Mixed Conifer Forest Duff Consumption during Prescribed Fires: Tree Crown Impacts

Marco G. Hille and Scott L. Stephens

Abstract: Fire suppression has produced large forest floor fuel loads in many coniferous forests in western North America. This study describes spatial patterns of duff consumption in a mixed-conifer forest in the north-central Sierra Nevada, California. Overstory crown coverage was correlated to spatial patterns of duff depth after prescribed fire. On one site that was burned under dry conditions, almost all duff was consumed, with some remaining in overstory gaps. On a second site that was burned under moist conditions a few days after the first annual precipitation, strong spatial patterns of duff consumption were recorded with increasing distance from the base of the nearest overstory tree, the probability of duff remaining after prescribed fire increased significantly. There is strong evidence that spatial variation of precipitation throughfall resulted in higher duff moisture in gaps, whereas duff beneath crown cover was drier, and therefore, totally consumed. This study demonstrates that including a spatial component in a process-based duff consumption model would improve the accuracy of fire-effect predictions. FOR. SCI. 51(5):417–424.

Key Words: Forest fire, fire effects, smoldering combustion, restoration, Sierra Nevada, ground fuels

CONSUMPTION OF THE DUFF LAYER (O_F and O_H layers) during wildfires or prescribed fires influences postfire stand development by the destruction of rhizomes and seeds that are stored in the forest floor (Schimmel and Granström 1996), and by overstory-tree mortality caused by the prolonged heat released by smoldering combustion. Additionally, duff consumption is the largest contributor to smoke production and has a large impact on soil nutrient cycling (Neary et al. 1999).

In the case of partial consumption of the duff layer, heat tolerance and storage depth of seeds and rhizomes can play an important role in the re-colonization pattern of the site (Granström and Schimmel 1993). Furthermore, the exposure of mineral soil by complete consumption of the duff layer favors the establishment of many forest species (Thomas and Wein 1985, Hille and Den Ouden 2004).

Tree mortality due to heat-induced injury of the cambium or the roots can alter overstory composition and eliminate seed sources (Stephens and Finney 2002). The prolonged heat release by combustion of the accumulated organic material around the stem bases ("tree wells", Johnson et al. 2001) can be lethal for the cambium of overstory trees.

Next to safety and smoke production, duff consumption should be of major importance when planning a prescribed fire. Because major fire effects are strongly correlated to duff consumption, a precise estimation of duff consumption is crucial to predict postfire ecosystem dynamics. Duff consumption mainly proceeds by slow, smoldering combustion. The amount of consumption is dependent on duff characteristics such as moisture, inorganic content, layer depth, and density (Frandsen 1987, Stephens et al. 2004).

Several empirical models of duff consumption have been developed from data collected from wildfires or prescribed burns (Sandberg 1980, Brown et al. 1985, Reinhardt et al. 1991). These models have been used to predict duff consumption during prescribed fires. However, these models cannot be generalized beyond the site and the conditions under which the data were collected.

Process-based models of duff consumption are based on a two-step process of smoldering, with an endothermic process of char forming (pyrolysis), followed by an exothermic process of oxidation (Miyanishi and Johnson 2002). Therefore, propagation of smoldering combustion is dependent on sufficient heat being transferred from the exothermic oxidation zone to the adjacent duff to cause pyrolysis. Factors that affect this heat transfer therefore strongly influence duff combustion.

Process-based models of duff consumption are based on physical mechanisms of pyrolysis, char oxidation, and heat transfer under all conditions of smoldering combustion, and therefore, generalizable for duff with different bulk density, mineral soil, and water contents (van Wagner 1972, Frandsen 1987). However, these duff consumption models only estimate average duff consumption at the stand level (average duff moisture content is the input variable). Hence,

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spatial variation of duff properties within the stand, which can cause spatial variation of duff consumption, cannot be predicted.

Duff moisture was found to have the strongest impact on the smoldering combustion process (Frandsen 1987), and is the most important input variable in both empirical and process-based models. Stored moisture results in a latent heat flux for water evaporation, which provides an effective heat sink. Thus it can slow down or extinguish smoldering combustion. Other characteristics such as duff depth, bulk density, amount of surface fuels, and inorganic content of the duff layer will influence heat generation and heat transfer, and therefore, smoldering combustion (Burgan and Rothermel 1984, Miyanishi and Johnson 2002).

