

# Influences of moisture content, mineral content and bulk density on smouldering combustion of ponderosa pine duff mounds

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**Abstract.** When applying prescribed fire to long-unburned but fire-adapted ecosystems, fuels managers require better decision-support models to determine appropriate conditions for achieving desired effects. Prolonged combustion in duff accumulations at the base of large conifers may lead to fine root mortality, cambial injury, enhanced susceptibility to bark beetle attack, and possibly tree death. A laboratory experiment was conducted to investigate how moisture content, mineral content, and bulk density affect smouldering combustion in ponderosa pine (*Pinus ponderosa* C. Lawson) duff mound fuels of the south-eastern Klamath Mountains, California, USA. Samples were divided between upper and lower duff for a total of 100 burn tests. Moisture content was adjusted to observe the transition through the ignition and spread limit. Bulk density, mineral content and percentage consumption were recorded for each burn. The moisture content threshold for smouldering combustion was 57 and 102% respectively for upper and lower duff. Percentage consumption was inversely related to moisture content for both layers of duff, and partially dependent on mineral content for lower duff. Bulk density was a non-significant factor in either ignition or percentage combustion for the conditions examined here. Results from this study identify important attributes of duff that control the burning process in order to inform prescribed burning decisions.

**Additional keywords:** ecological restoration, Klamath Mountains, old-growth forest, *Pinus ponderosa*, prescribed fire.

## Introduction

Following decades of fire exclusion, managers of fire-adapted forests are now faced with competing goals of using prescribed fire to reduce hazard fuels and promote other positive fire effects while protecting large old trees from mortal fire injury. Ironically, large trees, which should possess the greatest resistance to fire injury, are now in many cases at high risk during the reintroduction of fire (Varner *et al.* 2007). Many fire-adapted species, such as ponderosa pine (*Pinus ponderosa* C. Lawson), experience an increased susceptibility to fire injury as they age due to an unnatural accumulation of fuel at the tree base and reduced tree vigour (Keane *et al.* 2002). Duff mounds, or deep organic material surrounding the base of large trees, often burn for days following the passage of a flaming front in a process of smouldering combustion (Frandsen 1987; Miyanishi 2001). Smouldering combustion in duff mounds delivers substantial and protracted heat exposure that may lead to fine root mortality and cambial injury, possibly leading to reduced vigour, enhanced susceptibility to bark beetle attack, and potentially tree death (Ryan and Frandsen 1991; Swezy and Agee 1991; Varner *et al.* 2005; Hood 2010).

Forest fuels are consumed by either flaming or smouldering combustion; duff is largely consumed by the latter (Frandsen 1991; Hungerford *et al.* 1995; Miyanishi and Johnson 2002), which is characterised by low temperatures of long duration

(Wein 1983; Ohlemiller 1995). In duff, high packing ratios and relatively high contents of lignin (which does not release volatiles readily upon heating) combine to prevent rates of heat release sufficient to sustain flames (Miyanishi 2001). The resulting smouldering combustion spreads horizontally through the duff layer three orders of magnitude slower than the slowest spreading surface fire (Frandsen 1987). Smouldering combustion can be thought of as a series of small sequential ignitions that take place until a barrier, such as moisture content, is met. Its propagation relies on the balance between the energy released in the combustion process and that which is required to vaporise and drive off water, a significant heat sink in the combustion process (Wein 1983).

Yet duff often constitutes the single largest fraction of surface and ground fuels (Finney and Martin 1993), a point that emphasises the need to provide managers with improved decision support of duff-burning properties. Prescribed burn plans may indicate a desired range of duff consumption or mineral soil exposure based on site-specific objectives. Sufficiently moist duff insulates mineral soil from heating and protects fine roots and other below-ground living tissues (Swezy and Agee 1991; Hartford and Frandsen 1992). In contrast, a dry duff layer may burn completely and sustain long-term lethal heating that can cause physical, biological and chemical changes in the mineral soil (Hartford and Frandsen 1992). Near-complete or rapid

consumption of excessive surface fuels has been directly related to tree injury (Ryan and Frandsen 1991). Varner *et al.* (2007) found duff consumption due to smouldering combustion to be the only fire effect consistently related to longleaf pine (*Pinus palustris* Mill.) mortality across scales and treatments. Ideally, weather and surface fuel conditions will allow fire to carry through the stand, reducing litter and duff fuel accumulations while preventing excessive exposure to heat that may damage or kill trees.

Two additional duff characteristics – bulk density and mineral content – have been identified as primary determinants of duff consumption in pine species (Frandsen 1987; Varner *et al.* 2005). The likelihood that sustained smouldering combustion will take place decreases as either of these properties increase (Hartford 1989). High bulk densities in duff result in low oxygen concentrations that decrease the probability of independent burning at a given moisture and mineral content (Hartford 1989). Mineral content reduces the probability of ignition by replacing organic material and absorbing heat that would have contributed to combustion (Hungerford *et al.* 1995). The presence of inorganics may also prevent the spread of smouldering combustion in duff (Frandsen 1987).

