered. Few large woody fuel pieces fell over the winter in the unburned controls, and these were identified by comparison with pre-treatment data. Other fuel categories in the unburned controls were not similarly corrected, but their amounts were presumed to have been negligible (far more fuel was added to the late season burn plots over the winter due to loss of scorched needles and instability of partially consumed snags).

To more accurately evaluate litter and duff consumption in areas where fire burned, duff pins consisting of 30 cm nails or 75 cm sections of rebar were pounded into and flush with the forest floor and extending into the mineral soil. Four duff pins were installed adjacent to each grid point. Shortly after each burn, pins were reexamined and distances from the top of the duff pin to the top of remaining unburned forest floor material as well as the total distance from the top of the pin to mineral soil were measured.

2.4. Litter and duff depth: weight relationships

Forest floor samples were collected across the study area prior to treatment to develop a regression equation relating forest floor depth to forest floor mass. A 30 cm × 30 cm metal frame was pushed into the forest floor 5 m from the end of one fuel transect per gridpoint, at a random bearing. Litter and duff was excavated using a metal cutter and composition of the litter was scored visually as belonging to one of the three following categories; >80% short needle (*Abies* sp. and *Calocedrus decurrens*), >80% long needle (*Pinus* sp.), and mixed. Litter and duff were bagged separately. To ensure collection of all organic material, duff was collected past the mineral soil surface and later washed to remove the soil and rock portion. After the forest floor sample was removed, the depth of each layer was measured at the center of each side of the excavated square and averaged by layer for that sample. All litter and washed duff samples were dried at 85 °C in a mechanical convection oven for 48 h. After weighing the litter samples, all woody fuels with a diameter less than 7.6 cm were removed from the sample and weighed (woody fuels larger than 7.6 cm were not collected—the sampling frame was moved if the sampling point intersected with a section of woody fuel larger than 7.6 cm). Weights of woody fuels were subtracted from the total sample weight in developing the litter and duff depth: weight relationships.

2.5. Other fuels

Estimates of live fuel mass were not taken because the biomass contained within the understory (tree seedlings, grasses, forbs, and shrubs) was minimal relative to mass of dead and downed surface fuel. Although these live fuels did often burn and occasionally resulted in locally more intense fire activity, the overall contribution to fire effects was likely very low.

2.6. Coarse woody debris

Additional measurements were made on larger logs in order to obtain a better understanding of changes in habitat value, such as cover and volume, that could not be gained from Brown's transect data. Course woody debris (CWD) data were collected using methods similar to those described in Bate et al. (2002). A 4 m × 20 m strip plot was established along the second Brown's transects at every other gridpoint, with the transect forming the centerline of the plot. All logs or portions of logs that were at least 1m in total length and with a large end diameter of at least 15 cm (in or out of the plot) were counted and large end and small end diameters measured. If a log extended outside the plot, diameters were measured at the line of intercept with the plot boundary and the CWD piece. Logs were assumed to end when the diameter fell below 7.6 cm. Logs were not measured if more than half of the log was buried within the forest floor material. Two log lengths were measured—the length within the plot area, and total length. Log number was estimated as a count of logs with midpoints falling within the boundaries of the plot.

2.7. Data analysis

Separate fuel depth to weight regression equations were calculated for litter and duff composed primarily of fir, primarily of pine, and mixed species. In all calculations, the y-intercept was assumed to be equal to zero. The hypothesis of no difference between slopes of the lines for the three forest floor categories was tested using equations given in Zar (1999).

Fuel moisture of different classes and the percentage of residual litter and duff remaining in areas that burned were summarized at the experimental unit level and arcsine square root transformed prior to analysis using one-way ANOVAs with treatment (early season burn and late season burn) as the sole factor. Differences among treatments in fuel and CWD variables were evaluated with analysis of covariance (ANCOVA), using the pre-treatment numbers as a covariate. The treatment × covariate interaction was included in the model as well in cases where it was statistically significant. Linear contrasts, set a priori, were used to estimate the effect of burning (burns versus unburned control), and the effect of season of burning (early versus late). If the treatment × covari-covariate interaction was significant, the contrasts were calculated on the interaction at the level of the mean of the covariate. Differences between burning treatments in percentage of area burned, number of unburned patches per 20 m, and unburned patch size were evaluated using one-way ANOVAs. While both the average number of unburned patches and average unburned patch size variables did not require transformation, average percentage of area burned was arcsine square root transformed prior to analysis. A statistical significance level of $P < 0.05$ was used for all tests. Calculations were made using either SYSTAT v. 10 (SPSS Inc., Chicago, IL) or SAS v. 8 (SAS Institute, Cary, NC).