Duff moisture within a stand is seldom spatially uniform. Factors such as precipitation throughfall, which is mainly influenced by overstory crown structure, and differences in water uptake by ground layer vegetation can cause spatial duff moisture variation. In conifer forests, the highest throughfall rates are found at the periphery of the crown (canopy drip line) and in areas with no crown coverage (Bouten et al. 1992, Bruckner et al. 1999). At the stand level, Chrosciewicz (1989) and Miyanishi and Johnson (2002) found significantly drier duff beneath trees when compared to duff beyond tree crowns in pine/spruce (*Pinus*/*Picea*) stands. This spatial variation of duff moisture has not been considered when predicting duff consumption.

Because duff moisture strongly influences duff consumption, temporal and spatial variation of duff moisture should become evident in patterns of duff remaining after fire (Robichaud and Miller 1999). A patterning of duff consumption has been observed mainly in boreal forests (Dyrness and Norum 1983, Zasada et al. 1983, Miyanishi 2001), but also in dry coniferous stands (Sweeney and Biswell 1961). Miyanishi et al. (1999) and Miyanishi and Johnson (2002) reported a significant spatial correlation between burned patches of duff and standing boles of trees killed by the fire.

The objective of this study is to evaluate and explain spatial variation in duff patterns after two prescribed fires in a mixed-conifer forest. Following common practices, only an average duff moisture value was calculated for the first prescribed fire, which was burned 3 days after a significant rainfall event. We therefore cannot present spatial, prefire data for the first prescribed fire, but present the observed strong spatial pattern of duff consumption. For the second prescribed fire, which was burned under dry conditions the following year, spatial prefire duff moisture was sampled. The absolute and relative position of a given duff sample within the setting of surrounding trees will be used to explain spatial variation in duff consumption.

Our hypothesis is that spatial variation in duff moisture, as affected by overstory canopy cover, will result in differing patterns of duff consumption. If overall duff moisture is low enough to ensure propagation of smoldering combustion (such as in the prescribed fire under dry conditions), most of the duff on site will be consumed and therefore no spatial pattern can be found. In contrast, if duff moisture varies spatially around marginal conditions for smoldering propagation (such as after the prescribed fire that closely followed the first significant rainfall event, and where tree crowns caused spatial variation in duff moisture), we expect spatial variation in duff consumption. Information from this study could be used to improve predictions of duff consumption by prescribed fire.

Methods

Study Site

The experiment was established in a young-growth mixed-conifer forest (Fuel Model 10; National Wildfire Coordinating Group (NWCG), 1989) at the University of California Blodgett Forest Research Station, latitude 38°54′45″N, longitude 120°39′27″W. The experimental stand (compartment 292 of the research station) is located in the north-central Sierra Nevada approximately 1,400 m above sea level and covers 19 ha of a north facing, gentle slope (<15%). No harvesting operations have occurred in the stand for more than 25 years.

The majority of precipitation (total of 1,500 to 2,000 mm yr^{-1}) in this area falls between Nov. and Feb., either as snow or rain. During the summer and early fall, almost no rainfall occurs, leading to very dry conditions in late summer. Often summers occur with no significant rainfall for five months.

Fire was once a common ecosystem process in the mixed conifer forests at Blodgett Forest (Stephens and Collins 2004). Mean fire return intervals varied from 5 to 15 years from the late 1600s to the beginning of the 20th century. After 1900, fires have been very rare, and this coincides with the introduction of fire suppression into this region (Husari and McKelvey 1996).

To characterize existing forest structure, information was collected from 0.04-ha systematic forest inventory plots placed in compartment 292. The circular inventory plots are separated by 120 m. Height and dbh of all trees >2.5 cm dbh were measured. Average basal area, average number of trees per hectare, and average diameter were calculated using the forest inventory plots.