Yet forest floor duff has highly variable characteristics. Depth and moisture content exhibit wide spatial and temporal variability throughout forest stands (Potts *et al.* 1983) due to interception of precipitation within drip lines and the proportionally greater accumulation of fuels beneath tree crowns. Predicting forest floor consumption from measurable attributes is vital in order to limit the deleterious effects of prolonged smouldering combustion and to achieve management duff-reduction goals. The objective of this study was to better define the consumption threshold for duff mounds in a laboratory combustion experiment where three recognised determinants of duff consumption – (1) moisture content; (2) mineral content; and (3) bulk density – were controlled or quantified.

## Methods

### Study area

The study was conducted with duff samples from a long-unburned ponderosa pine stand at the National Park Service's Whiskeytown National Recreation Area in the south-eastern Klamath Mountains, located 13 km west of Redding, California, USA (40°61'N, 122°66'W). The site is of particular significance to Whiskeytown National Recreation Area managers due to a growing desire to protect relict stands of ponderosa pine that are in decline (Leonzo and Keyes 2010). The study area is ~6 ha and moderately sloping (10–15%) to the north at an elevation of ~1650 m, ~250 m below the summit of Shasta Bally mountain. Soils are well developed and well drained, resulting from either andesitic mudflow or granitic and granodiorite parent materials (Fry and Stephens 2006). Average annual rainfall is ~105 cm.

The stand was dominated by an overstorey of relict ponderosa pine, with patchy groundcover dominated by shrub tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehder), and a thick organic forest floor. Dead surface fuels were sparse and discontinuous and consisted primarily of needle litter and herbaceous material. A component of relict sugar pine (*Pinus lambertiana* Douglas) was also present in the overstorey. The stand last

burned in 1925. Few trees in the stand had either exposed or healed-over fire scars, and most showed no evidence of previous fire history, which indicated frequent, low-intensity fires in the past and a lack of sustained smouldering at the base of trees.

### Data collection

A total of 100 duff samples were collected around the base of 50 relict ponderosa pines during 23–29 October 2009. Study trees were chosen from a population of trees that were all over 50-cm diameter at breast height (DBH). Tree DBH ranged from 50 to 141 cm (mean = 83 cm). All relict ponderosa pines in the study area were sampled. At each tree, a 25 × 25-cm sample containing the entire organic profile was cut within a metal frame from the duff mound and removed with minimal disturbance. Samples were carefully transported in sturdy boxes to the USDA Forest Service's Fire Sciences Laboratory in Missoula, Montana, where attributes were measured and burning was conducted.

### Laboratory methods

A laboratory study was designed to obtain accurate measurement of properties that influence consumption of duff. All burn tests were conducted at ambient room temperature and relative humidity under a fume hood with enough air flow to remove smoke but not affect burning conditions. Burning took place between 16 November and 8 December 2009.

Duff was wetted before burning by placing samples on raised wire mesh inside a plastic container with drainage holes, soaking with a hose, and equilibrating for 7 days. Subsamples were pared to a standardised 10 × 10-cm size, distinguished into upper and lower duff and divided by cutting with a butcher's knife, and then microwave dried to specific moisture contents to examine the influence of moisture on ignition and consumption. The procedure for drying was developed to gradually and homogeneously dry the entire sample and attempt a burn until a burn–no-burn outcome was equally likely. After the sample had reached the anticipated moisture condition, a 1 × 10-cm slice was taken from the lateral side where burning was initiated to determine mineral content and moisture content at the time of the burn. Samples were at least 4 cm deep to ensure full contact with the ignition coil, and no more than 8 cm deep due to the depth of the burn box (10 cm) and to guarantee the insulative properties of the burn box. Excessively deep duff was removed using a butcher's knife. These dimensions equate to moderate depths used by Hawkes (1993), although depth of burn was not a response variable.

Burn protocol was modified from the widely accepted ignition test developed by Frandsen (1987). Burning was conducted in an open-topped box constructed of 2.5-cm thick ceramic board that restricted heat loss during the smouldering process, as expected in a duff mound. Ceramic board is non-burning (melting point of 1760°C) and provides an insulating layer between the sample material and air (Hawkes 1993). The rate of heat transfer through the walls is similar to the rate within duff (Hungerford *et al.* 1995). Samples were positioned with dried sphagnum peat moss (Premier Tech Horticulture, Rivière-du-Loup, Quebec, Canada) placed in contact with one of the lateral sample edges, to perform as a uniform ignition transfer medium. Peat was packed to approximately the same

depth and bulk density as the duff sample using a flat piece of aluminium slightly smaller than the opening of the burn box. The 10 × 10-cm dimensions of the burn box are therefore sufficient for assessment of the duff burning process, considering the slow rate of spread during the smouldering process in duff and peat (Hungerford *et al.* 1995).

