Fire behavior, fuel consumption, and forest-floor changes following prescribed understory fires in Sierra Nevada mixed conifer forests

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We quantified fire behavior, fuel consumption, and forest-floor responses to understory fires prescribed to cover a wide range and variable combination of fuel loadings, fuel moisture levels, and weather conditions in Sierra Nevada mixed conifer forests. At each of three locations, five burns were conducted under each of four different prescriptions ($n = 60$). Fuel loads ranged from 75–102 Mg/ha on an open site of low productivity to 125–177 Mg/ha on more productive sites. Total fuel consumption ranged from 15% in early spring burns to 92% in early fall burns. Organic horizons (litter and duff) composed 62–84% of the total fuel load. Consumption of the organic horizons ranged from 11 to 94%. Lower duff (Oa horizon) moisture content was 135% in the former and 15% in the latter. Consumption of the organic horizon was significantly correlated with lower duff moisture content ($r^2 = 0.51$). More than 72% of all fuel was consumed after the flaming front had passed over an area. Postburn mineral soil exposure was strongly influenced by fuel consumption, season of burn, and characteristics of the site. In the late spring burns at one site, bare ground exposure was 3% before fire, 60% two months after fire, and 8% thirteen months after fire. There were slight to nonexistent increases in bare ground exposure from burns prescribed during early spring or late autumn (i.e., burns of low to moderate consumption).

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Les auteurs ont quantifié le comportement du feu, la destruction des combustibles ainsi que la réponse du parterre forestier à des brûlages contrôlés du sous-bois prescrits, dans le but de couvrir une grande variation et diverses conditions de charges de combustibles, d'humidité des combustibles et de temps rencontrées dans les forêts conifériennes mixtes de la Sierra Nevada. À chacun de trois endroits, cinq brûlages ont été exécutés suivant quatre prescriptions différentes ($n = 60$). La charge des combustibles variait de 75–102 Mg/ha dans une station à découvert de faible productivité à 125–177 Mg/ha dans des stations plus productives. La destruction des combustibles totaux a varié de 15% dans les brûlages de l'avant-printemps à 92% dans ceux réalisés en début d'automne. Les horizons organiques (litière et humus) formaient de 62 à 84% de la charge totale des combustibles. La destruction des horizons organiques a varié de 11 à 94%. Le contenu en humidité de la couche inférieure de l'humus (horizon Oa) était de 135% dans ce cas-ci et de 15% dans l'autre. La destruction de l'horizon organique était corrélée de façon significative avec le contenu en humidité de la couche inférieure de l'humus ($r^2 = 0{,}51$). Plus de 72% de tous les combustibles ont été détruits après le passage du front des flammes au-dessus d'une surface. L'exposition du sol minéral après le brûlage était fortement influencée par la destruction des combustibles, la saison du brûlage et les propriétés spécifiques de la station. À la suite d'un brûlage effectué tard au printemps, le sol minéral dénudé occupait 3% avant le feu, 60% après deux mois et 8% au bout de 13 mois. On n'a observé que peu ou pas d'augmentations de l'exposition du sol minéral avec les brûlages exécutés tôt le printemps ou tard l'automne (c'est-à-dire avec ceux dont la destruction des combustibles était de faible à modérée).

[Traduit par la revue]

Introduction

The policy of fire exclusion in mixed conifer forests of western North America has resulted in unnatural alterations in ecosystem structure and function, including increases in organic debris (fuel loads) (Biswell 1967, 1972; Hall 1974; Parsons and DeBenedetti 1979; van Wagtendonk 1974). These changes have resulted in declines in some resource values of these forests. Fuel load increases can result in changes from low-intensity surface fires to catastrophic stand-replacement fires. With increasing realization that total fire suppression is not necessarily a feasible or a reasonable management philosophy, the use of prescribed burning could provide a rational alternative.

Prescribed understory burning in ponderosa pine – mixed conifer ecosystems is utilized for a variety of land management activities including fuel hazard reduction, site preparation for conifer regeneration, range and wildlife habitat improvement, and simulation of natural fire regimes and events (van Wagtendonk 1974; Martin and Dell 1978; Kilgore and Curtis 1987). If prescribed understory burning is to be utilized, knowledge about the variable rates of fuel consumption, fire intensity, and changes in forest floor cover is necessary. This is particularly important when considering the costs and benefits of prescribed understory burning, including burn safety, and the accurate assessment of postfire effects on resource values (e.g., air quality, vegetation, wildlife, soils, and water). The objectives of this study were to document the ranges of fire behavior, patterns of combustion, fuel consumption, and forest floor cover as a result of prescribed fall and spring understory fires in mixed conifer ecosystems. This included quantification of the rela-

TABLE 1. Mean moisture content (dry-weight basis) of the surface litter (Oi horizon), lower duff (Oa horizon), and soil surface (Al horizon) at the time of burning