Fuel Loads

On the stand level, pre- and postfire fuel load measurements were performed in the entire 19-ha compartment with the transect method (Brown 1974) the week before and after the fires. Sample points were on a 60 × 60-m grid. From each sample point, two transects were installed in random directions. Litter and duff depth were measured at 0.33, 0.66, and 0.99 m on each transect. Ground and surface fuel loads were calculated by using appropriate equations developed for Sierra Nevada forests (van Wagtendonk et al. 1996, 1998). Coefficients required to calculate ground and surface fuel loads were arithmetically weighted by the basal area fraction (percent of total basal area by species) to produce accurate estimates of fuel loads (Stephens 2001).

To assess the spatial variation of duff depth and moisture with respect to the position of the canopy, one transect in a random direction was installed from the base of ten overstory trees in the compartment. To be selected, the trees had to have symmetric crowns that were separated by at least 2 m from the crowns of neighboring trees and no understory trees or shrubs present beneath their crowns. In total, ten dominant trees (five sugar pines [*Pinus lambertiana* Dougl.] and five ponderosa pines [*Pinus ponderosa* Laws]) within the compartment were selected for the measurements.

In the four cardinal directions, the distance between the base of the tree and the projected crown perimeter was measured. Duff depth was also measured on each transect: (a) directly next to the stem base, (b) at half the distance to the crown perimeter, (c) directly at the crown perimeter and, (d) 1.5× the distance of the crown perimeter (Figure 1). At each point ($n = 40$), a steel pin was installed flush with the duff surface to allow the measurement of duff depth reduction. Postfire duff depth was measured the day after the prescribed fire.

An hour before the prescribed fire, duff samples of approximately 250 cm^3 were taken at points a–d, with a clockwise offset of 15 cm from the original point (Figure 1). These samples were weighed, oven-dried (105°C for 12 hr) and re-weighed to determine duff moisture on a dry weight basis.

Prescribed-Fire Application

The southwest portion of compartment 292 (2.7 ha) was prescribed burned in Nov. 2001 one week after the first significant precipitation event, which delivered 25 mm of rain (Figure 2). Hereafter this prescribed fire is identified as the "moist burn." For this burn only average prefire duff moisture data from samples taken at the center of each circular forest inventory plot, are available.

The remaining area of compartment 292 (16 ha) was burned in Oct. 2002 under much drier conditions (also, no rainfall the previous 3 months) (Figure 2). Hereafter, this prescribed fire is identified as the "dry burn." Previous to the fire, extensive duff moisture samples were collected.

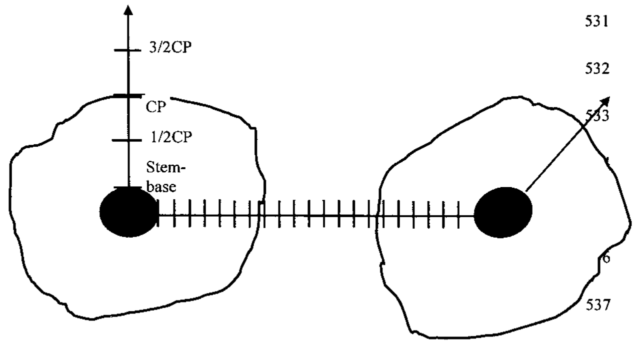

Figure 1. Sample design of duff moisture and depth measurements used in the dry burn, with CP as the distance from the stem base to the crown perimeter. Sampling points were at the stembase, and at 0.5, 1, and 1.5 CP. The design of the tree-to-tree lines is also illustrated as a connection between two neighboring dominant trees. From the right tree in the figure, the line was extended into a random direction to the next dominant tree.

The ignition pattern used in both prescribed fires was a strip head fire (Martin and Dell 1978). Strip width varied from 2 to 3 m. The rate of spread in both burns was approximately 1 m min^{-1}. Flame heights of 0.30 to 1.00 m were observed during the moist burn, flames reached 1.50 m in height in the dry burn.

Postfire Duff Sampling

Postburn measurements were taken after smoldering combustion ended (24 hr after the flaming front passed). Duff consumption was measured using the installed steel pins in the dry burn area. Duff consumption was measured as the difference between the head of the pin and the postfire surface. Duff consumption in the moist burn area was measured at fixed intervals along fuel transects without the use of steel pins. Changes in duff depth after fire (cm) were converted to duff consumption (Mg ha^{-1}) using appropriate equations developed for Sierra Nevada conifers (van Wagtendonk et al. 1998).

