2010

Factors that influence ponderosa pine duff mound consumption

Emily Claire Garlough

The University of Montana

FACTORS THAT INFLUENCE PONDEROSA PINE DUFF MOUND

CONSUMPTION

By

EMILY CLAIRE GARLOUGH

B.S., University of Michigan, Ann Arbor, Michigan, 2006
B.A., University of Michigan, Ann Arbor, Michigan, 2006

Thesis

presented in partial fulfillment of the requirements
for the degree of

Master of Science in Forestry

The University of Montana
Missoula, MT

May 2010

Approved by:

Perry Brown, Associate Provost for Graduate Education
Graduate School

Christopher Keyes, College of Forestry and Conservation

Lloyd Queen, College of Forestry and Conservation

Charles Palmer, Department of Health and Human Performance

Garlough, Emily, Master of Science, May 2010 Forestry

Factors that influence ponderosa pine duff mound consumption

Chairperson: Christopher Keyes

When applying prescribed fire to long-unburned but fire-dependent ecosystems 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 can lead to fine root mortality, cambial injury, enhanced susceptibility to bark beetle attack, and possibly tree death. Pre-burn sampling to predict duff mound consumption from measurable attributes is vital in order to limit the deleterious effects of prolonged smoldering combustion. The objective of this study was to determine the conditions that influence duff consumption and analyze the variability of these factors in the field.

Duff moisture content, mineral content, bulk density, composition and depth were spatially quantified to inform prescribed burning decisions. Variability in factors influencing consumption was analyzed within and between duff mounds to improve pre-burn sampling procedures. Results show that a significant amount of variability in properties that could influence consumption due to differences between and within duff mounds. Duff properties did not vary significantly between uphill and downhill sampling locations. There was a positive relationship between tree size and duff depth. There was no association between lower duff moisture content and duff depth. Sampling recommendations were developed for the most appropriate protocols of efficient and meaningful duff sampling on an operational basis.

A laboratory experiment was conducted to investigate how measurable attributes of duff affect smoldering combustion in duff mound fuels. 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 percent consumption were recorded for each burn. The moisture content threshold for smoldering combustion was 57% and 102% respectively for upper and lower duff. Percent consumption was inversely related to moisture content for both layers of duff, and partially dependent on mineral content for lower duff. Results from this study aim to identify important attributes of duff that control the burning process in order to inform prescribed burning decisions.

ACKNOWLEDGMENTS

This study was made possible with funding from the Whiskeytown National Recreation Area, and with the support of Jennifer Gibson, Ecologist, and hardworking volunteers in the park. I would like to thank Chris Keyes for his guidance and encouragement, and my graduate committee members Lloyd Queen and Charlie Palmer for all of their help. I appreciate the support of the National Center for Landscape and Fire Analysis at the University of Montana for assistance in conducting preliminary research and support throughout the project. I would also like to thank Mick Harrington, Jim Reardon, and Sharon Hood for their valuable insights and the Rocky Mountain Research Station, Fire Sciences Laboratory in Missoula, MT for use of laboratory facilities for sample processing and burning.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

Chapter 1

Chapter 2

LIST OF FIGURES

OVERVIEW

Deepening fuel accumulations at the base of large trees in long unburned but fire adapted stands has resulted in a unique hazard fuel known as duff mounds. This fuel presents resource managers with a challenge in the successful reintroduction of fire to long-unburned stands, as prolonged smoldering combustion of duff mounds leads to tree injury and mortality. While the deleterious effects of smoldering duff have been well-documented, little is known about the variability in duff mound properties that influence consumption.

The increased hazard associated with prescribed burning in old growth stands with significant duff mounds has drawn the attention of resource managers at Whiskeytown National Recreation Area (WNRA), where the 2008 Whiskeytown Complex wildfires came within a mile of one of their few surviving remnant stands. In those ponderosa pine old growth forests with elements of historical structure, restoration and the reduction of threats are high priorities. In response, a study was conducted to assess variability in measurable attributes that influence duff mound consumption, as well as to determine the effect of these factors on duff consumption. Together, these two chapters aid in decision support for prescribed burning by improving pre-burn sampling techniques and prediction of duff consumption.

Several characteristics of duff – moisture content, mineral content, depth, and bulk density – have been previously identified as the primary determinants of the rate and amount of duff consumption and resulting injurious effects in pine species. Samples collected from the WNRA were processed to determine variability in these factors within and among duff mounds. The experimental design featured a three-factor mixed model analysis of variance with random blocking in order to analyze variability among duff mounds, sample locations, and duff layers. We hypothesized differences between upper and lower duff, sampling locations on the uphill and downhill sides of a tree, and individual duff mounds. We found differences in moisture content, mineral content, depth and bulk density between duff layers and individual duff mounds.

Results of that descriptive study were utilized in designing a laboratory burning study to analyze the influence of moisture content, mineral content and bulk density on upper and lower duff consumption. Duff samples were divided by layer, dried to desired moisture contents, and placed in a burn box where smoldering combustion was initiated. Percent consumption was calculated for 100 burn tests, wherein duff consumption exceeding 60% was considered a 'burn' outcome. Multiple regression was used to test relationships between the independent variables of moisture content, mineral content and bulk density and the dependent variable of percent consumption. We hypothesized moisture content would significantly influence consumption of upper duff, and lower duff consumption would be partially dependent on all three factors. We found that consumption of upper duff was influenced by moisture content, whereas lower duff consumption was dependent on both moisture content and mineral content.

Findings indicated that in order to best protect remnant trees at WNRA, managers should constrain burning this surviving ponderosa pine stand to threshold conditions wherein upper duff moisture content is below 57% and lower duff moisture content is above 102%. Our laboratory results indicated that burning under these conditions should permit the spread of surface fires, while preventing the total consumption of duff mounds that results in tree injury.

VABIABILITY IN FACTORS INFLUENCING DUFF MOUND CONSUMPTION IN LONG-UNBURNED PONDEROSA PINE ECOSYSTEMS

Abstract

Consumption of materials on the forest floor is important to successful restoration burning in fire-dependent old-growth forests, but excessive consumption via prolonged smoldering combustion at the base of large trees can contribute directly to injury and mortality. Hence, pre-burn sampling to predict duff mound consumption from measurable attributes is vital in order to develop a prescription that could limit the deleterious effects of prolonged smoldering combustion. In this study, duff moisture content, mineral content, bulk density, composition and depth were spatially quantified to inform prescribed burning decisions. Variability in factors influencing consumption was analyzed within and between duff mounds to improve pre-burn sampling procedures. Results show that a significant amount of variability in properties that could influence consumption is due to differences between and within duff mounds. Duff properties did not vary significantly between uphill and downhill sampling locations. There was a positive relationship between tree size and duff depth. There was no association between lower duff moisture content and duff depth. Sampling recommendations were developed for the most appropriate protocols of efficient and meaningful duff sampling on an operational basis. Results will help fire managers better protect large trees in old-growth stands while achieving restoration goals, reducing hazard fuels, and preventing or limiting costly mop-up operations.