Location and layer	Early fall	Late fall	Early spring	Late spring
Blodgett				
Litter	12.9*a* (1.2)	26.4*c* (2.2)	17.0*bc* (0.3)	15.5*b* (1.1)
Duff	23.2*a* (4.6)	90.1*b* (7.8)	135.0*c* (16.3)	51.6*a* (10.6)
Soil	18.7*a* (2.9)	34.8*b* (5.5)	58.2*c* (4.2)	43.0*b* (2.0)
Challenge				
Litter	12.8*a* (0.9)	16.0*b* (0.7)	17.9*b* (1.0)	11.7*a* (0.9)
Duff	15.7*a* (1.7)	43.4*a* (5.8)	119.5*b* (17.3)	31.8*a* (10.2)
Soil	11.1*a* (0.9)	22.3*b* (3.1)	44.1*c* (13.6)	25.8*b* (2.9)
Quincy				
Litter	10.8*a* (0.8)	18.3*b* (1.8)	11.1*a* (3.6)	12.4*a* (0.9)
Duff	8.7*a* (1.3)	63.0*b* (10.2)	35.0*c* (9.2)	18.7*a* (3.1)
Soil	3.6*a* (0.5)	11.3*b* (1.3)	20.3*c* (2.0)	11.0*b* (2.2)

NOTE: Numbers in parentheses indicate the standard error of the mean. Values within rows followed by a different letter are significantly different.

tionships of fuel consumption with fuel moisture levels and fire behavior.

Methods

Three study sites were selected to represent a wide variation in fuels and topography among mixed conifer forests in the northern Sierra Nevada of California. These sites were mature stands located at the Blodgett Forest Research Station of the University of California, the Challenge Experimental Forest of the USDA Pacific Southwest Forest Research Station, and the Massak Unit of the Quincy Ranger District, Plumas National Forest. These sites will be referred to as the Blodgett, Challenge, and Quincy sites, respectively.

The Blodgett site was located in a second-growth stand approximately 70 years of age. Mean basal area was 72.6 m^2/ha. Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), white fir (*Abies concolor* (Gord & Glend.) Lindl. ex Hildebr.), and incense-cedar (*Calocedrus decurrens* (Torr.) Florin) dominated the overstory. Elevation is approximately 1310 m. Mean annual precipitation is approximately 1700 mm. Topography is nearly level, with north-facing slopes of 1–12%.

The Challenge site was logged in the 1870s; however, a few scattered old-growth ponderosa pine remain. The overstory was dominated by Douglas-fir, incense-cedar, and ponderosa pine with a mean basal area of 80.5 m^2/ha. Slopes vary from 35 to 55%, with a western aspect. Elevation is 1005 m and mean annual precipitation is 1800 mm.

The Quincy site is characterized as an open stand of Jeffrey pine (*Pinus jeffreyi*, Grev. & Balf.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and incense-cedar. There is no record of prior harvest on this site, with the exception of selected salvage cuts for insect damage in the 1960s and 1970s. Mean basal area was 48.0 m^2/ha. Slopes vary in steepness from 35 to 75%, elevation is 1350 m, and mean annual precipitation is 900 mm.

According to site index productivity classes (Dunning and Reineke 1933), the Quincy site is characterized as class III–IV, whereas the Blodgett and Challenge sites are class I–II.

Data from 60 prescribed burns were collected for this study. At each of the three locations, six experimental blocks were established in an unbalanced incomplete randomized block design. Treatments consisted of four different experimental prescribed burns (based on different fuel moisture levels and climatic conditions) and a control (no burn). Each burn treatment was replicated in five of the six blocks and the control was replicated in three to four of the blocks. Each replicate was at least 0.063 ha in area.

The four burn treatments were prescribed to cover the wide range and various combinations of fuel moisture and weather conditions commonly experienced in prescribed burns. The burn treatments were named according to the season in which they were carried out: (*i*) early spring, (*ii*) late spring, (*iii*) early fall, and (*iv*) late fall. Each treatment represented a period of distinct climatic conditions, fuel moisture conditions, and phenological stage of vegetation development (Tables 1 and 2; Kauffman 1986).

The early spring burn was prescribed to be implemented as early as it was possible for sustained ignition and spread to occur following cessation of winter weather patterns. The late spring burn treatment was prescribed to be conducted as late in the spring as was safely possible, but before the active fire suppression season (after at least 1 month of no precipitation). The early fall burns were prescribed to be implemented before a major autumn precipitation event had occurred, yet after some moderation of high summer temperatures and low relative humidities. Lower duff and presumably coarse woody debris were lower in moisture content than in any other treatment (Table 1). Late fall burn treatments were prescribed to be conducted 1 or more days after the occurrence of a significant fall–winter precipitation event, and hence, after a significant increase in fuel moisture content.

If the other variables of the prescription could be met to insure a safe burn, it was preferred that the late spring and early fall treatments be burned with a lower duff (Oa horizon) moisture content of less than 15–20%. The early spring and late fall burn treatments were prescribed to occur when lower duff moisture levels were greater than 30%; in actuality they were often much higher (Table 1).

To monitor changes in ground cover, 15 permanent 2-m^2 plots were established in each replicate of each block. Percent cover of litter (duff), rock, bare ground, moss–lichen, and woody material was measured in each plot before burning and for 2 years after burning.