It has been recognised that duff is primarily consumed by smouldering combustion (Frandsen 1987; Miyanishi and Johnson 2002). Hawkes (1993) found that the limit of ignition depends on both the amount of heat exposure and its duration. Increasing either factor allowed smouldering combustion to initiate at increasing moisture contents. The ignition condition implemented in this study was comparable to the moderate heat load (5.13 MJ m<sup>-2</sup> for a short duration (13 min)) treatment described by Hawkes (1993). A glowing resistance coil ignited the peat moss, which served as an ignition transfer medium. Smouldering was always present as long as the red-hot ignition coil was in contact with the peat. Electricity was discontinued once the ignition material supported sustained smouldering (up to 10 min), simulating ignition by a lateral combustion zone similar to field conditions.

Once smouldering peat fire reached the duff material, samples were then observed to determine whether smouldering combustion continued unaided. Sample response was recorded binomially as either burned (≤60% consumption by volume) or unburned (>60% consumption). The 60% consumption discrimination threshold has been used in previous ignition studies (Reardon *et al.* 2007), as few outcomes border this threshold. In addition, percentage consumption was calculated as a continuous response: the weight of organic material after the burn divided by pre-burn organic weight. This weight-based calculation of consumption eliminates bias in outcomes by visual appearance of the burn sample.

Each sample's bulk density, mineral content, and moisture content were recorded for each test. Bulk density was obtained for each sample of upper and lower duff by removing a 10 × 10-cm piece from the remainder of the 25 × 25-cm sample. Subsamples were divided into upper and lower duff layers (approximately half the total depth of the subsample) and depth was measured at four sides of each layer. Volume was calculated as average depth (cm) multiplied by the standardised length and width of each subsample. Samples were placed in a drying oven at 100°C for 24 h to determine dry weight. A 1 × 10-cm slice of each sample was oven dried to determine moisture content at the time of the burn, and then burned in a muffle furnace at 450°C for 24 h to obtain initial mineral content. Mineral content was calculated as the ratio of mineral (ash) mass to total oven-dry weight. Mineral content and bulk density were fixed properties of each sample, but moisture content was adjusted and controlled in order to observe the transitions through the ignition limit. Moisture contents were initially prepared over a relatively broad range to isolate the ignition limit, and were subsequently refined with moisture contents more closely targeted to this observed limit.

#### Experimental design

The following hypotheses were tested based on study objectives, to identify factors and possible interactions that determine percentage consumption of duff, including: (1) moisture

content; (2) mineral content; and (3) bulk density. A total of 100 burn tests were conducted: 50 each of upper duff and lower duff. Initial regression analysis revealed that factor effects differed significantly by duff layer, so further analysis examined upper and lower duff layers independently. We hypothesised significant negative relationships between moisture content, mineral content and bulk density to percentage consumption. We expected to identify limits for each factor wherein percentage consumption would be reduced to zero, within both the upper and lower duff fractions. Statistical significance was determined at  $\alpha = 0.05$ .

Multiple regression was used to express a predictive relationship of percentage consumption over a range of moisture contents, mineral contents and bulk densities. Similar to the design of Frandsen's (1987) ignition test, only moisture content was artificially modified to examine the transition through the ignition limit. The mineral content and bulk density were properties fixed in individual samples but varied between samples, with effects on consumption potential that were assessed through the multiple regression model. The assumption of linearity for multiple regression was assessed with scatterplots of all variables of interest. Normal probability plots were reviewed for distribution of the residuals, in addition to *F*-tests, which are robust with regard to violations of the normality assumption. In addition, logistic regression analysis was conducted to determine an odds ratio for sustained combustion. This ratio approximates how much more or less likely it is for combustion to continue with incremental changes in each independent variable.

## Results

### Duff mound properties

Duff mound length and width averaged 15 and 38 cm respectively. Throughout the stand, upper duff had a narrow mineral content range of 1.37–10.88% (mean = 4.19%, s.d. = 2.02) (Fig. 1, top). Upper duff bulk densities ranged from 0.04 to 0.18 g cm<sup>-3</sup> (mean = 0.08 g cm<sup>-3</sup>, s.d. = 0.03) (Fig. 1, bottom). Lower duff varied more than upper duff, with mineral contents ranging from 4.32 to 80.38% (mean = 25.01%, s.d. = 21.71%) and bulk densities ranging from 0.07 to 0.28 g cm<sup>-3</sup> (mean = 0.15 g cm<sup>-3</sup>, s.d. = 0.05) (Fig. 1). There was overlap in the distribution of mineral content and bulk density between upper and lower duff. Due to significant differences between upper and lower duff for all variables, further assessment is examined by layer.