Introduction

Minimizing excessive tree injury and resulting mortality is one of the greatest challenges to the successful reintroduction of fire to large diameter and old growth fire-adapted ecosystems. Prolonged consumption of accumulated duff around the base of old trees, or duff mounds, is among the most significant factors contributing to mortality in pines (Ryan and Frandsen 1991, Swezy and Agee 1991, Stephens and Finney 2002, Varner et al. 2005, Hood et al. 2007). Several characteristics of duff – moisture content, mineral content, depth, and bulk density – have been identified as the primary determinants of rate and amount of duff consumption and resulting injurious effects in pine species (Frandsen 1987, Hartford 1989, Hungerford et al. 1995, Varner et al. 2005). Prescribed fire is increasingly used as a tool in restoring ponderosa pine (*Pinus ponderosa* Laws.) ecosystems to more historical conditions, yet its potentially harmful effects warrant the need for an understanding of duff conditions that may cause deleterious results.

Duff is defined as decomposing organic matter above the mineral soil and below freshly fallen litter (Van Wagner 1972). In some forest types, it is composed of two distinct layers: a top fermentation layer of organic material, including branch woods, cones, and bark in the early stages of decomposition and a lower humus layer of mostly indistinguishable organic matter (Harrington 1987). The humus layer is in an advanced state of decomposition and is dark brown to black in color (Potts et al. 1986). In other sites, those layers are less distinct. The duff layer lies beneath an organic litter layer, which consists of undecomposed bark, needle litter, leaves and twigs (Miyanishi 2001). In the forestry and fire ecology literature, the three horizons of litter, lower duff, and upper duff are jointly known as the forest floor.

Forests that experience frequently occurring fires have reduced fuel loadings and fires burn out quickly. Without fire at regular intervals to consume newly accumulated fuels, the forest floor deepens with leaf litter, bark flakes, fallen branches and other organic material because in the dry, western forests accumulation exceeds decomposition (Wein 1983, Keane et al. 2002). This problem is most pronounced underneath large trees, where needles and bark slough may create duff mounds to depths of 25cm or more (Varner et al. 2005). Duff depth increases from the canopy drip line to the bole, with a sharp rise at the bole, forming a mound (Ryan and Frandsen 1991). Such accumulations near the bole can support extended smoldering, thus creating favorable conditions for tree injury and mortality. While the deleterious effects of prolonged smoldering combustion at the base of large pines have been well studied, little is known about the structure, composition, and variability in factors influencing consumption of duff mounds. A better understanding of these dynamic properties will allow a better grasp of the smoldering process which should then inform prescribed burning decisions in these vulnerable stands.

Results from combustion experiments using both forest floor duff and peat moss have shown that the probability of sustained smoldering is strongly influenced by duff moisture content, and is partially dependent on bulk density and mineral content. The likelihood that sustained smoldering combustion will take place decreases as any of these properties increase after some threshold has been reached (Hartford 1989). Both depth and moisture content exhibit wide spatial and temporal variability throughout forest stands (Potts et al. 1983). A positive relationship has been found between moisture content and depth; higher moisture levels require a greater minimum duff depth to initiate smoldering combustion (Miyanishi and Johnson 2002). The probability of ignition decreases as the ratio of mineral content to organic material increases, as mineral content absorbs heat that would have contributed to combustion (Hungerford et al. 1995). The presence of inorganics may also prevent the spread of smoldering combustion in duff (Frandsen 1987). The composition, or fuel particle type, of duff mounds is an important characteristic as it affects consumption (i.e. greater ratio of bark flakes on the downhill side is more likely to support smoldering combustion). Densely packed or deep duff may reduce the oxygen concentration and extinguish smoldering combustion. Higher bulk densities have been found to decrease the probability of independent burning at a given moisture and mineral content (Hartford 1989). Given the influence of these variables on duff consumption, a better understanding of their vertical and horizontal gradients within duff mounds and the ease in which they are quantifiable could aid in predicting duff consumption to limit tree mortality.

Fire-induced mortality must be addressed if fire is to be an effective restoration tool in large diameter old growth stands. This study examined variation in ponderosa pine duff mound properties in order to provide useful information relative to the combustion process and ultimately to better protect large trees while achieving restoration goals, reducing hazard fuels, and preventing or limiting costly mop-up operations. The objectives of this study were to spatially quantify the main variables influencing duff mound consumption in ponderosa pine as reported in the literature, including: (1) moisture content, (2) depth, (3) mineral content, (4) bulk density, and (5) fuel particle type.

Specific interactions were analyzed to answer questions about efficient sampling of duff at individual duff mounds, sample locations (uphill/downhill), and duff layers (upper/lower). We hypothesize a difference in factors influencing combustion on the uphill and downhill side of a mound. We also expected to find differences in moisture content, mineral content and bulk density between the upper and lower duff layer. Additionally, we hypothesize differences in these variables between duff mounds and within layers. Based on findings in the literature that duff depth increased with tree diameter (Ryan and Frandsen 1991), we hypothesized a relationship between duff depth and tree size. Pre-burn moisture content is a significant independent variable in many regression models for predicting depth-of-burn (Hawkes 1993). Thin duff dries three times as fast as a duff bed that was 10cm deep (Cooper 1985). Therefore, one may assume then that there is an interaction between duff depth and moisture content. We hypothesized a relationship between lower duff moisture content and depth of duff mounds. Spatial patterns in moisture, mineral content, bulk density and depth within and between duff mounds would suggest pattern in consumption rates in the field. The application of such findings will simplify sampling techniques prior to prescribed burning and improve efficiency in duff sampling prior to prescribed burning while filling a knowledge void about duff characteristics.

Methods

Study Site Description

This study was conducted in a long-unburned ponderosa pine stand at Whiskeytown National Recreation Area (WNRA) in the southeastern Klamath Mountains, located 13km west of Redding, California, USA (40° 61'N, 122° 66'W). The site is of particular significance to WNRA due to the growing desire to protect its relict stands of ponderosa pine (Leonzo and Keyes 2007). The Whiskeytown Complex wildfire of 2009 came within one mile of the study site. The stand is approximately 6ha and moderately sloping (10-15%) to the north with a prevailing north wind. The elevation is approximately 1650m. The study area is located mid slope, approximately 250m below the summit of Shasta Bally mountain. Soils are well-developed and well-drained, resulting from either andesitic mudflow or granitic/granodiorite parent materials (Fry and Stephens 2006). Average annual rainfall is approximately 105cm (CDEC Brandy Creek Station, 40° 61'N, 122° 56'W).

Data Collection

Study trees were chosen from a population of trees that were all over 50cm DBH. A total of 61 trees were sampled for uphill and downhill duff depths (122 samples). Mineral content, bulk density and fuel particle type were analyzed for a subsample of four collections from each of ten trees (40 samples). Moisture content was measured at 44 of the sample trees; four samples each (176 samples). Subsamples for analysis of different properties were arbitrarily selected from the entire sample lot in the laboratory. The stand is dominated by an overstory of relict ponderosa pine and a thick organic floor typical of long-unburned pine ecosystems. A component of relict sugar pine (*Pinus lambertiana* Dougl.) is also present in the overstory.