To measure preburn biomass of litter and duff layers (the organic horizons Oa, Oe, and Oi) and the quantity consumed by fire, three measurements were taken at each of the 15 plots. Biomass was predicted from regression equations utilizing depth as the independent variable (Agee 1973). These measurements were made at the plot center and at 1 m upslope and 1 m downslope of the plot center (i.e., n = 45 measurements/replicate × 5 = 225 for each treatment at each location).

Downed woody fuels were measured before and after burning by the planar intersect method (Brown 1974). A total of 20 transects was established in each treatment at each location. Length of the transects varied with fuel particle size. Transects for 1-, 10-, 100-, and 1000-h time lag fuels were 1, 3, 5, and 15 m in length, respectively. The organic horizon depths and all woody fuel transects

TABLE 2. Dates of prescribed burns, weather conditions during prescribed burns, and moisture content (FMC) of the 10-h fuel stick at the time of ignition

Location and treatment	Date of burn	RH (%)	Temp. (°C)	Stand wind speed (km/h)	FMC (%)
Blodgett					
Early fall	84 28 09	25–48	19–23	0–8	9–11.5
Late fall	83 10 08	49–63	16–18	0–3	13–15
Early spring	84 06 26–29	21–72	17–27	0–3	7–11
Late spring	84 05 17	31–57	16–17	0–3	10–11
Challenge					
Early fall	83 09 26	54–67	16–22	0–5	9–9.5
Late fall	83 10 20	46–64	16–22	0–3	9.5–10
Early spring	84 06 20	37–52	21–24	0–3	8–9
Late spring	84 04 16	52–61	16–18	0–8	8–11
Quincy					
Early fall	83 09 15	15–38	22–29	0–3	5–9
Late fall	83 10 12	46–67	9–20	0–3	10–14.5
Early spring	84 05 24	29–57	13–21	0–11	8
Late spring	84 05 07–09	23–39	14–20	0–11	7

were measured before burning and immediately following complete cessation of fuel combustion. Total fuel loads and consumption were calculated from these data.

Moisture contents were measured by collecting 25 lower duff (Oa and (or) Oe horizon), 20 surface litter (Oi), and 15 soil surface (A1) samples at random in each treatment before burning. Samples were sealed in 10-cm soil cans and weighed upon return from the experimental burn units. They were oven-dried at 100°C for 24 h and then reweighed to calculate percent moisture content on a dry-weight basis. Ten-hour time lag fuel moisture content was estimated by weighing fuel sticks before and during burns. Before and during all burns, relative humidity, temperature, and in-stand (midflame) wind speed were monitored with hand-held devices from belt weather kits.

A strip head fire was the ignition technique used to burn all experimental units (Kilgore and Curtis 1987). Firing was begun on the upslope and (or) upwind end of the burn units. Flame lengths (m) and rate of spread (s/m) were measured from observations of the head fires during each burn (Alexander 1982). All the fire behavior data were collected by randomly selecting five to nine areas for observation in each burn. We measured only the behavior associated with the combustion of the surface fuels. The combustion of living fuels (i.e., crown fires of shrubs or small trees) was not included in behavior measurements.

We calculated fire-line intensity, which is defined as the rate of heat release per unit length of fire line, using its relationship with flame length as reported by Byram (1959). Fire-line intensity (I) (kW/m) and flame length (F) (m) are related as follows:

$$I = 258F^{2.17}$$

Heat per unit area is the total energy or heat released per unit area. Rothermel and Deeming (1981) calculated heat per unit area (H) (kJ/m^2) by dividing fire-line intensity by the rate of spread. This accounts for only the heat released in the flaming front, which we denote as H_f. The total heat per unit area (H_t) is the sum of H_f and the heat released later (H_l) in both flaming and glowing combustion: $H_t = H_f + H_l$. H_t was calculated by multiplying the biomass of litter and duff consumed by the net heat of combustion (kJ/m) of the organic horizons.

To estimate the biomass of litter and duff consumed by the flaming front, H_f was divided by the net heat of combustion. Byram (1959) defined the net heat of combustion as being numerically equivalent to the gross heat of combustion minus heat losses associated with radiation, complete combustion, and the presence of moisture in fuel. Net heat of combustion was calculated following the recommendations of Alexander (1982). Our value of gross heat of combustion (19 211 kJ/kg) was calculated from data given by van Wagtendonk (1974).

Multivariate analysis of variance was used to test for differences in fuel moisture, fire behavior, and fuel consumption between treatments, locations, and treatments within locations. If significant, a univariate analysis of variance and multiple comparison procedures (Scheffé's test) were used to detect where significant differences occurred. Change in ground cover composition was tested by analysis of variance and multiple comparison procedures (Scheffé's test). Unless otherwise specified, statistical significance in this paper is implied to be at the $p \leq 0.10$ level.

Results and discussion

Fuel loads before burning

Fuel loads at the Challenge and Blodgett sites were significantly greater than those at the Quincy site (Table 3). Total fuel loads ranged from 130.9 to 154.5 Mg/ha at Blodgett, and from 124.3 to 163.9 Mg/ha at Challenge. In contrast, fuel loads at Quincy ranged from 74.8 to 102.5 Mg/ha.