3. Results

3.1. Fuel moisture

Fuels within all size categories were significantly wetter during the early season burns than during the late season burns (Table 1). The difference in moisture was especially pronounced for large woody fuels and duff. Early season fuel moisture was for most woody fuel categories somewhat higher than the range within which Sequoia and Kings Canyon National Parks usually conducts prescribed burns in this vegetation type (Table 1). While woody fuels in the late season were within the prescription range, the 1000 h fuels were on the dry end of the prescription (Table 1).

3.2. Fuel loading and consumption

Separate regression coefficients for the depth to weight relationship were initially calculated for the three tree overstory categories—short needled, long needled, and mixed. However, neither the slope coefficients for the three litter categories nor the slope coefficients for the three duff categories were found to differ significantly from each other. Therefore, all data were combined and single equations were calculated for the litter and duff layers. A significant linear relationship with high r^2 was found between depth and mass for both litter and duff fuel samples (Fig. 2).

Prior to treatment, total fuel load averaged 191.6 Mg/ha across treatments (Table 2). Over half of this fuel (105.7 Mg/ha) was found in the litter and duff layers. Large logs (>7.6 cm diameter) comprised the majority of the woody fuels (77.5 Mg/ha), and 69% were classified as rotten. All surface fuel categories were significantly reduced by either early or late season burning, relative to the unburned control (Table 3). However, significantly less total fuel was consumed by early season burns (Table 3). The early season and late season burns consumed 67% and 88% of the available surface fuel, respectively. When broken down into individual surface fuel categories, significantly less was consumed for most with early

Table 1
Percentage moisture of fuels at the time of early season and late season prescribed burns in Sequoia National Park

Fuel type (fuel diameter)	Fuel moisture (%)		P-value	Fuel moisture prescription range (%)
	Early season (June 2002)	Late season (September/October 2001)		
1 h (0–0.6 cm)	13.5	8.9	0.018	5–12
10 h (0.6–2.5 cm)	12.7	8.8	0.001	6–13
100 h (2.5–7.6 cm)	16.9	10.4	0.032	7–14
1000 h (>7.6 cm)	26.4	10.6	0.020	10–20
Litter	22.5	11.3	0.011	–
Duff	37.9	11.7	0.002	–

Litter was considered the freshly cast and fermentation layers, while duff was considered the humus layer. Statistical significance of difference between treatments was tested using analysis of variance after arcsine square root transformation.