Groundcover is dominated by patches of shrub tanoak (*Lithocarpus densiflorus).* Dead surface fuels are sparse and discontinuous and consist primarily of needle litter and herbaceous material. The stand last burned in 1925 (Fry and Stephens 2006). Few trees in the stand have either exposed or healed-over fire scars. Most show no evidence of previous fire, indicating a history of frequent, low-intensity surface fires and a lack of sustained smoldering at tree bases—pointing to the novelty of current fuel accumulations. The area is classified as a closed long-needle pine fuel type (fuel model 9) for fire behavior purposes (Anderson 1982).

Study trees were typical of an old-growth, long-unburned ponderosa pine ecosystem. Tree diameter at breast height (DBH), ranged from 50 to 141cm (mean=83cm). Samples were collected from October 23-29, 2009 from uphill (southerly) and downhill (northerly) locations on each tree. Duff depth was measured at 10cm from the tree bole, as closer sampling was prevented by the bark collar and roots. Depth of upper duff and lower duff were measured from the organic profile in the field where duff samples had been removed using a metric ruler.

To determine differences in ambient duff moisture content within a duff mound (uphill and downhill) separate sample tins were used to collect upper and lower duff. Volumetric moisture content, or volume of water in a sample divided by the total volume of the sample, was measured using the Duff Moisture Meter 600 (DMM600) in order to assess the utility of this sampling tool. Results from the DMM600 were converted to gravimetric moisture content and compared to absolute values obtained by weighing and oven-drying samples in the laboratory. Values were calculated based on the standardized $0.34 g/cm^3$ compressed bulk density for ponderosa pine duff. The conversion to gravimetric moisture content may be obtained by following the *DMM600 Duff Moisture Meter Calibration Guide for Resource and Fire Applications*.

A 25 x 25cm sample containing the entire organic profile was cut within a metal frame at 10cm from the tree bole from the uphill duff and downhill duff and removed with minimal disturbance. Samples were transported to the laboratory in sturdy boxes where they were processed to determine bulk density, fuel particle type and mineral content.

Bulk density was determined by removing a 10 x 10cm subsample from the larger sample. Subsamples were divided into upper and lower duff (approximately half the total depth of the subsample) and depth was measured at four sides of each layer. Volume was calculated as average depth of the four sides, multiplied by the standardized length and width of each subsample. Samples were placed in a drying oven at 100^{o} for 24h to determine dry weight. Bulk density was calculated as the mass of dry total weight per unit volume.

A separate 10 x 25cm subsample of the 25 x 25cm duff sample was used to determine duff composition. Organic material was hand sorted into needle litter, bark, cones, roots, woody debris, leaves and fine particles (passed through a 5 mm sieve). Each component was then weighed to determine the ratio of the total mass of the sample.

Mineral content was calculated as the ratio of mineral (ash) content to total oven-dry weight. This measurement was determined by placing oven-dried samples in a muffle furnace at 450^{o}C for 24h. Just as with bulk density and composition, this procedure was repeated four times for each tree; uphill and downhill, upper duff and lower duff. Additionally, we investigated the average mineral content of the three major components of duff. Ten samples of needle litter, bark flakes and fine material were hand sorted, weighed, oven-dried and placed in the muffle furnace to determine mineral content.

Experimental Design

Hypotheses were tested based on the study objectives of spatially quantifying four characteristics of ponderosa pine duff mounds, including: (1) moisture content, (2) depth, (3) mineral content, and (4) bulk density. All hypotheses were tested at alpha=0.05. A three-factor mixed model analysis of variance with random blocking was conducted to determine variability among duff mounds, sample locations, and duff layers on the response variables. Sample location and duff layer factors were both fixed and had two levels—uphill and downhill, upper duff and lower duff—respectively. Individual duff mounds were random treatment blocks in the experiment. The interaction between factors was tested.

Results from the duff fuel particle type, or composition, evaluation are presented as graphic comparisons and were not subjected to statistical analysis due to the exploratory nature of the research. Linear regression was performed to determine the strength of the relationship of variables in the two supplementary hypotheses and to evaluate the accuracy of the DMM600.

Graphical examinations of residual values were used to adequately justify the assumptions of analysis of variance for all response variables.

Results

Moisture Content

The mean moisture content of all 176 observations was 23.36%, notably dry given a rain event totaling 47cm just 6 days prior to sampling (CDEC Brandy Creek Station, 40º 61'N, 122º 56'W). No moisture contents were collected leading up to the rain event. There was no difference in moisture content of duff mounds by uphill and downhill sample location (p=0.314; Table 1). Upper duff was wetter than lower duff (p=0.024). Upper duff moisture contents ranged from 8.34-44.47% (mean=23.88%) and lower duff moisture contents ranged from 9.74-

39.19% (mean=22.85%)(Table 2). Differences in moisture content between duff mounds were significant ($p \leq 0.0001$). The interaction between factors sample location and duff layer was non-significant ($p=0.560$).

The DMM600 field measurements of volumetric moisture content showed a similar trend to average values calculated in the laboratory: 12.05% and 11.97%, respectively, for upper and lower duff. After converting to gravimetric moisture content using the DMM600 Calibration Guide, the DMM600 upper duff moisture contents ranged from 14.69-70.50% (mean=35.61%) and lower duff moisture contents ranged from 14.69-64.64% (mean=35.31%). The predictability of gravimetric moisture content was stronger for lower duff than upper duff, r-squared 0.697 and 0.497, respectively (Figure 1a and 1b). The equation of the regression line relating DMM600 gravimetric moisture content and oven-dry moisture content for upper and lower duff is estimated as:

Upper Duff Oven-Dry GMC%: 12.722 + 0.952DMM (n=85)

Lower Duff Oven-Dry GMC%: 12.905 + 0.975DMM (n=85)

We would expect an increase of .975% in lower duff oven-dry moisture content for every one percent increase in DMM600 gravimetric moisture content. On average, the DMM600 results are 11.73% and 12.46% higher for upper and lower duff, respectively, than oven-drying samples (Figure 1b).

<u>Depth</u>

Duff mound size (length and width) averaged 15cm and 38cm respectively (40% slope). Total duff mound depth for 122 observations of combined upper and lower duff averaged 10cm (Table 3). There was a difference in duff depth between layers ($p \leq 0.0001$; Table 1) and between mounds ($p \leq 0.0001$): the lower duff layer (mean=6cm) was found to be deeper than the upper duff layer (mean=4cm). Duff depth did not differ between uphill and downhill sample locations (p=0.983). The interaction between sample location and duff layer was non-significant (p=0.446).

Mineral Content

Mineral content differed between upper and lower duff layers (p≤0.0001; Table 1) and between mounds (p=0.040). Lower duff had higher mineral content and was more variable than upper duff. Lower duff values ranged from 6 to 65% (mean=34.65%; Table 4). Upper duff values ranged from 2 to 8% (mean=3%; Table 4). Mineral content did not differ between uphill and downhill sample locations (p=0.578). The interaction between factors sample location and duff layer was non-significant (p=0.553).

Bulk Density

Average bulk density for 40 observations was 0.1474g/cm^3. Unlike the response variables above, a difference in bulk density was only found between duff layers (p=0.013; Table 1). Like mineral content findings, there was more variation among lower duff bulk densities than upper duff. Lower duff bulk density ranged from 0.0748 to 0.4980g/cm^3(mean=0.1943 g/cm^3; Table 5). Upper duff bulk density ranged from 0.0353 to 0.2111g/cm^3 (mean=0.1006 g/cm^3; Table 5). Bulk density did not differ by uphill and downhill sample location (p=0.950), mound (p=0.059), or for the interaction term (p=0.282).