One-hour time lag fuels made up less than 1% of the fuel load at all locations, and the 10- and 100-h fuels each contributed less than 4% of the total fuel load. The 1000-h time lag fuels composed up to 37% of the fuel load in some blocks at the Blodgett site. On all sites, the litter and duff component accounted for 62–84% of the total fuel load.

Fuel moisture

Typically, plots burned during early spring or late fall had higher moisture contents of the surface litter and 1- and 10-h fuel components (Tables 1 and 2). However, this was not always consistent. Diurnal characteristics, especially relative humidity, strongly influenced moisture contents of these components. In contrast, moisture contents of the duff and 1000-h component appeared to be most strongly influenced by season and (or) time since the previous precipitation event.

The pattern of fuel dry-down was not the same at the three sites. The Blodgett site, which was at a higher elevation, with nearly level north slopes and a dense overstory, tended to retain higher fuel moisture levels later in the season than the other, more open sites on steeper slopes. The Quincy site represented the other extreme. The open nature of this

TABLE 3. Mean fuel loads (Mg/ha) before and after prescribed burns

Treatment	Litter–duff	1-h (0–0.64 cm)	10-h (0.64–2.54 cm)	100-h (2.54–7.62 cm)	1000-h sound (>7.62 cm)	1000-h rotten (>7.62 cm)	Total
			Blodgett Experimental Forest				
Early fall							
Before	118.1 (9.1)	0.3 (0.1)	5.7 (0.8)	4.0 (0.8)	9.9 (1.4)	14.0 (5.8)	146.0 (18.1)
After	7.7 (1.3)	0.2 (0.0)	0.7 (0.3)	0.7 (0.2)	5.9 (1.3)	0.5 (0.4)	15.0 (3.1)
% reduction	93.5*a*	93.3	88.5	82.8	40.3	96.1	74.7*a*
Late fall							
Before	105.8 (10.4)	0.2 (0.1)	4.0 (1.2)	2.5 (0.6)	56.7 (13.3)	7.9 (5.7)	177.0 (18.7)
After	37.8 (3.9)	0.1 (0.1)	3.5 (1.3)	2.7 (0.7)	5.0 (1.9)	7.6 (4.9)	57.0 (6.6)
% reduction	64.2*b*	40.9	13.9	9.6	81.1	4.2	67.8*b*
Early spring							
Before	97.5 (2.4)	0.7 (0.3)	6.0 (1.3)	6.1 (2.7)	33.1 (14.9)	11.3 (9.0)	154.5 (13.1)
After	86.4 (4.8)	0.1 (0.1)	2.5 (0.6)	4.6 (1.7)	20.8 (12.6)	15.0 (9.1)	129.4 (15.1)
% reduction	11.3*c*	87.9	57.8	24.7	37.3	33.4	16.3*c*
Late spring							
Before	83.3 (3.8)	0.7 (0.3)	4.7 (0.8)	1.8 (0.5)	9.3 (3.6)	31.1 (19.9)	130.9 (23.4)
After	20.1 (4.4)	0.1 (0.0)	0.8 (0.3)	1.0 (0.3)	17.5 (4.5)	11.6 (10.1)	51.0 (12.5)
% reduction	75.9*b*	91.7	83.9	44.2	+87.4	62.8	61.1*b*
			Challenge Experimental Forest				
Early fall							
Before	118.3 (13.0)	0.9 (0.2)	4.7 (0.8)	6.3 (1.1)	19.2 (6.8)	7.7 (3.2)	160.9 (16.1)
After	7.1 (7.1)	0.2 (0.1)	0.5 (0.1)	1.0 (0.3)	4.1 (1.7)	0.0 (0.0)	12.8 (1.9)
% reduction	94.0*a*	78.4	89.8	85.0	78.6	100.0	92.0*a*
Late fall							
Before	125.8 (10.7)	0.8 (0.1)	3.4 (0.8)	3.8 (1.1)	10.7 (4.2)	6.2 (2.2)	150.7 (5.5)
After	20.0 (3.7)	0.2 (0.1)	1.2 (0.5)	2.5 (0.9)	8.9 (2.0)	0.8 (0.8)	33.5 (5.5)
% reduction	84.1*a*	80.2	64.5	33.4	17.0	87.0	77.8*b*
Early spring							
Before	103.9 (6.4)	1.1 (0.2)	4.5 (1.2)	3.7 (0.6)	4.8 (1.2)	7.2 (5.2)	124.3 (9.1)
After	30.9 (4.1)	0.4 (0.1)	2.2 (0.3)	2.5 (1.2)	6.5 (4.3)	9.7 (8.4)	52.5 (7.4)
% reduction	70.0*b*	67.0	51.6	31.8	+35.6	+35.2	57.7*c*
Late spring							
Before	120.7 (16.0)	0.7 (0.2)	4.4 (0.6)	4.0 (1.8)	22.2 (6.4)	12.6 (4.1)	163.1 (83.1)
After	9.5 (2.2)	0.1 (0.0)	0.2 (0.1)	0.3 (0.1)	13.4 (3.9)	4.7 (3.5)	28.1 (2.4)
% reduction	92.1*a*	93.3	95.7	92.5	39.6	62.5	82.8*b*
			Quincy Experimental Area				
Early fall							
Before	65.8 (5.3)	0.8 (0.3)	2.7 (0.5)	3.7 (1.1)	24.2 (9.5)	5.3 (2.8)	102.5 (12.2)
After	17.9 (2.3)	0.2 (0.1)	0.4 (0.2)	1.6 (0.3)	4.0 (2.3)	0.0 (0.0)	22.9 (10.9)
% reduction	72.8	69.1	84.9	84.0	83.7	100.0	77.6
Late fall							
Before	59.3 (5.5)	0.2 (0.1)	3.0 (0.6)	3.5 (1.1)	26.3 (8.3)	2.9 (2.8)	95.2 (10.6)
After	19.2 (5.8)	0.1 (0.1)	1.1 (0.4)	1.2 (0.7)	24.3 (11.7)	0.0 (0.0)	45.8 (17.1)
% reduction	67.6	65.2	63.8	65.9	7.9	100.0	51.9
Early spring							
Before	61.4 (3.0)	0.4 (0.1)	2.1 (0.2)	2.3 (0.6)	7.1 (3.6)	4.3 (2.6)	76.7 (3.5)
After	10.8 (2.2)	0.1 (0.0)	0.7 (0.3)	0.8 (0.5)	4.2 (3.7)	0.8 (0.6)	17.4 (4.1)
% reduction	82.5	85.7	65.9	64.5	48.0	81.5	77.3
Late spring							
Before	60.7 (7.2)	0.5 (0.1)	1.9 (0.5)	0.9 (0.5)	10.3 (7.9)	0.4 (0.4)	74.8 (11.3)
After	7.5 (1.0)	0.2 (0.1)	0.6 (0.2)	0.4 (0.3)	6.0 (5.5)	0.0 (0.0)	15.9 (4.3)
% reduction	87.6	85.7	70.7	55.7	42.3	100.0	78.7