### Laboratory burning: upper duff

Upper duff samples classified as 'burn' outcomes averaged 80.07% consumption and samples classified as 'no burn' outcomes averaged 22.82% consumption. Multiple linear regression showed that moisture content had a highly significant ( $P = 0.0017$ ), negative effect on consumption (Table 1). Upper duff samples did not sustain smouldering combustion >57% moisture content (Fig. 2, top). Moisture content explained only 18% of the variance in combustion. Sustained smouldering in upper duff is variable at moisture contents between 0 and 57%. Moisture content was divided into three 20% class ranges to observe trends in consumption approaching the moisture threshold. Average consumption of duff with moisture contents

from 0 to 20% was 61.45%, samples from 20 to 40% moisture content were consumed 56.92% on average, and samples from 40 to 60% moisture contents were 45.70% consumed on average. Average consumption above the 57% moisture threshold was 21.84%.

The remaining variables and their interactions were not found to be significant factors influencing the percentage consumption of upper duff and were therefore not included in the model. The two samples with the highest mineral content (severe outliers with moisture contents <11%) had opposing burn outcomes; the remainder seemed to have an equally likely

chance of burning regardless of mineral content (Fig. 2, middle). Similarly, samples at both high and low bulk densities had a high likelihood of burning (Fig. 2, bottom). A report of model-selection steps is presented in Table 1. The model ( $F = 1.096$ ) ( $P = 0.0017$ ) relating moisture content (%MSTR) to percentage consumption (%CONS) is highly significant, but poorly predictive:

$$\%CONS = 65.328 - (0.4092 \times \%MSTR) \tag{1}$$

where the 95% confidence intervals (95% CI) of %MSTR are lower =  $-0.6562$  and upper =  $-0.1622$ .

Logistic regression was used to obtain an odds ratio of sustained smouldering for upper and lower duff (Table 2). The upper duff moisture content odds ratio represents a decreased chance that duff samples will sustain smouldering with an increase in moisture content. The change in odds due to an increase of 1% moisture content is 0.952 (95.2%). A 5% increase in moisture content will decrease the odds of sustained smouldering by  $1 - 0.952^5$ , or 0.218 (21.8%).

Laboratory burning: lower duff

Lower duff samples classified as ‘burn’ outcomes averaged 91.28% consumption and samples classified as ‘no burn’ outcomes averaged 23.33% consumption. Multiple regression analysis produced coefficients that were significant for moisture content ( $P < 0.0001$ ) and mineral content ( $P < 0.0001$ ) (Table 3). The intercept is significant at the 0.05 probability level. The relationship of each to consumption was negative. Lower duff samples did not sustain smouldering combustion >102% moisture content (Fig. 3, top). Samples with moisture content from 128.66 to 223.78% (mean = 164.07) resulted in 22.53% consumption on average. Sustained smouldering in lower duff is variable at moisture contents between 0 and 102%. The results indicate an upper threshold for mineral content; no samples with >55% mineral content resulted in a burn (Fig. 3, middle). Samples with mineral contents from 60.03 to 80.38% (mean = 73.31) resulted in 18.12% consumption on average. Bulk density and interactions of all main variables were not found to be significant factors influencing the percentage consumption of lower duff and were therefore not included in the model (Fig. 3, bottom). Of the lower duff samples that sustained smouldering combustion, over half were thoroughly (90–100%) consumed.