Composition

Figure 2 shows bar charts of percent composition by fuel particle type. These charts indicate few differences in composition by sample location, yet important differences between upper and lower duff. Fine material (≤5mm) made up 73.35-76.44% of the composition of lower duff. Bark comprised 14.64-20.52% of lower duff samples. However, upper duff was composed of 34.10-49.46% bark, 35.31-38.11% fine material, and 8.79-15.30% needle litter. Other categories accounted for less than 7% of the total fuel particles in both upper and lower duff.

An exploratory study of the average mineral content of the main duff components for combined upper and lower duff showed that bark contained 2% inorganics, needle litter contained 5% inorganics, and fine material contained 28% inorganic material.

Lower duff moisture content vs. depth

Duff depth was not a significant indicator of lower duff moisture content (LMC) ($p=0.221$). The R-squared is 0.035, meaning that 3.5% of the variability of lower duff moisture is accounted for by duff depth.

Depth vs. Tree size

Tree size was positively related to duff depth ($p \leq 0.0001$). The equation of the line relating depth and DBH (Figure 4) is estimated as:

$$\text{Depth} = 3.770 + 0.115\text{DBH} \quad (n = 54)$$

We would expect an increase of 0.115cm in duff depth for every one centimeter increase in tree size. The R-squared is 0.288, meaning that 28.8% of the variability of depth is accounted for by tree size.

Discussion

Moisture Content

It is widely recognized that moisture content is the primary determinant in consumption. Understanding how this dynamic factor varies within and between duff mounds is important in predicting duff mound consumption. In the present study, moisture content was found to differ between mounds and duff layers. We found no difference in moisture content between uphill and downhill sampling locations. This finding suggests that moisture content sampling of duff mounds may take place at either location around the mound. Significant differences between duff layers and mounds suggest samples should be taken from both the upper and lower duff at multiple mounds to better understand variability in moisture content. Yet the implication of these findings is limited by the duration of the sampling period. Further study of seasonal changes in duff moisture is still needed.

Duff moisture content is controlled by several spatial and temporal factors. Within a forest stand, it has been shown that consumption occurs largely at the base of live trees where moisture content is lower due to interception of precipitation by tree crowns (Miyanishi and Johnson 2002). Temporal models have been developed to predict large scale drying and wetting of duff based on precipitation (Ferguson et al. 2002). Time elapsed following a significant rainfall event has been used as a determinant to quickly predict duff moisture. However, it has been shown that thick duff beds, at least 10cm deep, dry three times slower than thin duff (Cooper 1985). One week prior to sampling the study area received approximately 47cm of rain. Given this significant rain event in late fall, it seemed reasonable to assume that duff moistures were within an acceptable range of prescribed burning conditions (30-120% for forest floor duff). Yet we found that the average duff mound moisture content for upper and lower duff was 23.36%, below the ignition threshold where ambient duff burns independently of surface fires (Brown et al. 1985). In this instance, failure to properly sample duff moisture content throughout the stand would have caused excess duff mound consumption under these conditions. A better understanding of duff moisture content burning thresholds is necessary to predict consumption from pre-burn sampling data.

Comparison of the DMM600 to oven-dried samples showed moisture contents 11.73 to 12.46% higher with the moisture meter for upper and lower duff, respectively. While the

DMM600 showed similar trends in moisture content found by oven-drying samples, this discrepancy is nonetheless noteworthy. A better understanding of the moisture content thresholds of duff mounds is necessary to interpret the significance of this difference. The linear regression equations for upper and lower duff developed in this study will improve accuracy in converting DMM600 output to gravimetric moisture content results. We found that when using this device, the higher bulk density values common in lower duff correspond more closely to the standard 0.34g/cm^3 compressed bulk density used for the calibration to gravimetric moisture content. Due to low bulk densities typical of upper duff, accurate measurement of upper duff samples with the DMM600 requires calculation of compressed bulk density for a number of duff samples, followed by the calibration procedure to gravimetric moisture content used for lower duff.

The majority of researchers and field personnel commonly work with gravimetric moisture content, yet the DMM600 generates output as volumetric moisture content. The DMM600 Calibration Guide aids in conversion from one system to another, yet this requires an additional step in the process which limits the usefulness of the tool and introduces another level of possible inaccuracy. The DMM600 is a useful tool for observing trends in moisture content in the field, but results should be confirmed by oven-drying samples.

Mineral Content

Properties such as mineral content and bulk density may vary by microsite as a result of freeze/thaw processes, insect and small animal activities, overland flow, windthrow or management activities (Hartford 1989). Mineral content of duff therefore displays natural variability fixed by the origin of the sample. While moisture content can be expected to change noticeably over time and in short lateral distances due to interception of precipitation by tree crowns and variable drying rates due to different sun exposure, mineral content would not be expected to change as dramatically (Hungerford et al. 1995). Moisture limits would therefore dictate smoldering combustion as mineral content levels would be relatively constant. Yet results from the current study suggest otherwise. We found areas in the lower duff where mineral content exceeded 64%. It can be assumed that such exceedingly high mineral content levels would inhibit the spread of smoldering combustion. The higher the inorganic ratio the lower the duff moisture must be for independent consumption (Frandsen 1987). Further study of mineral content ignition thresholds is needed to better understand combustion potential in duff mounds.

Bulk Density

Results show that upper and lower duff differ by compaction, or bulk density. Bulk density is a measure of mass within a sample relative to the volume occupied by the sample (Frandsen 1987). This measurement is important due to its influence on diffusivity, which plays a key role in the heat transfer rate from the heat generating oxidation zone to the unburned duff (Miyanishi and Johnson 2002). Increasing bulk density has been shown to lower the probability of ignition, especially at high moisture levels (Hartford 1989). The combustion rate of duff increases with decreasing total bulk density (Wein 1983). Bulk density is commonly reported as an important variable in combustion studies, yet little is known about the variability of this factor in the field.

Bulk density of duff is often held constant in combustion experiments. An average duff bulk density near 0.10g/cm^3 is a common value for coniferous forests (Hungerford 1995). Results from the current study show a broad range of bulk densities for lower duff (max=0.4980g/cm^3, mean=0.1943 g/cm^3), which may account for some of the differences between upper and lower duff consumption. Ignition points within upper duff are further spatially distributed than lower duff, which may impede sustained smoldering as the heat source must connect a larger matrix of combustible material. Further research examining combustion limits at different bulk densities would be useful in better defining this relationship.

<u>Composition</u>

Defining differences in the composition of duff layers may be useful in understanding duff consumption, as various organic particles in duff have different burning properties. We found that the composition of lower duff was dominated by fine material, with a secondary bark component. Fine material is comprised of bark, needle litter and other organic materials in the latter stages of decomposition. Upper duff is mainly composed of bark, fine material, and needle litter. The investigation of the average mineral content for the main duff components may explain some of the variability in mineral contents found in lower duff samples. Samples with a higher proportion of fine material will be more likely to show high mineral contents; conversely, samples composed of primarily bark flakes and needle litter will have lower mineral contents.