NOTE: To convert to tons per acre, divide estimates by 2.24. Numbers in parentheses indicate standard error of the mean. Values within columns followed by a different letter are significantly different. Fuel loads were rounded to the nearest one-tenth megagram, therefore percent consumption may differ from mathematical divisions of these figures.

site allowed for increased insolation and wind movement within the stand, resulting in more rapid moisture increase and decrease in fuels.

Fire behavior

Rate of spread did not vary among burn treatments except for a consistently slower flame front advance during the late fall burns (Table 4). Flame lengths and hence fire-line intensity were significantly less in these late fall burns than in late spring burns. These fire behavior parameters were greatest during late spring burns. In a vegetation management context, fire-line intensity may be of importance because of its positive relationship with scorch height and crown mortality (Van Wagner 1973). Apparently, the combinations of environmental and biotic factors encountered during the late spring burn treatment interacted to create more flammable, and hence potentially damaging, conditions during this season. This is corroborated by observations of more spotting and crown combustion at the Challenge and Blodgett sites during late spring burns than with any other treatment.

As would be expected, the high fire-line intensities experienced during late spring burns resulted in the highest H_f values of all treatments (Table 5). This is particularly evident in the late spring burns at Blodgett. The combination of lower relative humidities, level slopes, and dry fuel conditions resulted in the consumption of large amounts of fuel by the flaming front at this site. This high H_f value (16 193 kJ/m) is believed to be a good representation of the more severe (and potentially damaging) burning conditions that were present at Blodgett during this burn treatment. In contrast, H_f for early fall burns was 7089 kJ/m. Even though H_f was less than half of the value for the late spring burns, H_t and fuel consumption were greater. We estimated that 86% of the total combustion occurred after the flame front had passed in late spring burns, while 96% was consumed after flame front passage in early fall burn treatments (Table 5).

At both Challenge and Blodgett the percentage of fuels consumed by the flame front during any treatment was highest during the early spring. This corroborates observations of combustion during these burns. It appeared that after the flame front had passed over the fuel bed, there were fewer areas of glowing combustion with these treatments than with the others. As the moisture content of the lower duff was high at this time (greater than 119%), there was less fuel available to burn.

Fuel consumption

When treatments were compared within each site, the total amount of fuel consumed by all combustion processes was generally highest in early fall burn treatments (75–92%) and lowest in early spring burn treatments (16–77%) (Table 3).

Comparisons of different locations during the same burn treatment clearly indicated that the characteristics of each site influenced fuel consumption. The site with the highest percentage of fuel consumed during the early spring was the Quincy site (77%). This can be explained by the significantly lower fuel moisture content present on this site (Table 1). Similar relationships at the other end of the moisture gradient existed at the Blodgett site (77%). Even though this site was the last study area burned during the early spring prescription, percent consumption was lowest. The fuel moisture contents were higher well into the burning season, which also resulted in the lowest percentage of the fuel consumption during the late spring (Tables 1 and 3).