To assess the impact of overstory tree crowns on duff consumption, we sampled postfire duff patterns in both prescribed fires in compartment 292. From a randomly determined starting point, the nearest overstory fir or pine was selected. A line was extended from this tree to another overstory tree in a random direction (±20° search angle). If no tree was found within 25 m, another direction was randomly selected. Trees had to be dominant to be selected. On this tree-to-tree line, duff depth was measured every 50 cm and at distances of 0, 10, and 25 cm from each tree base (Figure 1). For the analysis, only lines from trees with a crown-to-crown gap to the neighboring tree of >2 m were selected ($n = 59$ for the moist burn, $n = 56$ for the dry burn).

Statistical Analyses

Pre- and postfire data were compared with paired *t*-tests. Moisture content and duff depth from the ten overstory trees in each prescribed fire (dry and moist) were analyzed with one-way analysis of variance (ANOVA) procedures. The duff depth data from tree-to-tree lines was transformed from absolute distance to relative distance to the stem base by creating classes of 1/10 of the distance from stem base to the projected crown perimeter and assigning the actual values to the nearest relative class. This enabled us to compare duff consumption under trees with different absolute crown widths. The Chapman–Richards equation, as a flexible growth function (Richards 1959), was used to model the probability of duff remaining after the two prescribed fires.

Results

Overstory tree species in this stand include white fir (*Abies concolor* Gord. & Glend.), Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco), ponderosa pine, and sugar pine. Incense-cedar (*Calocedrus decurrens* Torr.) and California

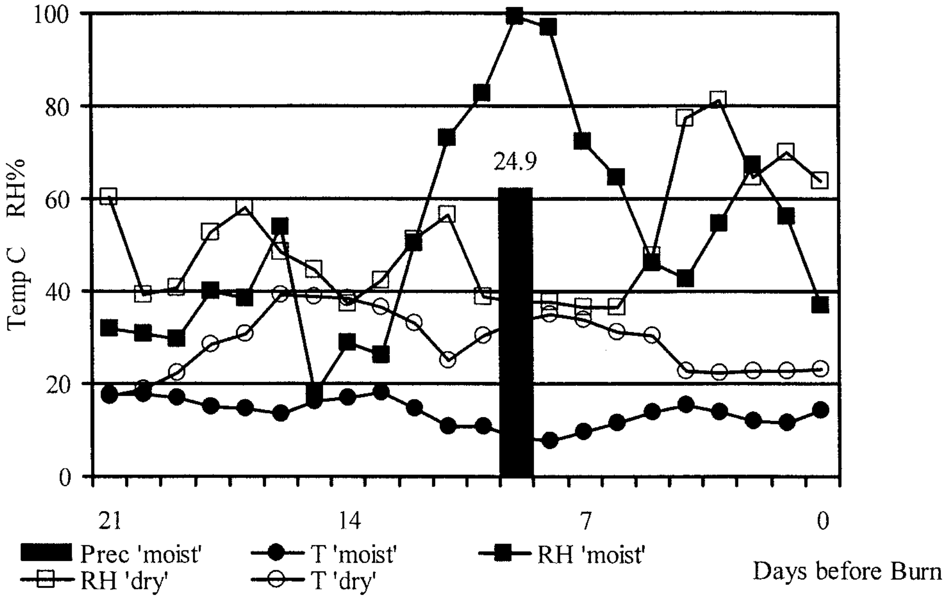

Figure 2. Temperature (°C), relative humidity (RH %), and precipitation (mm) 3 weeks before the burn and the day of the prescribed fires. Values are daily averages, generated from 15-minute interval measurements. Note rainfall before the moist burn, but no rain before the dry burn.

Table 1. Prefire stand variables for compartment 292 at Blodgett Research Forest, California.

Tree species	Stand density N/ha (±SD)	Average DBH (cm)	Basal area m^2/ha (±SD)	Height (m)
Black oak	8 (1)	46.19	1.23 (3.04)	11.45
Douglas-fir	31 (2)	28.11	3.53 (8.72)	26.54
Incense-cedar	252 (13)	19.11	10.02 (25.58)	13.91
Ponderosa pine	6 (1)	74.43	2.95 (7.69)	39.80
Sugar pine	11 (1)	77.85	5.73 (14.42)	39.45
White fir	181 (9)	22.74	15.50 (39.18)	26.40
Total	497 (15)	23.25	39.53 (100)	20.73

black oak (*Quercus kelloggii* Newb.) comprise a second-canopy strata. White fir seedlings and sapling dominate the understory (Table 1).