<u>Depth</u>

Duff depth determines whether the heat generated by vertical oxidizing is sufficient to compensate for convective heat loss from the surface of the duff (Miyanishi and Johnson 2002). Assuming horizontal propagation of smoldering, a thick fuel bed will have a larger zone of oxidation causing more heat to be trapped within the fuel bed and not lost convectively to air above (Miyanishi and Johnson 2002). Deep duff, such as the case in duff mounds, is a contributing factor in the propagation of smoldering combustion. Previous laboratory studies have revealed a positive relationship between moisture content and duff depth using peat moss (Miyanishi and Johnson 2002). Given the predictive capabilities of the lower duff moisture content on consumption in ponderosa pine stands (Harrington 1987), we tested for a relationship between duff depth and lower duff moisture content. We found a slight increase in moisture content as duff depth increased, yet the relationship was not significant over this range of moisture contents. Duff depth only accounted for 3.5% of the variability in lower duff moisture content, indicating duff depth is a poor indicator of lower duff moisture content.

Ryan and Frandsen (1991) reported that duff depth increases with tree diameter and decreases with distance from the bole. Results from this study support this finding, as tree size explained 28.8% of the variability in duff depth. Average pre-burn duff depth can also vary by cardinal direction, with a trend towards deeper duff on the uphill and windward directions (Ryan and Frandsen 1991). Results from the current study did not find a relationship between duff depth and sample location. Total duff depth on the uphill and downhill sides of the mound averaged 10cm.

This study did not find a difference between uphill and downhill duff for any response variable. Sampling location results indicate that moderate hill slopes (10-15% in this case) and prevailing winds (north) did not significantly influence differences in the consumption variables of duff mounds. However, it may be possible on this site that the effect of slope (north-facing) and prevailing wind direction (north) negate one another, as the lee side of the tree was uphill.

Recommendations

When applying fire to long-unburned but fire-dependent ecosystems, managers must pay close attention to basal duff accumulations. Due to the novelty of this fuel type, difficulties in field measurement, and a shortage of information, pre-burn duff mound sampling is often overlooked. The objective of this study was to fill knowledge voids about duff characteristics that are important to combustion. The information gained will improve the efficiency and accuracy of sampling techniques. Moisture content, mineral content, bulk density and depth should be sampled from both upper and lower duff layers and from multiple trees within the burn area. Mineral content, bulk density, and depth would not be expected to change in the weeks prior to burning, and may be sampled when convenient. Moisture content is a dynamic variable and should be sampled in the days and hours prior to burning. Such pre-burn sampling entails additional preparation before burning, but will result in a reduction of fire-induced tree injury in valuable old-growth stands.

The DMM600 is a useful tool for showing trends in moisture content, yet we do not recommend use of this tool in the field for accurate duff moisture measurement until an relationship between its analog values and actual moisture is developed. We recommend using this tool to monitor moisture content of lower duff informally, but accurate measurement of moisture content prior to burning should be conducted by oven-drying samples.

Although the basic relationships have been described for typical ambient duff conditions, the ability to predict burning characteristics of duff mounds at the base of old trees is poor. The First Order Fire Effects Model (FOFEM), which includes a duff consumption model, does not accurately predict duff consumption when the duff is deep, as it typically is at the base of long-unburned old pines (Hood et al. 2007). This stresses the need for future research examining the relationship between forest floor duff and basal accumulations of duff. Neither smoldering nor observed tree response to duff mound burning can be adequately predicted by current fire effects modeling software (Hiers et al. 2005).

Fuels on the surface, ground and canopy will continue to accumulate in the absence of fire, or biomass removal, thereby increasing the risk of uncharacteristically severe, stand-replacing fire. Prescribed fire may be employed to treat these excess fuel conditions, yet a the broader challenge is in understanding the role of basal accumulations of fuel and tree mortality in long-unburned ecosystems. Individual tree fuel reduction strategies have been utilized to address the same problem, yet such methods are expensive and time consuming. Raking duff mounds has had varying success in preventing tree injury (Hood 2009, Swezy and Agee 1991). Extinguishing fires in individual duff mounds may save large old trees at small scales, but a more efficient approach is needed.

Characterization of moisture gradients of duff mounds prior to burning, coupled with an assessment of onsite mineral content, bulk density and depths will provide valuable information to fire managers who face these challenges. This information will help limit large tree mortality by providing appropriate prescribed burn conditions where fuel reduction goals can be accomplished. Planning burn prescriptions to account for sustained smoldering and limit excessive duff consumption is integral to the success of restoration burning in fire excluded ecosystems. Duff consumption models are needed by managers that allow for assignment of values for moisture content, mineral content, depth, and bulk density. Such models would enable the information gleaned from this study to be applied to efficient and effective pre-burn duff sampling protocols.

Table 1. Analysis of variance by response variable

Factor	DF	Sum of Squares	Mean Square	F-Ratio	P-value
Moisture Content					
Sample location	1	48.185	48.185	1.04	0.314
Layer	1	523.883	523.883	5.44	0.024*
Mound	43	7073.009	164.489	5.03	0.000*
Sample location x Layer	1	11.256	11.256	0.34	0.560
Depth					
Sample location	1	0.023	0.023	0.00	0.983
Layer	1	215.392	215.392	44.15	0.000*
Mound	60	1076.277	17.938	8.17	0.000*
Sample location x Layer	1	1.291	1.291	0.59	0.446
Mineral Content					
Sample location	1	33.051	33.051	0.33	0.578
Layer	1	9716.313	9716.313	34.48	0.000*
Mound	9	2975.631	330.626	3.44	0.040*
Sample location x Layer	1	36.519	36.519	0.38	0.553
Bulk Density					
Sample location	1	0.0000	0.0000	0.00	0.950
Layer	1	0.0878	0.0878	9.50	0.013*
Mound	9	0.0647	0.0072	2.99	0.059
Sample location x Layer	1	0.0031	0.0031	1.31	0.282

*Significant at the 0.05 level

Table 2. Sampling site moisture content characteristics (Gravimetric Moisture Content%)

Duff Layer	***N***	**Min.-max. (%)**	**Mean**	**s.e.**
	Upper Duff			
Uphill	44	8.34-53.75	25.36	1.4096
Downhill	44	10.26-44.47	22.39	1.1904
	Lower Duff			
Uphill	44	9.74-56.13	24.84	1.6842
Downhill	44	9.89-39.19	20.86	1.2168

Table 3. Sampling site depth characteristics (cm)

Duff Layer	***N***	**Min.-max. (%)**	**Mean**	**s.e.**
	Upper Duff			
Uphill	44	1-11	4.32	0.1094
Downhill	44	1-13	4.17	0.1189
	Lower Duff			
Uphill	44	1-17	6.05	0.1959
Downhill	44	1-20	6.19	0.2651

Table 4. Sampling site mineral content characteristics (%)

Duff Layer	***N***	**Min.-max. (%)**	**Mean**	**s.e.**
	Upper Duff			
Uphill	44	2.29-5.73	3.43	0.3174
Downhill	44	1.78-7.73	3.53	0.6549
	Lower Duff			
Uphill	44	6.96-63.35	36.51	6.6127
Downhill	44	11.34-64.57	32.79	6.0417

Table 5. Sampling site bulk density characteristics (g/cm^3)