The general pattern of duff consumption was similar to that of total fuel consumption. The estimate of duff consumption at Quincy in the early fall burn is believed to be low. For this location, postfire duff depths were measured to the nearest centimetre, whereas for all other locations and seasons duff depth was measured to the nearest 0.5 cm. This difference in measurement accuracy is thought to have resulted in the lower estimate of consumption.

Based upon consumption levels, it appears that in these mixed conifer forests the rate of moisture accumulation and loss was more rapid in the duff component than in 1000-h fuels. For example, duff moistures did not differ significantly between early fall and late spring burns (Table 2), and there was no significant difference in duff consumption between these two treatments at the Challenge and Quincy sites. However, significantly greater percentages of 1000-h fuels were consumed in early fall burns than in late spring burns. For example, at the Quincy site, 73 and 28% of the 1000-h time lag fuel component (sound and rotten combined) was consumed during the early fall and late spring (high-consumption) burns, respectively. In contrast, duff consumption between the two treatments was 73 and 88%, respectively. Regression equations of the relationship between 1000-h and duff moisture levels were not calculated. However, a threefold difference in 1000-h fuel consumption and small differences in duff consumption between these two treatments indicate that rates of fuel dry-down are unequal.

TABLE 4. Summary of fire behavior data for the experimental prescribed burns

Location and treatment	Flame length (cm)	Fire-line intensity (kW/m)	Rate of spread* (m/min)
Blodgett			
Early fall	74*ab* ± 12	152*b* ± 56	1.3 ± 0.2
Late fall	26*b* ± 6	16*a* ± 5	0.2 ± 0.5
Early spring	85*a* ± 23	255*b* ± 164	1.0 ± 0.2
Late spring	64*ab* ± 3	97*b* ± 8	1.1 ± 0.2
Challenge			
Early fall	31*b* ± 5	21*b* ± 4	0.9 ± 0.7
Late fall	56*b* ± 8	86*ab* ± 10	0.8 ± 0.4
Early spring	97*a* ± 15	273*a* ± 15	2.4 ± 0.2
Late spring	71*ab* ± 5	126*ab* ± 5	1.0 ± 0.2
Quincy			
Early fall	44*a* ± 13	56*ab* ± 23	2.1 ± 0.3
Late fall	31*b* ± 2	21*a* ± 3	0.9 ± 0.3
Early spring	60*a* ± 15	111*b* ± 45	1.8 ± 0.4
Late spring	49*a* ± 7	64*ab* ± 18	1.9 ± 0.1

NOTE: Values are expressed as mean ± standard error. Values within columns followed by a letter(s) are significantly different ($P \le 0.1$).

*For calculation of heat per unit area (H_f), rate of spread must be expressed in metres per second.

The duff–litter component is often assumed to be the most important element of the total fuel load affecting vegetation composition, erosion potential, and nutrient storage. For this reason, it is important to be able to predict the consumption of duff before burning. Sandberg (1980) stated that most previous work, and common sense, indicates that duff moisture is the most important determinant of duff consumption. Results of regression analyses using duff consumption as the dependent variable and lower duff moisture, soil moisture, litter moisture, fire-line intensity, flame length, or total duff load as the independent variable, indicated that lower duff moisture was the single most efficient variable in predicting duff consumption. Using the combined data set of all three locations, we tested the relationship between duff moisture and consumption, using linear, exponential, logarithmic, and power curves. The linear model (consumption = 92.84 − 0.3628 (duff moisture)) best explained the relationship between duff moisture and consumption ($r^2 = 0.51$, $p < 0.001$, $n = 60$). However, description of the moisture-consumption relationship was greatly improved when locations were treated separately. For example, at Challenge the linear regression model had an r^2 value of 0.76 ($P < 0.001$, $n = 20$, $y = 96.24 - 0.186$ (duff moisture)). Different slopes and equations that predict fuel

TABLE 5. Net heat of combustion, total heat per unit area (H_t), heat per unit area of the flame front (H_f), biomass consumed by the flame front, and the percentage of total consumption attributed to the flame front for prescribed understory fires in three Sierra Nevada mixed conifer forests

Location and treatment	Net heat of combustion (kJ/kg)	H_t (kJ/m)	H_f (kJ/m)	Biomass consumed by flame front (g/m)	Percentage of total fuel consumption*
Blodgett					
Early fall	17 793	196 435	7 015	394	3.6
Late fall	17 631	119 891	4 800	272	4.0
Early spring	17 762	102 339	16 193	912	14.4
Late spring	17 774	19 729	5 471	308	27.7
Challenge					
Early fall	17 794	197 869	1 389	78	0.7
Late fall	17 756	187 858	6 176	345	0.3
Early spring	17 808	190 025	6 899	390	3.5
Late spring	17 733	129 451	8 102	457	6.3
Quincy					
Early fall	17 818	85 348	1 613	91	1.9
Late fall	17 728	71 089	1 148	67	1.6
Early spring	17 799	94 691	3 716	209	3.9
Late spring	17 815	90 144	2 006	113	2.2

*Estimated percentage of the total amount of duff that was consumed by the flaming front.