Fuel Load

The total prefire fuel load in compartment 292 was approximately 155 Mg ha^{-1}, of which approximately 100 Mg ha^{-1} consisted of duff (Table 2). Litter depth averaged 3 cm across the unit. Duff depth averaged 9 cm throughout the unit, though depths up to 18 cm were sampled on individual transects.

The postfire fuel load was significantly reduced by both prescribed fires (Table 2). Total fuel loads were reduced by 51% in the moist burn and 88% in the dry burn. An especially high reduction occurred for the litter and duff layer in the dry burn. Small dead-and-down fuels were also reduced, but at the time of the sampling (1 yr after the burn), new fuels have probably begun to accumulate.

Duff Depth and Moisture Pattern

The dbh, height, and crown radii of the ten trees selected for the duff measurements varied from 75 to 96 cm, 35 and 40 m, and 2.5 and 4 m., respectively. Prefire duff depth varied with respect to distance from the stem base. The duff layer around the base of all sampled overstory trees was significantly deeper (depth of up to 20 cm) than at any other location either under the canopy or beyond the canopy (ANOVA, $F_{3,36} = 17.51$; $P = 0.001$; Figure 3). The average

Table 2. Prefire fuel load (Mg ha^{-1}) by size classes (average ± SD) for compartment 292 at Blodgett Research Forest, California.

		Postfire Fuel Load	
Fuel Class (size class (cm))	Prefire Fuel Load ($n = 25$)	Moist Burn ($n = 14$)	Dry Burn ($n = 10$)
	--------------------Mg ha^{-1}	--------------------	
1-hr (0–0.6)	2.0 (0.2)	0.7 (0.2)	0.3 (0.1)
10-hr (0.6–2.5)	6.3 (0.7)	2.0 (0.5)	0.4 (0.1)
100-hr (2.5–7.6)	5.8 (1.6)	7.0 (1.9)	1.7 (0.2)
1000-hr sound (>7.6)	6.0 (3.3)	4.6 (3.8)	6.9 (3.5)
1000-hr rotten (>7.6)	15.8 (4.3)	3.1 (2.4)	0.0 (-)
Litter [O_L]	17.8 (3.6)	19.4 (6.4)	5.2 (1.1)
Duff [$O_F + O_H$]	101.0 (11.9)	38.4 (15.2)	4.1 (0.4)
Total fuel load	154.5	75.2	18.7

duff depth decreased from 6 to 2 cm with increasing distance from the stem and especially in gaps. However, the decrease in duff depth further away from the tree (under the crown to the gap) was not significant at the 95% level.

In the dry burn, duff moisture was low with an average of 12% and a range from 10 to 14%. There was no significant pattern found for duff moisture and its position to the nearest stem base (Figure 3; ANOVA, $F_{3,36} = 1.18$, $P = 0.33$). There was very little variation in duff depth within and between crown position classes (coefficient of variation between 11 and 13%). In the moist burn, duff moisture varied from 30 to 65%.

Postfire Duff Patterns

At all sample-points within the two burned areas, the litter layer was totally consumed and at least the top duff layer was charred. There was little duff remaining after the dry burn. At 97% of the sample points on the tree-to-tree lines (in the dry burn), there was no organic material on the soil surface. The few remaining areas with duff were less than 3 cm thick. In the moist burn, a higher percentage of duff remained unburned. At 82% of the sample points, no duff was found after the prescribed fire, but areas with duff remaining were up to 6 cm thick.

In both prescribed fires, a spatial trend of duff consumption with regard to crown coverage was observed. Although there was no duff found in the direct vicinity of the overstory trees, the probability to find duff increased to 7% for the dry burn and 65% for the moist burn with increasing distance from the tree (Figure 4). In reference to the absolute distance from the tree base, a strong increase in the probability of duff remaining after fire was observed in the moist burn at distances between 2 and 4 m (Figure 4A). In the dry burn, no increase in the probability of duff remaining was found. The same data, transformed to a relative position to the crown structures, shows a very similar trend, with an even stronger increase of probability of duff remaining between 0.5 and 1.5 of the relative distance to the crown perimeter (Figure 4B).