Duff Layer	***N***	**Min.-max. (%)**	**Mean**	**s.e.**
	Upper Duff			
Uphill	44	0.0618-0.1406	0.0909	0.0080
Downhill	44	0.0358-0.2111	0.1103	0.0161
	Lower Duff			
Uphill	44	0.0852-0.4980	0.2023	0.0364
Downhill	44	0.0748-0.3509	0.1863	0.0301

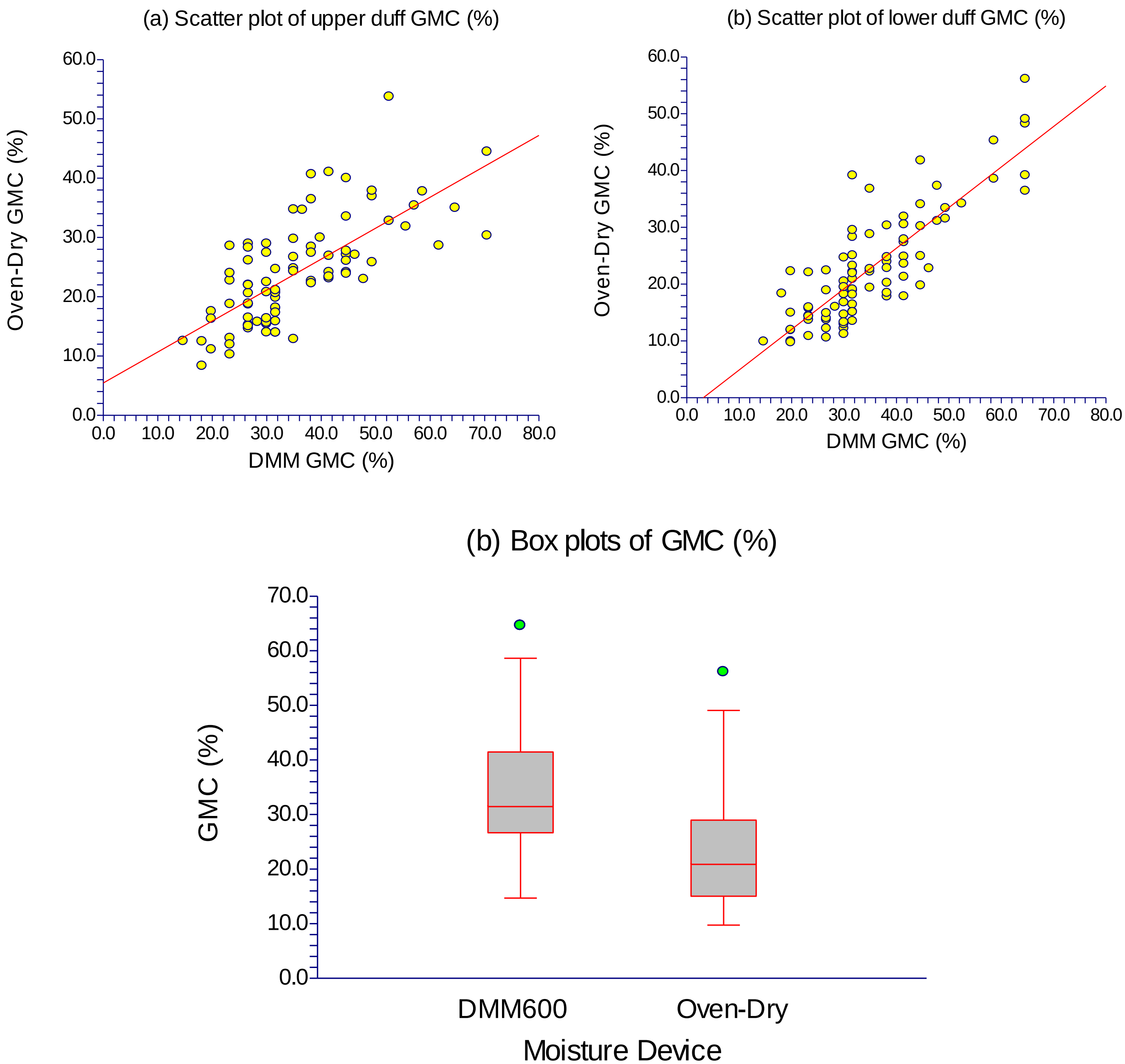


Figure 1. (a/b) Linear regression plot of the relationship between oven-dry duff samples and DMM600 results (n=85)(a: R^2=0.497 , b: R^2=0.697). (c) Box plots of DMM600 and oven-dry moisture contents.