TABLE 6. Percent ground cover before burning (1983) and one and two growing seasons after prescribed burning

	Early fall			Late fall			Early spring			Late spring			Control (no burn)		
	1983	1984	1985	1983	1984	1985	1983	1984	1985	1983	1984	1985	1983	1984	1985
Blodgett															
Litter-duff	86.7	nd	86.6	91.1	91.0	94.0	84.2	89.0	90.0	85.3*a*	56.8*b*	89.3*a*	85.2	90.5	92.0
Bare ground	2.2	nd	7.6	0.8*a*	2.6*b*	0.6*a*	1.6	0.8	1.0	2.1	37.5	3.6	4.7	2.3	1.7
Logs and trees	9.7*a*	nd	3.9*b*	7.0	4.9	4.7	10.6*a*	9.0*b*	7.3*b*	10.4	5.1	5.5	8.1	5.7	5.2
Challenge															
Litter-duff	88.1	73.0	87.4	87.4	80.1	90.3	90.5	87.4	92.2	84.1*a*	34.3*b*	83.0*a*	87.1	87.8	90.6
Bare ground	3.0*a*	21.4*b*	7.1*c*	4.2*a*	13.0*b*	4.4*a*	2.2*a*	4.4*b*	2.0*a*	2.8*a*	60.0*b*	8.8*c*	2.6*a*	2.2*ab*	0.9*b*
Logs and trees	8.5*a*	3.2*b*	3.2*b*	7.3	5.2	4.2	6.3	6.2	5.4	12.1*a*	4.9*b*	5.6*b*	9.0	8.7	6.9
Quincy															
Litter-duff	82.2*a*	67.2*b*	75.2*b*	86.9*a*	72.2*b*	82.7*ab*	78.9	74.0	79.2	83.6*a*	68.5*b*	83.1*a*	78.8	81.0	84.6
Bare ground	5.5*a*	22.4*b*	12.3*c*	4.7*a*	12.3*b*	10.7*b*	11.0*a*	19.3*b*	14.3*ab*	7.0*a*	25.0*b*	10.1*a*	8.0	10.0	6.4
Logs and trees	4.9*a*	3.0*b*	2.4*b*	4.3	3.4	5.0	4.2	3.4	3.7	-4.2	2.8	3.0	2.2	2.0	1.8

NOTE: Values within rows followed by different letter(s) are significantly different. At Blodgett. Fall high-consumption burns were not burned until 1984, therefore 1985 data represent conditions one growing season after fire. nd, no data.

consumption have also been reported by Brown et al. (1985), Martin (1981), Norum (1977), and Shearer (1975). These differences suggest that site-specific regressions may be necessary to accurately predict duff consumption.

Changes in ground cover after fire

In Table 6, the 1984 values represent conditions up to 9 months after burning in fall treatments and as early as 1–2 months after burning in spring treatments. Cover of the first postfire year in fall-burned plots would represent ground cover after one season of needle drop. Because ground cover estimates for spring burns were measured before the autumn needle drop they are reasonable estimates of the immediate postfire ground surface composition.

An apparent relationship with fuel consumption and percent bare ground exposure can be found by examining the spring burn data. Bare ground exposure was 60% in late spring plots at the Challenge site (92% fuel consumption). In early spring plots, where fuel consumption was 58%, bare ground exposure was 4% (Table 6). Percent bare ground and litter cover were not significantly different between control and early spring plots. Bare ground exposure was significantly greater in the late spring burn treatments than in both the control and early spring plots. At this site few changes in bare ground exposure occurred when 58% or less of the fuel biomass was consumed. At the Quincy site bare ground exposure increased from 7 to 25% in late spring (78% fuel consumption) (Table 6). After the late spring burns at the Blodgett site (61% consumption), bare ground exposure increased from 2 to 37%. These changes demonstrate the variable response among sites in bare ground exposure caused by prescribed burning.

There was a relatively rapid replacement of ground cover by needle drop the first autumn following fire. In the late spring burn plots at Quincy and Blodgett, bare ground exposure was not significantly different between preburn estimates and those taken 13 months after fire (1983 vs. 1985 data). This would represent differences resulting from

TABLE 7. Mean depth (cm) of the duff and litter layers before burning and one and two growing seasons after fire

Location and treatment	Before burning $\bar{x}$	Before burning SE	1st postfire year $\bar{x}$	1st postfire year SE	2nd postfire year $\bar{x}$	2nd postfire year SE
Blodgett						
Early fall (EF)	20.2*a*	0.8	3.8*b*	1.6	nd	
Late fall (LF)	18.6*a*	7.5	8.6*b*	5.0	10.4*b*	3.6
Early spring (ES)	18.1*a*	6.0	13.4*b*	5.7	13.2*b*	6.5
Late spring (LS)	16.4*a*	7.3	3.4*b*	3.8	6.6*c*	3.6
Control (C)	15.9	8.9	15.2	8.5	15.0	7.3
Challenge						
Early fall (EF)	20.4*a*	9.2	2.4*b*	1.6	4.5*c*	2.3
Late fall (LF)	22.3*a*	9.7	4.2*b*	2.4	7.1*c*	3.5
Early spring (ES)	18.4*a*	6.3	8.6*b*	4.8	10.0*b*	4.1
Late spring (LS)	21.9*a*	8.8	4.2*b*	22.5	4.6*b*	2.7
Control (C)	17.8	7.6	16.9	6.1	16.6	5.8