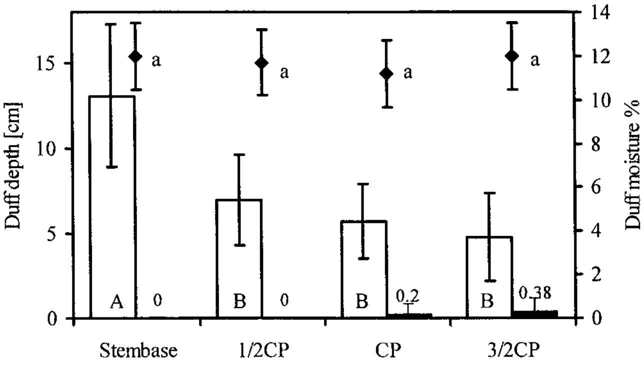

Figure 3. Mean duff moisture and duff depth in the dry burn at different positions related to the nearest overstory tree (mean ± SD, $n = 10$ for each location). Diamonds display duff moisture before the fire (right y-axis), bars display duff depth before (white) and after the fire (black). Bars/circles with the same letter are not significantly different at the 0.05-level. CP = distance from stem base to crown perimeter.

This probability is well described by an S-shaped curve following the Chapman–Richards equation (Richards 1959). The equation to predict the probability to find remaining duff after the fires (P(d)) for the absolute distance is

$$\mathrm{P(d)} = A * (1 - e^{-((d/3.5)^k)}) \qquad (1)$$

and

$$\mathrm{P(d)} = A * (1 - e^{-(d^k)}), \qquad (2)$$

with d = distance from tree, either in meters (Equation 1) or as a fraction of crown perimeter of the nearest tree (Equation 2). The asymptote A represents the probability of finding duff at locations in gaps (7% for the dry burn and 65% for the moist burn) and k determines the shape of the curve. Best-fit parameters are given in Table 3. High adjusted R^2-values indicate good model performance.

The spatial variation of duff reduction is visible in Figure 5. Directly at the stem base, the duff layer is reduced by 13 cm on average with large amounts of heat being released close to the cambium layer. Further away from the stem base, duff depth is less and duff consumption incomplete.

Discussion

Duff depth was significantly reduced by both prescribed fires, with a higher percentage of mineral soil exposed after

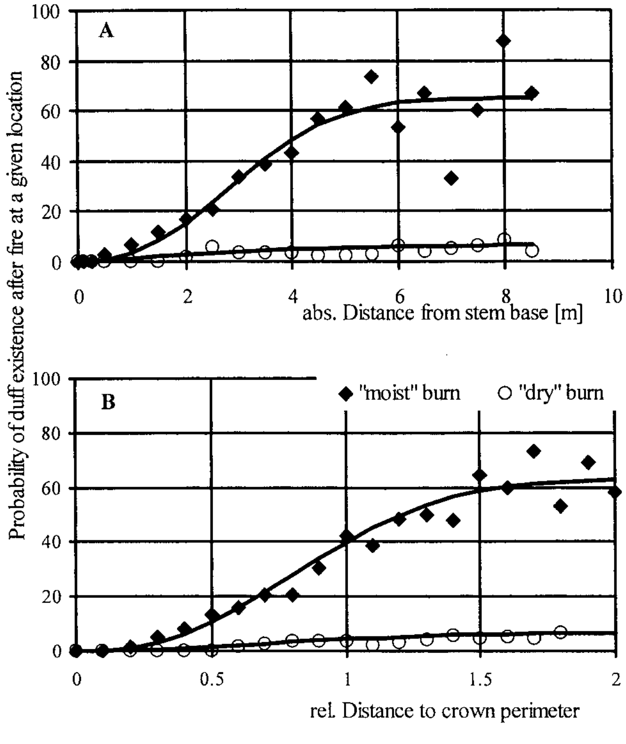

Figure 4. Spatial variation of duff remaining in the moist (diamonds) and the dry (empty circles) prescribed fires, related to absolute (A) and relative (B) distance from dominant trees. Lines are regressions with the Chapman–Richard equations. The probability of duff remaining (y-axis) is calculated from the percentage of data points where duff survived the fire. The relative distance from the stem base is expressed as ratio to the crown perimeter. A relative distance of "1" marks the edge of the crown.