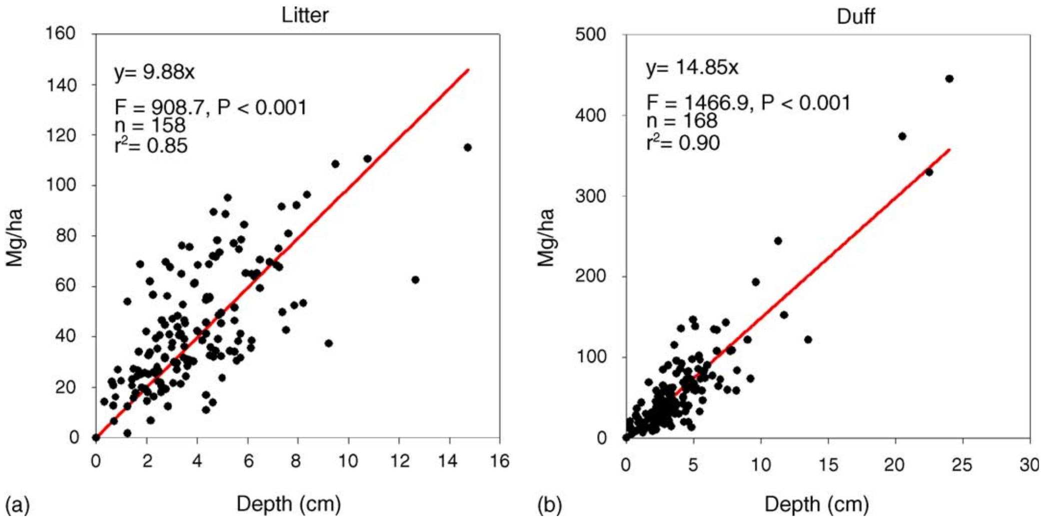

Fig. 2. Depth to mass regressions for (a) litter (freshly cast and fermentation layers) and (b) duff (humus layer) from systematic collections of litter and duff made throughout the study area. Samples were dried at 85 °C for two days before weighing.

season burns, and differences in the 10 h and 1000 h categories were nearly statistically significant. Average height of woody surface fuel above the forest floor was significantly reduced by fire, but there was no difference between the early and late season prescribed fire treatments (Table 3).

Less fuel consumption by early season burns was due to both a significantly greater amount of residual fuel remaining in areas that burned (Fig. 3a), and significantly less area burned within the fire perimeter (Fig. 3b). Early season burns left approximately five times more litter and duff unconsumed in areas where fire passed over the forest floor than late season burns. Early season burns were also significantly patchier (Fig. 3c) and the size of these unburned patches tended to be smaller (Fig. 3d).

3.3. *Coarse woody debris*

Large quantities of coarse woody debris were found in the study area. Prior to the prescribed burns, number of downed logs averaged 173/ha (91 with a diameter <30 cm and 82 with a diameter ≥30 cm) and covered an average of 4.3% of the ground surface area (Table 4). The total length of logs averaged 1064 m/ha, with a total volume of 190 m^3/ha (Table 4). Log mass averaged 61.7 Mg/ha, less than the 78.6 Mg/ha of 1000 h fuel estimated with Brown's transects. The

Table 2
Mean mass (standard error in parenthesis) of different fuel categories and height of woody fuels above the litter surface prior to and after treatment by early season and late season prescribed burns

Treatment	Time of survey	1 h (<0.6 cm) (Mg/ha)	10 h (0.6–2.5 cm) (Mg/ha)	100 h (2.5–7.6 cm) (Mg/ha)	1000 h (>7.6 cm) (Mg/ha)	Litter (L&F layers) (Mg/ha)	Duff (H layer) (Mg/ha)	Fuel total (Mg/ha)	Fuel height (cm)
Unburned	Pre-treatment	1.4 (0.04)	2.8 (0.1)	4.8 (0.3)	95.8 (11.0)	40.5 (4.8)	66.8 (5.6)	212.0 (17.3)	10.6 (1.5)
Early burn	Pre-treatment	1.1 (0.1)	2.7 (0.2)	4.7 (0.3)	70.6 (6.6)	42.8 (0.7)	59.5 (5.9)	181.3 (12.2)	11.3 (1.2)
Late burn	Pre-treatment	1.0 (0.1)	2.4 (0.2)	4.4 (0.3)	66.2 (9.5)	38.0 (1.8)	69.5 (2.9)	181.4 (13.5)	9.4 (0.2)
Unburned	Post-treatment	1.1 (0.02)	2.5 (0.1)	5.0 (0.2)	86.5 (9.8)	37.9 (1.4)	76.5 (0.9)	209.4 (10.2)	12.2 (1.4)
Early burn	Post-treatment	0.3 (0.04)	0.7 (0.1)	1.6 (0.1)	31.0 (4.2)	7.7 (0.3)	18.4 (2.2)	59.7 (5.3)	4.0 (0.6)
Late burn	Post-treatment	0.1 (0.04)	0.2 (0.1)	0.3 (0.1)	15.0 (1.3)	2.0 (0.5)	4.9 (1.8)	22.5 (3.2)	4.0 (1.1)

Table 3
Significance of analysis of covariance results for fuel size categories and fuel height after application of the burning treatments

Effect	d.f.	P-value							
		1 h (<0.6 cm)	10 h (0.6–2.5 cm)	100 h (2.5–7.6 cm)	1000 h (>7.6 cm)	Litter (L&F layers)	Duff (H layer)	Fuel total	Fuel height
Covariate	1	0.019	0.031	0.001	0.051	<0.001	0.002	0.007	0.337
Treatment	2	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	<0.001	0.003
Burn vs. unburned	1	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	0.001
Early vs. late	1	0.008	0.070	0.001	0.068	0.004	0.004	0.004	0.441
Error	5								

Pre-treatment data were used as a covariate. The treatment × covariate interaction was not significant for any of the dependent variables and was therefore not included.

difference is likely due to the more restrictive definition of CWD.