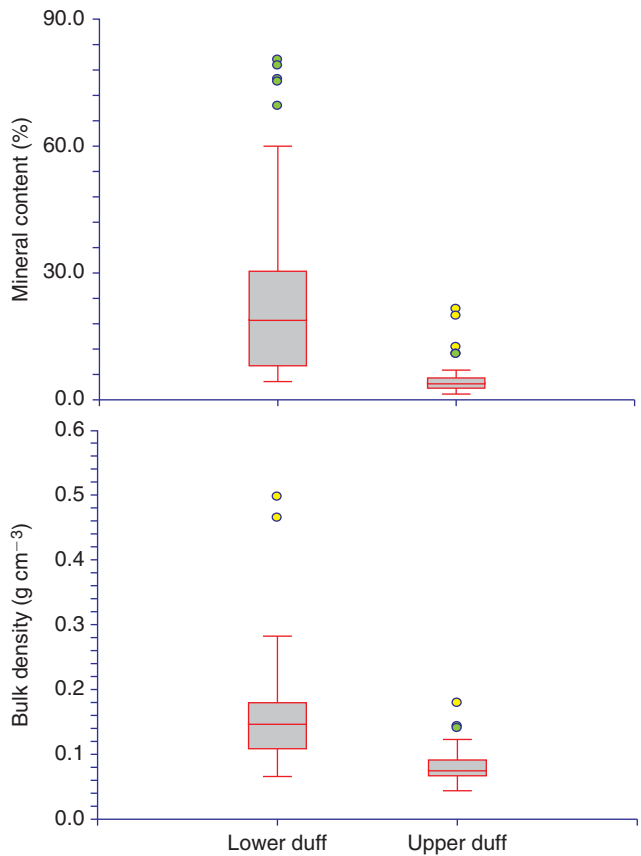


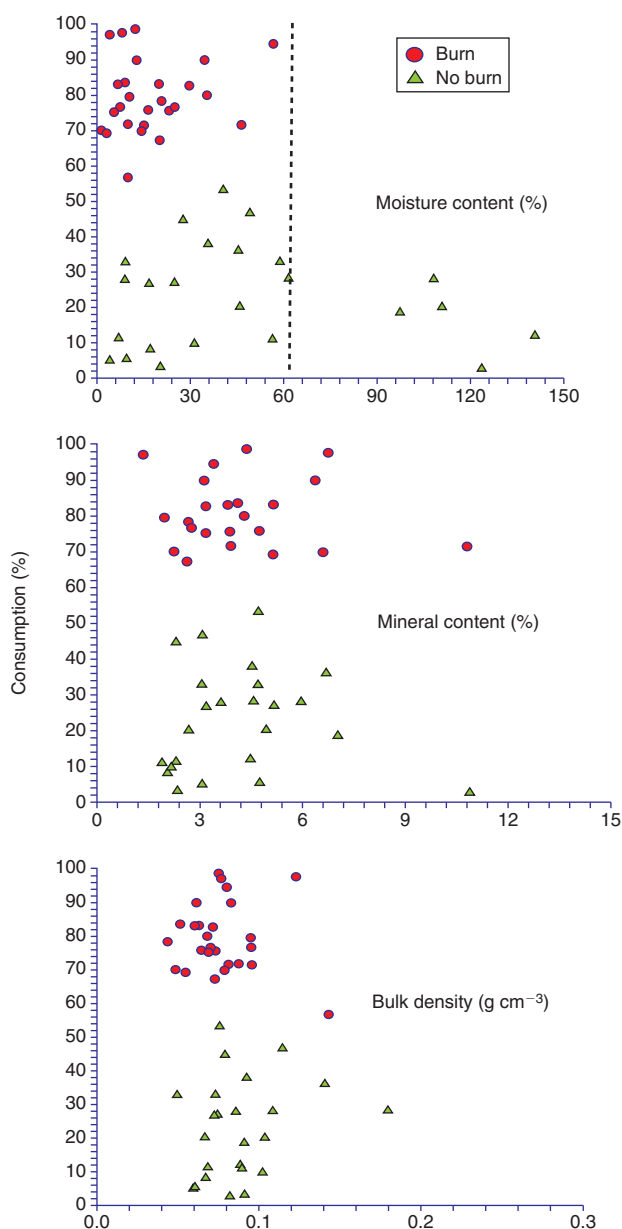
Fig. 1. Variability of physical duff mound properties (mineral content, bulk density), separately by layer.

Table 1. Results of multiple regression analysis of upper duff burn response  
Asterisks denote statistical significance at  $\alpha = 0.05$

| Model         | Factor           | <i>P</i> | <i>R</i> <sup>2</sup> | Estimate  | Intercept |
|---------------|------------------|----------|-----------------------|-----------|-----------|
| Single factor | Moisture content | 0.0017*  | 0.1878                | −0.4092   | 65.3280   |
|               | Mineral content  | 0.9663   | 0.0000                | −0.0995   | 51.5166   |
|               | Bulk density     | 0.2424   | 0.0284                | −206.3062 | 69.0813   |
| Two-factor    | Moisture content | 0.0018*  | 0.2004                | −0.4445   | 56.6952   |
|               | Mineral content  | 0.3281   | —                     | 2.2030    | —         |
|               | Moisture content | 0.0037*  | 0.1890                | −0.3983   | 68.6914   |
|               | Bulk density     | 0.7909   | —                     | −45.1695  | —         |
|               | Mineral content  | 0.8578   | 0.0354                | 0.4257    | 69.3908   |
|               | Bulk density     | 0.2106   | —                     | −247.7230 | —         |

A report of model-selection steps can be found in Table 3. The prediction model using moisture and mineral content ( $F = 31.432$ ) ( $P < 0.0001$ ) for percentage consumption is highly significant. The proportion of the variation in the data explained by the model ( $R^2$ ) is 0.5722. Moisture content (%MSTR) explained 45.0% of the variance in percentage combustion (%CONS) in the model, and mineral content (%MNRL) explained 37.3%:

$$\begin{aligned} \%CONS = & 130.7991 - (0.5472 \times \%MSTR) \\ & - (1.0959 \times \%MNRL) \end{aligned} \quad (2)$$



**Fig. 2.** Upper duff consumption rates and categorical burn outcomes for a range of moisture contents, mineral contents and bulk densities. Apparent combustion threshold is indicated by a dashed vertical line.

where the 95% CI of %MSTR are lower =  $-0.7037$  and upper =  $-0.3907$ ; and 95% CI of %MNRL are lower =  $-1.4401$  and upper =  $-0.7516$ .