the dry burn. High duff consumption in the dry burn was produced because of low fuel moisture contents after the dry Sierra Nevada summer (Figure 2). Duff moisture content was close to the historical annual minima during the dry burn (10–12%; Ziemer 1968). Duff moisture content was significantly higher (30–60%) in the moist burn because of a single rainfall event one week before the prescribed fire.

Duff depths in areas with less or no overstory cover were shallower, possibly due to lower litter input rates or extended spring snow coverage, which would produce higher moisture levels promoting increased microbial activity (Möttönen et al. 1999). The high accumulation of litter and duff around the base of overstory trees has been observed in other studies (Ryan and Frandsen 1991).

Our results indicate that there is substantial complexity in duff consumption, and this should be taken into account when planning a prescribed fire. At the time the dry burn was conducted, there was low variation in duff moisture because of the proceeding dry summer. No significant trend was found in duff moisture with respect to location of the nearest overstory tree. Slight variations in duff moisture did not affect duff consumption, because all duff had a moisture content below 30% and would be expected to burn completely (Brown et al. 1985).

In the moist burn, spatially differentiated duff data are not available, but based on moisture measurement at the stand level and reports of Ziemer (1968), Chrosciewicz (1989), Bouten et al. (1992), Otto (1994) and Möttönen et al. (1999), we believe duff moisture was approximately 60% in areas with no canopy cover or in areas under the crown drip-line, and approximately 30% beneath canopy cover.

From the observations made in this study, the question arises, under what conditions can spatial variation of duff consumption be expected? Previous research has shown the importance of duff moisture and has identified moisture thresholds with regard to smoldering combustion (Sandberg 1980, Brown et al. 1985). Three general categories of duff moisture are: (1) <30% duff moisture, which results in complete duff consumption, (2) 30–120% duff moisture, resulting in incomplete consumption, and (3) >120% duff moisture, where no duff consumption is possible unless woody fuels are dry enough to sustain combustion on the duff surface (Sandberg 1980, Brown et al. 1985). Spatial variation of duff moisture, especially within the moisture range of 30–120%, directly affects smoldering combustion and can create local differences in duff consumption (van Wagner 1972).

In this study, two of these three classes of duff consumption were observed. The dry burn consumed almost all organic material to the mineral soil and duff moisture was so low at all locations that smoldering combustion and propagation was not limited (<30% duff moisture), and no spatial pattern was found. The moist burn most likely encountered spatial variation in duff moisture that stopped smoldering combustion in areas with high moisture content (30–120% duff moisture). As a scenario, one can imagine a situation later in the rainy period, when duff moisture rises above 120% at all locations in the stand. Under these moist conditions, there would be no duff consumption (only the fast-drying litter fuels might be dry enough to burn).

Table 3. Parameters for the four S-shaped regression curves, following the Chapman–Richards Equations 1 and 2.

Data	Equation	A	k	adj. R^2
Absolute distance moist burn	1	65	2.37	0.937
Absolute distance dry burn	1	7	1.235	0.828
Relative distance moist burn	2	65	2.43	0.978
Relative distance dry burn	2	7	1.879	0.930