Burning treatments resulted in a significant reduction in all CWD measures except log number (Table 5). Many logs were not completely consumed by fire. While late season burns resulted in significantly greater reduction in log cover, log volume, and log mass compared to early season burns, reduction in log length and log number did not differ between burning season treatments (Table 5). This difference between CWD variables in response to burning season treatment may be related to the tendency of early season burns to consume just the outer layers of many of the larger logs. While the late season burns also often did not consume the entire log, a greater proportion of the wood circumference was typically consumed. The reduction in CWD mass between burning season treatments was similar for the

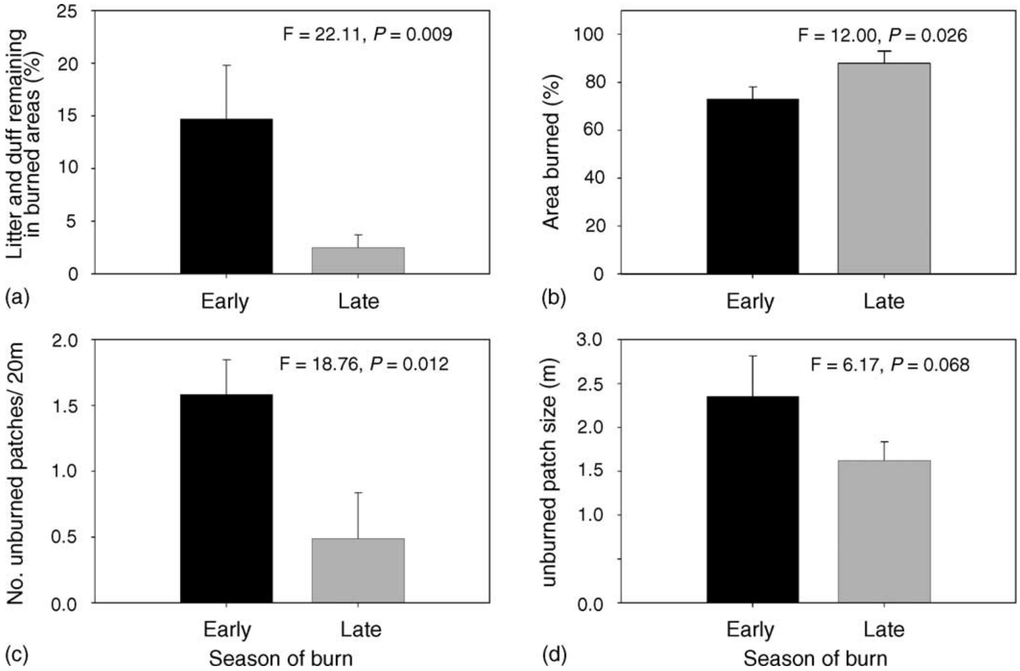

Fig. 3. Average percentage of residual litter and duff remaining in areas that burned (a), average percentage of area burned (b), average number of unburned patches within 20 m long Brown's fuel transects (c), and average size of unburned patches located within 20 m long Brown's fuel transects (d) in early season and late season prescribed fires.