Summary of tests between treatments within years

Blodgett					
Before burn	EF*a*	LF*ab*	ES*ab*	LS*b*	C*b*
1 yr after burn	C*a*	ES*a*	LF*b*	EF*c*	LS*c*
2 yr after burn	C*a*	ES*a*	LF*b*	LS*c*	
Challenge					
Before burn	LF*a*	LS*ab*	EF*ab*	ES*b*	C*b*
1 yr after burn	C*a*	ES*b*	LF*bc*	LS*bc*	EF*c*
2 yr after burn	C*a*	ES*b*	LF*c*	LS*d*	EF*d*

NOTE: Data followed by different letter(s) are significantly different when testing for differences between years.

1 year's needle drop. At Challenge, the 1985 bare ground exposure in late spring burns was still significantly greater than preburn estimates. However, bare ground cover decreased from 60% in 1984 to 9% in 1985.

As in the second season of prescribed spring burns, the first postburn cover estimates in fall plots illustrate the rapid recovery of ground cover following fire. In early fall burn plots at Blodgett and Quincy there were no significant differences in litter cover during the preburn and first postburn seasons (Table 6). On Challenge early fall burn units, bare ground cover increased from 3% in 1983 to 21% in 1984. However, bare ground exposure declined to 7% by 1985. In contrast, bare ground exposure in early fall plots at the Quincy site was 12.3%. This is reflective of the lower productivity, and hence less needle drop, on this site.

Even though there was little or no difference in percent litter cover after 2 years, there were significant differences in preburn and postburn litter depths in all treatments (Table 7). At the Challenge and Blodgett sites, litter depths before burning ranged from 16 to 22 cm. Two years following fire the depths were significantly lower in the early fall and late spring burn plots (4.5–6.6 cm) than in other burn treatments (7.1–13.2 cm). Depths of organic horizons did not significantly differ between the unburned control and the early spring burn at the Blodgett site, where consumption was 11%. Alterations in organic horizons can affect erosion potentials, nutrient dynamics, and species composition. Before burning, understory conifer composition was almost exclusively of those species that were capable of establishment in well-developed organic horizons (e.g., incense-cedar). In early fall and late spring burns, there were exponential increases in the abundance of the conifer seedlings whose establishment potentials were greatly enhanced by the presence of mineral soil (e.g., ponderosa pine, sugar pine, white fir, and Jeffrey pine) (Kauffman 1986).

The percentage of ground covered by moss and (or) lichens was usually minor (less than 1% at Blodgett and Challenge and 4% or less at Quincy). Though not always significant, cover of this component tended to increase after fall burns and decrease after spring burns.

Preburn cover of woody material (living and dead) was 6–12% at Blodgett and Challenge and 2–5% at Quincy (Table 6). Early fall burn treatments caused the greatest decrease in wood cover. The results reported in Table 7 are the combined coverage of downed woody materials and the basal coverage of living trees. Therefore, the reductions in wood cover are conservatively biased. The living tree cover (boles) was approximately a constant and therefore tended to mask any large declines in downed woody cover. Changes in the biomass of the 1000-h fuels probably provide a better estimate of fire effects on this fuel component.

Conclusion

In this paper we have attempted to adequately describe preburn fuel conditions, weather conditions at the time of burning, fire behavior, fuel consumption, and postfire surface cover changes. Tremendous variations in the levels of organic matter (fuel) consumption are possible between prescribed fires. These differences will affect responses such as nutrient loss and accumulation, postfire vegetation composition, and succession pathways. Total fuel consumption in the 60 plots utilized in this study ranged from 16 to 92%. Only slight changes in the postfire cover of the forest floor resulted from burns at the lower end of this consumption gradient, while dramatic effects on the cover of woody debris, organic horizons, and bare ground resulted from the high-consumption fires.

Duff consumption rates as low as 11% were measured when burns were conducted in the early spring. In contrast, duff consumption was greater than 90% when fires were prescribed during late spring or early fall (late May to late September). This was largely related to fuel moisture and microclimatic conditions present at the time of burning. In areas where significant levels of duff consumption may be desired (i.e., for seedbed preparation), other ecosystem components may come into consideration. Our prescribed fires that were conducted in the late spring had the highest fire-line intensities and hence greater potential for damaging the conifer overstory. In contrast, the high-consumption burns of early fall resulted in lower fire-line intensities but significantly higher consumption levels of 1000-h fuels.

Prescribed understory fires are frequently used in the Sierra Nevada mixed conifer forests for management activities such as fuel hazard reduction, wildlife habitat improvement, manipulation of seedbeds, and emulation of natural fire processes. This study demonstrated the wide range of postfire conditions possible following prescribed fires conducted under variable fuel moisture, topographic, and climatic conditions. To achieve land management goals without undue damage to the existing conifer canopy or long-term site productivity, site-specific criteria relating to these parameters can be implemented.

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