Logistic regression was used to obtain an odds ratio of sustained smouldering (Table 2). The lower duff moisture content represents a decreased chance that duff samples will sustain smouldering with an increase in moisture content. The change in odds due to an increase of 1% moisture content is 0.903 (90.3%). Similarly, the mineral content odds ratio represents a decreased chance that duff samples will sustain smouldering with an increase in mineral content. A 1% increase in the mineral content will decrease the odds of sustained smouldering by 0.861 (86.1%) (Table 2).

Frandsen (1987) investigated how combinations of moisture content and mineral content affect smouldering combustion, producing a linear estimate of the smouldering limits of peat moss. Adding inorganic material to his samples reduced the moisture limit that had previously permitted smouldering. Results from the present study showed this relationship in the lower duff (but not upper duff), where the interaction of mineral content and moisture content was strong but barely non-significant ( $P = 0.0559$ ). Fig. 4 illustrates how successful combustion and burn outcomes occurred when combinations of moisture content and mineral occurred in an apparent relationship that is comparable to that observed in peat by Frandsen (1987). An elevated level of each variable also resulted in combustion failure and a no-burn outcome: smouldering was not sustained in samples with high moisture contents ( $>102\%$ ) or high mineral contents ( $>55\%$ ).

## Discussion

Enhancing the understanding of properties relating to smouldering combustion in ponderosa pine duff mounds was the focus of this study. Reducing the fuel hazard posed by duff mounds is essential to successful restoration burning in fire-dependent old-growth forests. Findings from this study show that consumption in upper duff is constrained by moisture content, and in lower duff is limited by moisture content and mineral content. Though caution must be exercised in applying laboratory models to field-based conditions, our predictive models serve as a good tool for the evaluation of smouldering duff mound combustion and fuel consumption in ponderosa pine stands of similar condition.

Results from previous studies using both forest floor duff and peat moss have shown that the probability of sustained smouldering is inversely related to duff moisture content once a moisture threshold is approached, and is partially dependent on mineral content and bulk density. The likelihood that

**Table 2.** Odds ratios from logistic regression analysis of upper and lower duff burn response

Upper and lower bounds were calculated for a 95% confidence interval

| Duff layer | Factor           | Odds ratio | Upper bounds | Lower bounds |
|------------|------------------|------------|--------------|--------------|
| Upper      | Moisture content | 0.952      | -0.013       | -0.085       |
| Lower      | Moisture content | 0.903      | 0.967        | 0.843        |
|            | Mineral content  | 0.861      | 0.942        | 0.861        |

**Table 3. Results of multiple regression analysis of lower duff burn response**Asterisks denote statistical significance at  $\alpha = 0.05$ 

| Model         | Factor             | <i>P</i> | <i>R</i> <sup>2</sup> | Estimate  | Intercept |
|---------------|--------------------|----------|-----------------------|-----------|-----------|
| Single factor | Moisture content   | 0.0012*  | 0.1989                | −0.3258   | 88.0418   |
|               | Mineral content    | 0.0129*  | 0.1219                | −0.5611   | 79.4922   |
|               | Bulk density       | 0.0873   | 0.0622                | −160.973  | 90.7548   |
| Two-factor    | Moisture content   | 0.0000*  | 0.5722                | −0.5472   | 130.7991  |
|               | Mineral content    | 0.0000*  | —                     | −1.0959   | —         |
|               | Moisture content   | 0.0001*  | 0.3241                | −0.3727   | 121.9323  |
|               | Bulk density       | 0.0198*  | —                     | −191.9271 | —         |
|               | Mineral content    | 0.0955   | 0.1190                | −0.4153   | 93.6103   |
| Interaction   | Bulk density       | 0.2300   | —                     | −114.7343 | —         |
|               | Moisture           | 0.1548   | 0.0523                | −0.4752   | 81.2486   |
|               | Mineral            | 0.6975   | —                     | −1.4120   | —         |
|               | Moisture × Mineral | 0.0559   | —                     | 0.0579    | —         |
|               | Moisture           | 0.0544   | 0.0826                | −1.4646   | 115.2798  |
|               | Bulk density       | 0.0956   | —                     | −578.5775 | —         |
|               | Moisture × BD      | 0.0629   | —                     | 15.4776   | —         |
|               | Mineral            | 0.8100   | 0.0020                | −3.2359   | 82.8680   |
|               | Bulk density       | 0.8038   | —                     | −180.7157 | —         |
|               | Mineral × BD       | 0.7895   | —                     | 40.5321   | —         |

sustained smouldering combustion will take place decreases as any of these properties increase beyond a threshold value (Hartford 1989). The findings from this study support this relationship between moisture content and percentage consumption for both upper and lower duff; as moisture content approaches 57 or 102% respectively, the percentage consumption decreases.