Table 4
Means (standard errors in parentheses) of coarse woody debris attributes prior to and after treatment by early season and late season prescribed burns

Treatment	Time of survey	No. logs/ha, <30 cm diameter	No. logs/ha, ≥30 cm diameter	Log length (m/ha)	Log cover (%)	Log volume (m^3/ha)	Log mass (Mg/ha)
Unburned	Pre-treatment	90.3 (4.0)	108.8 (26.1)	1210.7 (128.3)	5.2 (0.6)	246.1 (19.6)	79.2 (6.4)
Early burn	Pre-treatment	134.3 (4.6)	76.4 (6.9)	1208.2 (51.5)	4.5 (0.7)	184.8 (48.6)	58.8 (14.8)
Late burn	Pre-treatment	48.6 (8.0)	62.5 (13.9)	772.2 (102.9)	3.3 (0.5)	138.5 (19.7)	47.2 (7.0)
Unburned	Post-treatment	111.1 (17.5)	104.2 (28.9)	1155.6 (102.0)	4.6 (0.5)	204.5 (22.8)	69.1 (8.5)
Early burn	Post-treatment	113.4 (11.6)	60.2 (6.1)	708.6 (35.8)	2.2 (0.1)	75.1 (51.3)	26.2 (2.6)
Late burn	Post-treatment	34.7 (10.6)	32.4 (6.1)	302.9 (57.3)	0.8 (0.1)	20.0 (2.1)	7.4 (0.9)

two measurement methods (percentage reduction of these components with early and late season burns averaged 55% and 77%, respectively, when measured using Brown's transects, and 56% and 84%, respectively, when measured using strip plot surveys).

4. Discussion

Fuel moisture was likely the main cause of differences in fuel consumption with early and late season burns. Because energy is necessary to drive off water before combustion is possible, more energy is required to propagate flaming combustion in moist fuels than dry fuels (Frandsen, 1987; Nelson, 2001). Consumption of large woody fuel is often quite high at moisture levels equal to or less than 10–15%, but less than half of these fuels are typically consumed when moisture levels exceed 25–30% (Brown et al., 1985). In this study, some logs were likely drier, while others, particularly partially rotten logs in shady locations, were likely considerably wetter than the average 26% moisture content of large logs (1000 h fuels) at the time of early season burns. Kauffman and Martin (1989) found that moisture content of the lower duff layer was the most important fuel or weather-related variable in multiple regression models of duff consumption. Little duff is consumed when the moisture content exceeds 110%, and the duff layer may burn independently of surface fire at a moisture content of less than 30% (Sandberg, 1980). Between these two values, consumption is related to both moisture content and heat of the surface fire (Reinhardt et al., 1991). Brown et al. (1985) reported an inverse linear relationship between duff moisture and percent duff consumption for mixed conifer forests in the northern Rocky mountains, and suggested that moisture content may become an even stronger predictor of consumption the deeper the duff layer.

Fuel moisture also influences fuel consumption through its effect on the amount of area within the

Table 5
Significance of analysis of covariance results for coarse woody debris attributes after application of the burning treatments

Effect	d.f. (treatment × covariate interaction included)	*P*-value					
		No. logs/ha, <30 cm diameter	No. logs/ha, ≥30 cm diameter	Log length (m/ha)	Log cover (%)	Log volume (m^3/ha)	Log mass (Mg/ha)
Covariate	1	0.132	0.353	0.070	0.009	0.007	0.007
Treatment	2	0.125	0.398	0.008	0.003	0.201	0.134
Treatment × covariate	2	–	–	–	–	0.038	0.024
Burn vs. unburned	1	0.122	0.251	0.003	0.001	0.004	0.003
Early vs. late	1	0.166	0.409	0.184	0.045	0.022	0.011
Error	5 (3)						

Pre-treatment data were used as a covariate. The treatment × covariate interaction was included when significant. In these cases, the contrasts for effect of treatments were calculated on the interaction at a value set to the mean of the covariate.

fire perimeter that burns. In fire simulation studies, Hargrove et al. (2000) reported that modeled fires under high fuel moisture conditions produced dendritic and patchy burn patterns, while at lower fuel moisture conditions, little of the landscape within the fire perimeter remained unburned. The model was based on fire ignition and spread in a gridded landscape where the probability of spread to neighboring fuels was evaluated in eight directions. The probability that fire will propagate to neighboring fuels (I) is reduced at higher fuel moisture levels. Interestingly, the maximum variability in fire burn pattern was predicted to occur near the critical threshold of $I = 0.25$, below which most fires remained small or went out. Using a different model, Miller and Urban (2000) also predicted that the functional connectivity of surface fuels would be reduced under higher fuel moisture conditions. Our findings of significantly reduced amount of area within the fire perimeter burned and greater patchiness of early season burns conducted under higher fuel moisture conditions are consistent with these model predictions. Slocum et al. (2003) similarly found that prescribed burns in Florida conducted under higher fuel moisture conditions were patchier than burns conducted when fuels were drier.