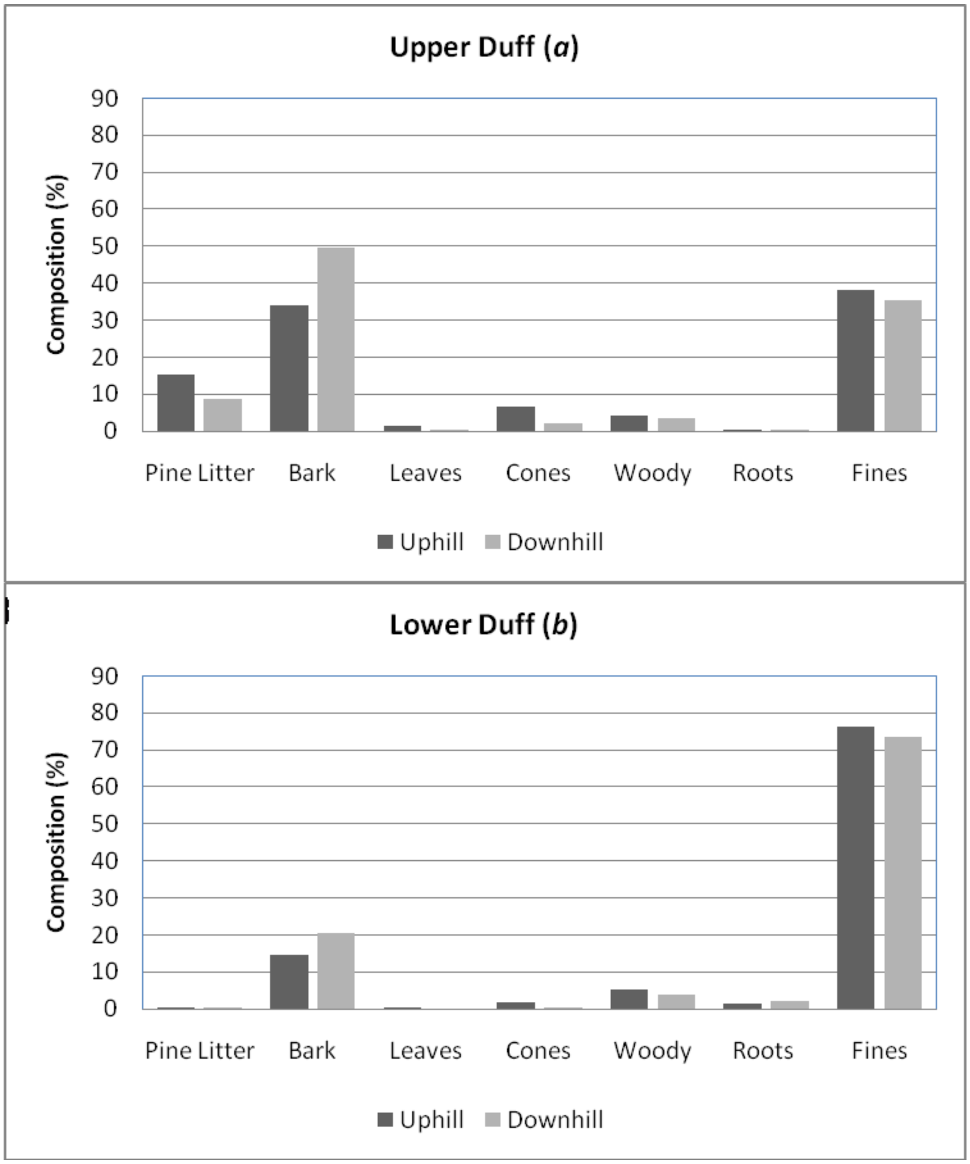


Figure 2. (*a)* Bar chart of upper duff composition by average percent of each component. (*b*) Bar chart of lower duff composition by average percent of each component.

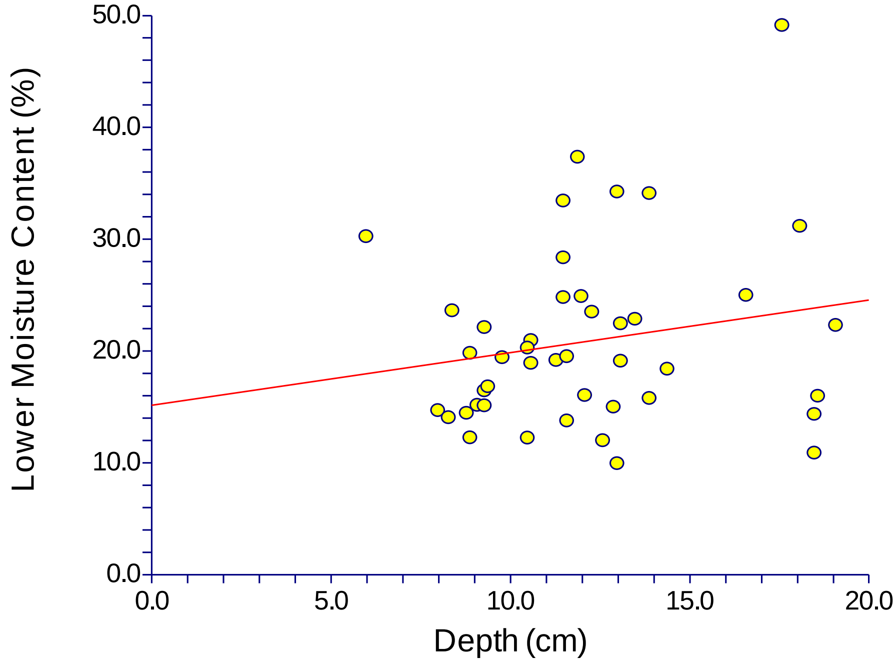


Figure 3. Linear regression plot of the relationship between lower duff moisture content and depth (cm) (R^2= 0.035).

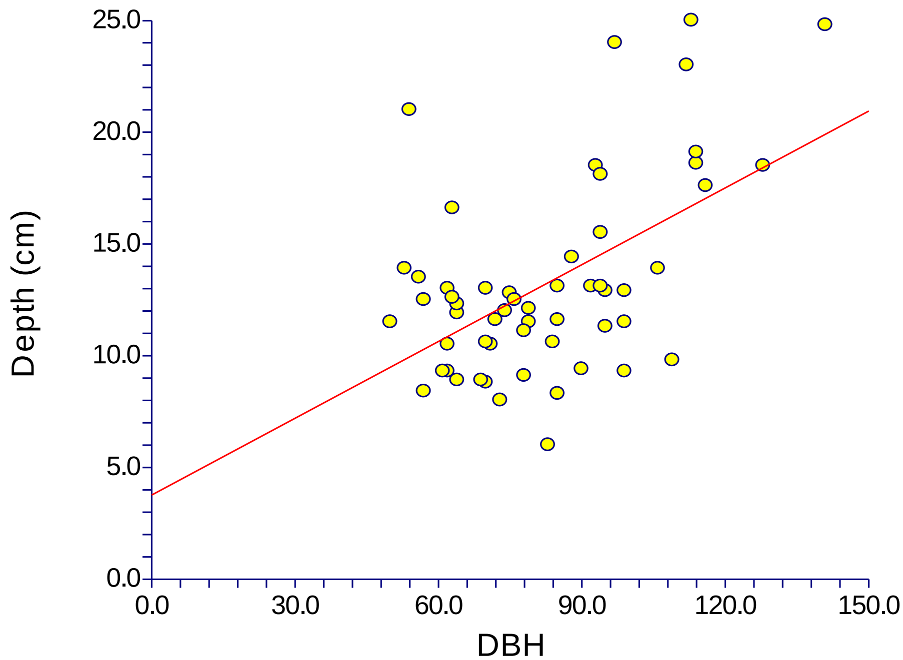


Figure 4. Linear regression plot of the relationship between depth (cm) and tree size (R^2=0.288).

References

Anderson HE (1982) Aids to determining fuel models for estimating fire behavior. USDA Forest Service, General Technical Report INT-122. pp 22.

Brown JK, Marsden MA, Ryan KC, Reinhardt ED (1985) Predicting duff and woody fuel consumed by prescribed fire in the Northern Rocky Mountains. USDA Forest Service, Research Paper INT-337. pp 23.

Cooper KL (1985) The occurrence of a dry lower duff layer in Western Washington and Oregon. M.S. thesis. College of Forest Resources, University of Washington, Seattle.

Ferguson SA, Ruthford JE, McKay SJ, Wright D, Wright C, Ottmar A (2002) Measuring moisture dynamics to predict fire severity in longleaf pine forests. *International Journal of Wildland Fire* **11,** 267-279.

Frandsen WH (1987) The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Canadian Journal of Forest Research* **17,** 1540-1544.

Fry DL, Stephens SL (2006) Influence of humans and climate on the fire history of a ponderosa pine-mixed conifer forest in the southeastern Klamath Mountains, California. *Forest Ecology and Management* **223,** 428-438.

Harrington MG (1987) Predicting reduction of natural fuels by prescribed burning under ponderosa pine in southeast Arizona. USDA Forest Service, Research Note RM-472.

Hartford RA (1989) Smoldering combustion limits in peat as influenced by moisture, mineral content and organic bulk density. In 'Proceedings of the 10^{th} Conference on Fire and Forest Meteorology Ottawa, Ontario'. (Eds DC Maciver, H Auld, R Whitewood) pp 282-286. (Forestry Canada, Netawawa Forestry Institute: Chalk River, ON.)

Hawkes BC (1993) Factors that influence peat consumption under dependent burning conditions: a laboratory study. PhD Thesis, University of Montana, Missoula.

Hiers KJ, Gordon DR, Mitchell RJ, O'Brien JJ (2005) Duff consumption and southern pine mortality. *Joint Fire Science Project* 01-1-3-11.