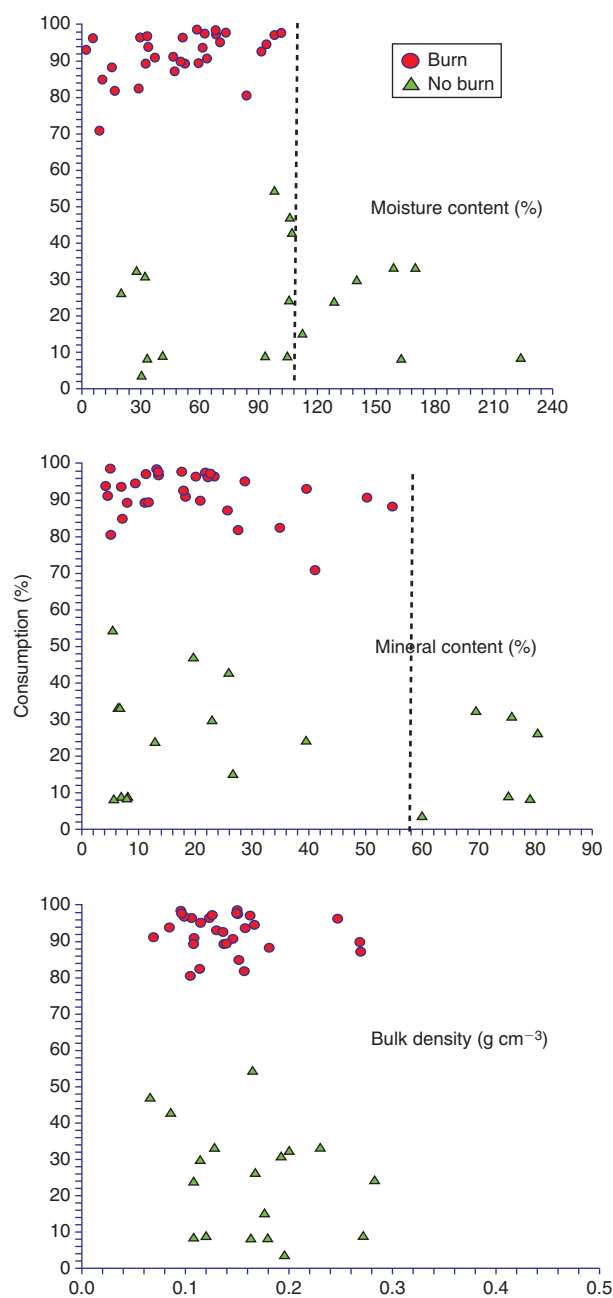
This study was designed to better define duff conditions influencing burning based on a natural range of field conditions. Moisture content was altered, as this factor displays seasonal variability, yet care was taken to ensure that mineral content and bulk density remained fixed by the origin of the samples themselves. The results indicate that these field samples were below the mineral content and bulk density threshold for upper duff and below the bulk density threshold for lower duff as no consumption limit was reached. A better understanding of the natural variability of mineral content and bulk density may be useful in assessing the importance of these factors in field applications. We found that moisture content influences consumption of upper and lower duff, yet further research is needed to improve the predictive quality of this factor.

Over the course of several months of handling and burning samples, a distinct difference was observed in the composition of upper and lower duff that may explain some of the variation in burn outcomes and factor effects. Upper duff is composed of a matrix of intact organic material including pine needles, bark flakes and woody debris. For upper duff to sustain smouldering combustion, it must maintain enough heat to connect a series of ignitions between individual pieces of material. Combustion in upper duff is limited by heat lost from air space within the material and from airflow above. Conversely lower duff is a carpet-like mat of well-decomposed homogenous material. Propagation of smouldering combustion in this layer is simplified by the presence of fine material in the sample. Lower duff is insulated by the high connectivity of particles and by the layer of upper duff above. It follows then that smouldering combustion

in upper duff may be more greatly affected by low bulk densities, whereas lower duff is resistant due to its insulative properties. Further research in duff structure may generate reasons for the large degree of unexplained variation that remains in upper duff.