Based on fire scar dendrochronology data collected adjacent to our study area, Swetnam (1993) suggested that a fire-free interval as long as that seen today is likely unprecedented in the last 2000 years. By the time of our prescribed burns, a minimum of three to four cycles of fire had likely been missed. As a result, the fuel mass and CWD attributes reported here (log number, log length, log cover, log volume, and log mass) were likely considerably higher than what might have been present without fire suppression. The average of 191.6 Mg/ha of fuel found prior to the prescribed burns in this study was greater than fuel loadings reported for second growth and old-growth mixed conifer forests in northern portions of the Sierra Nevada by Kauffman and Martin (1989) (range, 74.8–163.9 Mg/ha). Keifer (1998) estimated the amount of pre-burn fuel to be 143.5 Mg/ha in several plots of mixed conifer/giant sequoia forest in Sequoia National Park that hadn't burned in over 40 years. A nearby mixed conifer that had also not experienced fire since pre-settlement times contained 210 Mg/ha of fuel (Mutch and Parsons, 1998), which is comparable to levels found in this study.

Accurate estimates of fuel mass and consumption are essential to predicting fire effects. Slopes of the litter and duff depth to weight regression relationships developed for this study were very similar to the estimates reported by van Wagtendonk et al. (1998) for white fir (litter: 9.88 versus 10.05 for this study and van Wagtendonk et al. (1998), respectively; duff: 14.85 versus 15.18 for this study and van Wagtendonk et al. (1998), respectively), helping to validate the accuracy of both sets of numbers. The 88% reduction in fuel mass recorded in the late season burn treatment was comparable to levels of consumption seen in other fires in mixed conifer forests conducted under dry fall conditions (Kauffman and Martin, 1989; Kilgore, 1972; Mutch and Parsons, 1998), slightly lower than the 91% fuel reduction reported for a dry early fall prescribed fire on a nearby southeast-facing slope in the same watershed (Stephens and Finney, 2002), and somewhat greater than an average consumption of 71% for multiple prescribed fires conducted under a range of fuel moisture conditions in Sequoia National Park (Keifer, 1998). Fuel reduction in the early season burns (67%), while still substantial, was within the range of values reported by Kauffman and Martin (1989) for late spring burns in Sierran mixed conifer forest (61–83%). Our estimate of the percentage of ground surface area within the fire perimeter that burned in the late season prescribed fires (88%) was very close to estimates of Kilgore (1972), who found that 80% of study plots within a late season prescribed fire unit were completely burned, while 14% of plots were partially burned. Similar data has, to our knowledge, not been collected in this vegetation type for early season burns.

With a complete understanding of fire effects often lacking, resource managers may seek to conduct prescription burning operations for restoring the process of fire to these forests that mimic historical fires that the trees and other forest organisms on a site evolved with (Moore et al., 1999; Stephenson, 1999). While the majority of land area historically burned during the dry late summer to early fall period, prescribed fires at the same time of year may now generate fire effects outside of the historical norm, due to the current high fuel loading conditions. These fire effects are potentially a function of not only of changes in the abundance of fuels, but the changes in the proportion of fuels that are in a highly decayed state. The dominant woody fuels in this system tend to decompose relatively rapidly. Harmon et al. (1987) reported a half life of only 14 years for white fir logs. However, with frequent low to moderate severity fires, large amounts of decomposed wood on the forest floor was likely historically uncommon (Skinner, 2002). Under dry fuel moisture conditions, decomposed logs are more likely to be completely consumed than sound, more recently fallen logs (Kauffman and Martin, 1989; Skinner, 2002; Stephens and Finney, 2002). The cracking and breakage of decomposed wood over time also increases the surface to volume ratio, leading to more rapid consumption and therefore potentially greater heat generation.