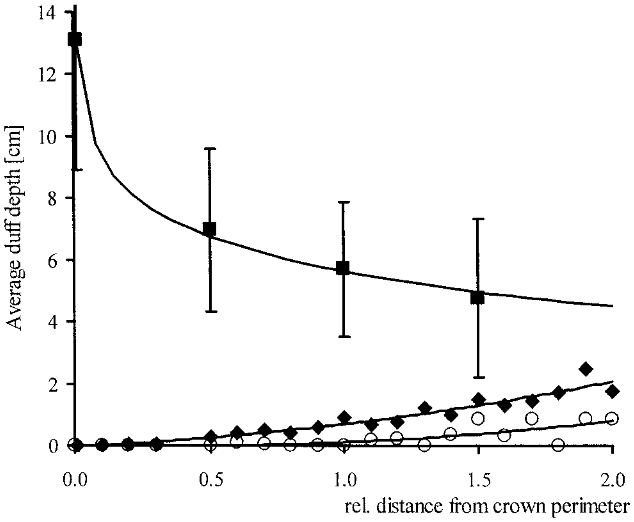

Figure 5. Average duff depth (pre- and postfire) in relation to relative distance from overstory trees (1.0 representing the edge of the crown). Prefire duff depth (filled squares) from the dry burn was modeled with $y = -1.63 \ln(x) + 5.64$ ($R^2 = 0.99$), postfire duff depth for the moist burn (filled diamonds) with $y = 0.32x^2 + 0.41x - 0.04$ ($R^2 = 0.93$) and for the dry burn (empty circles) with $y = 0.29x^2 - 0.21x + 0.02$ ($R^2 = 0.60$).

Although we can present prefire spatial duff moisture data only for the dry burn, we assume that duff consumption patterns in this burn (Figure 3) were influenced by spatial differences in duff moisture that were caused by spatial varying throughfall rates. The 25 mm of rain one week before the moist burn was likely intercepted by tree crowns or possibly drained off the crown toward the crown perimeter (Ziemer 1968, Otto 1994). This resulted in low duff moisture in areas close to stem bases of overstory trees, and higher duff moisture in areas below the crown edge or with no crown cover.

Given the slow desorption rate of conifer duff (average timelag of 50 hrs for *P. ponderosa*; Fosberg 1977), this moisture was stored longer in the duff than in the exposed, fast drying litter. In the moist burn, the higher duff moisture content in areas with no canopy cover lead to a high latent heat flux for water evaporation, which finally stopped the smoldering combustion process. This assumption is supported by previous research on throughfall patterns in conifer forests (Ziemer 1968, Chrosciewicz 1989, Bouten et al. 1992, Whelan et al. 1998), and it would explain the increase in postfire duff depth in the moist burn at distances of 2–4 m from the stem base or at a fraction of 0.75–1.25 of the crown perimeter (Figure 4).

The probability of duff remaining after prescribed fire is much lower under crown cover than in areas with no crown coverage. An S-shaped function is suitable to model this relationship (Figure 4). The low probability of duff surviving fire close to trees is due to less moisture and thicker, more continuous duff profiles (Miyanishi and Johnson 2002). The high correlation of our data with the Chapman–Richards equation indicates that this spatial trend in postfire duff depth can be modeled (Figure 5).

To improve duff consumption prediction on a stand-level, we suggest using process-based duff consumption models with spatial differentiation of duff moisture depending on the overstory crown coverage. This would allow more precise predictions of duff moisture, which can have a major influence on fire effects. For example, duff consumption around the stem base is an important variable when predicting postfire tree mortality (Stephens and Finney 2002).

Spatial variation in duff moisture should be considered when planning prescribed fires. Including this information should improve the accuracy of fire effect predictions. Duff moisture measurements from distinct locations (stem base, beneath the canopy drip-line, in openings) should be used as input for consumption and fire effects models. Ideally, this approach gives spatial differentiated predictions of duff consumption, and therefore, predictions of direct fire effects, such as tree mortality and mineral soil exposure.

Conclusions

Spatial variation of duff consumption is strongly dependent on duff moisture. Although many of the factors affect duff moisture and dynamic (such as throughfall, water uptake, weather, etc.), we conclude that duff consumption patterns can be improved by considering crown coverage of the dominant trees. In accordance with the model of decreasing influence of a single tree with increasing distance from it (Zinke 1962, Kuuluvainen et al. 1993), we found a strong positive correlation between the distance from the stem base and the probability of duff remaining after prescribed fires. Our aim was not to present a new process-based duff-consumption model, but our results show that a spatial component that considers stand structure and spatial duff moisture variation could significantly improve the quality of process-based models in general, and could be used to guide the construction of better models and to test current models for their accuracy.

The S-shaped functions used in this work are suitable to describe the probability of duff remaining after prescribed fire. Spatial interpolation techniques, such as used by Robichaud and Miller (1999) that include overstory stand structure could be linked to process-based duff consumption models to increase the accuracy of duff consumption and, consequently, fire effects.

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