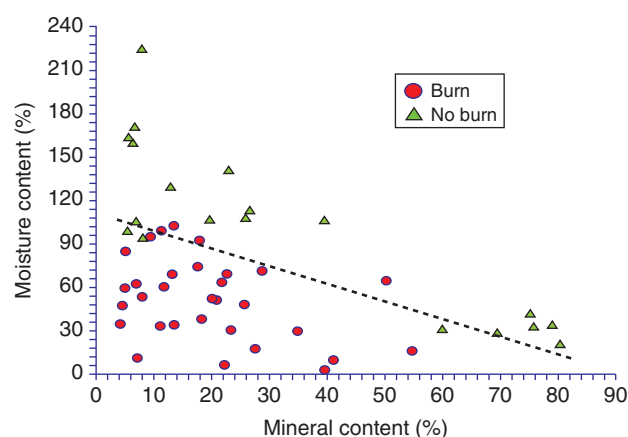
Frandsen (1987) developed an ignition test to determine the influence of mineral content and moisture content on ignition. In an evaluation of that test with peat moss, he reported that for mineral contents at or <10%, combustion failure occurs when moisture content exceeds 110%. That finding held true in the current study for lower duff (Fig. 4). The range of mineral contents in our upper duff samples was relatively narrow (1.37–10.88%), which may explain the lack of a statistically significant relationship as the bulk of values was below the mineral content threshold for burning. However, the data displayed in Fig. 4 supports Frandsen's findings (that increasing moisture content and mineral content decreases the probability of smouldering combustion) and extends it to the lower layers of ponderosa pine mounds. To what extent the mineral contents of our samples are representative of ponderosa pine duff mounds in other geographic areas is unknown. Given the importance of mineral content to combustion and the wide geographic distribution of ponderosa pine across diverse soil types, this subject is worthy of further inquiry.

Work by Norum (1977), Sandberg (1980) and Brown *et al.* (1985) showed the moisture limits of forest floor duff for Douglas-fir, finding that upper duff burns independently of surface fuels <30% moisture content. In longleaf pine forests, Wade *et al.* (1980) reported that the upper organic layer will ignite at <65% moisture content, then burn progressively wetter layers up to 150% moisture content. Hawkes (1993) reports ignition limits between 140 and 180% for commercial peat moss in his moderate-heat, short-duration heat treatment. However, this study found the upper duff moisture content threshold for combustion to be 57%. No samples above this moisture content were classified as a burn.



**Fig. 3.** Lower duff consumption rates and categorical burn outcomes for a range of moisture contents, mineral contents and bulk densities. Apparent combustion thresholds are indicated by dashed vertical lines.

Alternatively, the observation that lower duff is a more homogenous medium and upper duff a more fragmented matrix may indicate that peat moss is a surrogate strictly for lower duff. Studies of peat moss moisture content thresholds more closely relate to the findings of this study. Work by Norum (1977), Sandberg (1980) and Brown *et al.* (1985) found that lower duff from the forest floor burns independently of surface fuels <90% moisture content. Conversely, duff rarely burns above a moisture content of 120%. Most studies suggest that the ignition limit of organic soil horizons is <150% (Norum 1977; Brown *et al.*



**Fig. 4.** Interactions of moisture content and mineral content on lower duff burn outcomes. Dashed line approximates distinction of burn–no-burn outcomes for combinations of mineral content and moisture content.

1985). The combustion limit found in the present study was 102% for lower duff, which corresponds well with similar studies of peat moss combustion thresholds.

Contrary to our expectation, bulk density proved not to be a significant factor influencing duff consumption. Hartford (1989) had adjusted bulk density during burn trials, finding a lower probability of sustained combustion with increasing organic bulk density. Higher bulk densities have been found to decrease the probability of independent burning at a given moisture and mineral content (Hartford 1989). Despite significant differences in bulk densities between upper and lower duff samples, this variable did not affect percentage consumption in the present study. However, we qualify this finding by noting that it was true for the range of ambient mineral contents that our sample presented.

As an application of the experiment, ambient duff moisture content data collected at the study site during field sampling ( $n = 176$ ) were inserted to the duff consumption models. Those ambient upper duff moisture contents ranged from 8.34 to 44.47% (mean = 23.88%) and lower duff moisture contents ranged from 9.74 to 39.19% (mean = 22.85%). According to the upper duff consumption model, burning under those observed conditions would have resulted in 47.13–61.92% consumption. Similarly, predicted lower duff consumption rates were 71.38–87.50% for this range of moisture contents (calculated with the observed average ambient lower duff mineral content of 34.65%). Given a rain event totalling over 47 cm within 1 week of this reported moisture content, such levels of duff mound consumption seem surprisingly high. Managers would doubtfully have anticipated such high consumption rates so soon following such a major precipitation event.

This study focussed on combustion rather than burn effects, but limiting unintended effects by better understanding duff mound combustion (albeit in a laboratory setting) is our intended extension of the data presented here. Unintended consequences of burning commonly affect those trees that burning is most designed to protect. All factors held equal, survivability increases with tree size. Yet in separate studies, mortality of different pine species has been proven to increase

with tree size during dry burns in areas with deep forest floor accumulations (Swezy and Agee 1991; Stephens and Finney 2002; Varner *et al.* 2007), indicating that other factors are not often equal. It has been noted that if high survival of mature pines is a goal, it may be desirable to burn when duff is too wet to sustain ground fire (Frandsen 1987; Ryan and Frandsen 1991). Aside from manipulation of the duff mound itself (Hood *et al.* 2007), moisture content remains the sole factor available to managers seeking specific, partial burn outcomes that would result in reduction of upper duff layers without causing combustion of lower duff layers. Our study shows that mineral content must also be accounted for in order to achieve desired ponderosa pine burn outcomes.

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