In addition to the high surface fuel loadings at the time of the burns, the spatial continuity of these fuels was also likely greater than found historically. Frequent fires are predicted to reduce fuel continuity (Miller and Urban, 2000), and historical fires were therefore likely quite patchy. This same finding can be inferred from Swetnam (1993), who reported a negative relationship between the proportion of trees exhibiting fire scars in any given year and the fire frequency. With more time between fires, the extra fuel buildup apparently aided in fire spread. It is likely that prescribed fires conducted under current levels of fuel continuity and under dry conditions where fire spread is not limited by fuel moisture will result in a greater proportion of the area within the fire perimeter burned, compared to historical fires.

By burning less of the landscape within the fire perimeter, the pattern of consumption of the early season fires was possibly more similar to historical fires. This patchiness may aide in the post-fire recovery of plant and animal populations, as the spatial distribution and size of unburned islands can be important for the recruitment and persistence of species that are sensitive to fire (Turner et al., 1997). Andrew et al. (2000) suggested that refuges provided by unburned logs may allow ant diversity to be maintained, even with frequent fuel-reduction fires. The abundance and distribution of unburned patches may also influence the probability of erosion. From rainfall simulation experiments, Johansen et al. (2001) found that sediment yields resulting from erosion did not change greatly whether 0% or 60–70% of the ground surface was exposed by burning. However, once the threshold of 60–70% of bare ground was exceeded, sedimentation increased sharply, possibly because of the greater probability of the connectedness of bare patches, which made infiltration and sediment capture less likely. The amount of bare ground exposed by early season burns in this study was close to the threshold value reported by Johansen et al. (2001), while the bare ground exposed by late season burns substantially exceeded this threshold. Such erosion simulations may be helpful for better defining target burn area percentages in prescribed fires.

While this study demonstrated that early season burns were not as effective at reducing fuel loading, less fuel consumption and less area within the fire perimeter burned may be beneficial for the recovery rate of important ecosystem components. In addition, more habitat for animal species dependent on CWD was maintained. However, the habitat value of charred but only partially consumed logs, relative to unburned logs, is unknown. Comparisons of these burns with historical fires are not possible, but the early season burns may have produced a landscape closer in many ways to that found after historical fires. The idea of utilizing early season burning as a tool to more gradually get back to the desired forest conditions is not new. Kilgore (1972) described two different strategies for reintroducing fire to the mixed conifer forest after a period of fire exclusion—either a relatively hot ‘‘restoration’’ burn that consumes a large proportion of the total fuel and results in significant mortality of trees, followed by additional burns at longer intervals (necessary because fine fuel accumulation will be slower with fewer remaining overstory trees), or a milder restoration burn followed by additional burns at shorter intervals. Both Arno (2000) and Allen et al. (2002) suggested that fire-induced damage could be reduced by successive burns starting with damp fuels. In the Sierra Nevada, higher fuel moisture conditions can be found both early in the burning season after snow melt, or following the first fall rains but prior to snowfall that persists on the ground. The latter conditions do not occur in all years, and the window of opportunity is typically narrow if it does. Thus, to meet burn area targets with currently available resources and burning strategies will likely continue to result in substantial burning being conducted during the early season.

Considering burning season as a tool to obtain the desired fire effects needs to also balance other factors that could be influenced by season. For example, earlier burns often occur during the growth or active phase of many organisms, which could potentially result in undesired impacts. Managers have sometimes elected not to conduct burns during bird nesting season, especially for sensitive species that nest in the forest understory (Robbins and Myers, 1992) and early season burns when conditions are moist may coincide with the peak of amphibian surface activity (Pilliod et al., 2003). However, as shown in this study, early season burns conducted under higher fuel moisture conditions also consume less of the forest floor and CWD that provides habitat for these species. Agee (1993) suggested that fires occurring during active growth phase of trees may be more injurious than fires occurring during the dormant season. Early season burns can lead to higher tree mortality by killing more of the fine surface roots of conifers (Swezy and Agee, 1991). In addition, McHugh et al. (2003) found that early season burns result in higher bark beetle activity and greater secondary mortality of some conifer species. All of these factors will need to be considered in decisions about the most appropriate time of year to conduct the first restoration burn after a period of fire suppression. Studies to evaluate potential impacts of burning season on these additional ecosystem components are in progress.

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