Hood S (2009) Prescribed Burning and Big Trees: Can We Do It Without Killing the Trees? *Joint Fire Science Program*, Fire Science Brief 03-3-2-04.

Hood S, Reardon J, Smith S, Cluck D (2007) Prescribed burning to protect large diameter pine trees from wildfire – Can we do it without killing the trees we're trying to save? *Joint Fire Science Program*, Final Report 03-3-2-04.

Hungerford R, Frandsen W, Ryan KC (1995) Ignition and burning characteristics of organic soils. In 'Fire in wetlands: a management perspective. Proceedings of the Tall Timbers Fire

Ecology Conference, No. 19' (Eds SI Cerulean, RT Engstrom) (Tall Timbers Research Station: Tallahassee, FL.)

Keane RE, Ryan KC, Veblen TT, Allen CD, Logan J, Hawkes B (2002) Cascading effects of fire exclusion in Rocky Mountain ecosystems: A literature review. USDA Forest Service, General Technical Report RMRS-91.

Leonzo CM, Keyes CR (2007) Second-growth encroachment in relictual forest ecosystems at Whiskeytown National Recreation Area, California. Report on file at Whiskeytown National Recreation Area Headquarters, P.O. Box 188, Whiskeytown, California 96095.

Miyanishi K, Johnson EA (2002) Process and patterns of duff consumption in the mixedwood boreal forest. *Canadian Journal of Forest Research* **32,** 1285-1295.

Miyanishi K (2001) Duff consumption. In 'Forest fires: behavior and ecological effects.' (Eds EA Johnson, K Miyanishi) pp 437-475. (Academic Press: San Diego, CA.)

Potts DF, Ryan KC, Zuuring HR (1986) Stratified sampling for determining duff moisture content in mountainous terrain. *Western Journal of Applied Forestry* **1**, 29-30.

Potts DF, Zuuring HR, Hillhouse M (1983) Spatial analysis of duff moisture and structural variability. In 'Proceedings of the 7th Conference on Fire and Forest Meteorology.' Ft. Collins, CO pp 18-21. (American Meteorological Society: Boston, MA.)

Ryan KC, Frandsen WH (1991) Basal injury from smoldering fires in mature pinus ponderosa laws. *International Journal of Wildland Fire* **1**, 107-118.

Stephens SL, Finney MA (2002) Prescribed fire mortality of Sierra Nevada mixed conifer tree species: Effects of crown damage and forest floor combustion. *Forest Ecology and Management* **162**, 261-271.

Swezy DM, Agee JK (1991) Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. *Canadian Journal of Forest Research* **21**, 626-634.

Van Wagner CE, (1972) Duff consumption by fire in eastern pine stands. *Canadian Journal of Forest Research* **2,** 34-39.

Varner JM, Gordon DR, Putz FE, Hiers JK (2005) Restoring fire to long-unburned pinus palustris ecosystems: Novel fire effects and consequences for long-unburned ecosystems. *Restoration Ecology* **13**, 536-544.

Wein RW (1983) Fire behavior and ecological effects in organic terrain. In 'The role of fire in northern circumpolar ecosystems—scientific committee on problems of the environment.' (Eds RW Wein, DA Maclean) pp 81-96. (John Wiley and Sons LTD: Chichester, England)

FACTORS INFLUENCING PONDEROSA PINE DUFF MOUND CONSUMPTION

Abstract

When applying prescribed fire to long-unburned but fire-dependent ecosystems for restoration, fuels treatments, 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 smoldering combustion in ponderosa pine (*Pinus ponderosa*) duff mound fuels. 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 percent consumption were recorded for each burn. The moisture content threshold for smoldering combustion was 57% and 102% respectively for upper and lower duff. Percent consumption was inversely related to moisture content for both layers of duff, and partially dependent on mineral content for lower duff. Results from this study aim to identify important attributes of duff that control the burning process in order to inform prescribed burning decisions.

Introduction

Following decades of fire exclusion, managers are now faced with competing goals of using prescribed fire to reduce hazard fuels and other positive fire effects while protecting large old trees from mortal fire injury. Ironically, large trees which should have the greatest resistance to fire injury are now in many cases at high risk in the reintroduction of fire (Varner et al. 2007). Many fire-adapted species, such as the ponderosa pine (*Pinus ponderosa* Laws.*)*, experience an increased susceptibility to fire injury as they age due to an unnatural accumulation of fuel at the tree base and reduced tree vigor (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 known as smoldering combustion (Frandsen 1987, Miyanishi 2001) which may lead to fire-induced tree injury and subsequent mortality (Swezy and Agee 1991, Varner et al. 2005).

Historically, frequent low-intensity fires maintained fire-adapted stands such as the ponderosa pine (Hiers et al. 2005), controlling competing vegetation, aiding pine regeneration, and keeping fuel loadings light so fires would burn out quickly and with low intensity (Ryan and Frandsen 1991). Prescribed broadcast burning can be an important tool in restoring fire-suppressed old-growth ponderosa pine stands. Such burns can reduce excess fuel and improve stand growth, which may lessen the threat of severe wildfire (Busse et al. 2000). However, smoldering combustion in duff mounds delivers substantial and protracted heat exposure that may lead to fine root mortality and cambial injury, possibly leading to reduced vigor, enhanced susceptibility to bark beetle attack, and potentially tree death (Ryan and Frandsen 1991, Swezy and Agee 1991, Miyanishi 2001, Varner et al. 2007). In addition, smoldering ground fires often produce considerable smoke which may cause health problems and violate air quality standards. Such fires pose considerable risk of escaping fire lines due to their duration and may result in costly mop-up operations (Wein 1983, Heirs et al. 2005). Prediction of forest floor reduction is essential in planning prescribed fires to aid in regeneration of pine species, while minimizing the deleterious results of duff mound consumption.

Prescribed burn plans may indicate a desired range of duff consumption or mineral soil exposure based on site specific objectives. Duff that is too moist to burn insulates mineral soil from heating and protects fine roots beneath and other below ground living tissue (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). Ideally, weather and surface fuel conditions will allow fire to carry through the stand while preventing excessive exposure to heat that may damage or kill trees. 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 smoldering combustion to be the only fire effect consistently related to longleaf pine mortality across scales and treatments.

Combustion

Forest fuels are consumed by either flaming or smoldering combustion. The high packing ratio of duff and relatively high content of lignin which does not release volatiles readily upon heating, prevent rapid enough heat release to sustain flames (Miyanishi 2001). It has therefore been recognized that duff is largely consumed by smoldering combustion (Frandsen 1991, Hungerford et al. 1995, Miyanishi and Johnson 2002), which is characterized by low temperatures of long duration (Wein 1983, Ohlemiller 1995). Smoldering combustion in the duff layer spreads horizontally three orders of magnitude slower than the slowest spreading surface fire (Frandsen 1987). The duff layer is often the single largest fuel fraction of the surface and ground fuels (Finney and Martin 1992), which emphasizes the need to provide managers with improved decision-support of duff burning properties.

Ignition is initiated by a source of heat such as a flame or an ember and occurs when the heat from combustion is sufficient to overcome heat losses (Hungerford et al. 1995). Airflow has been shown to increase the possibility of the transition from smoldering to flaming combustion (Leisch 1983). Smoldering combustion can be thought of as a series of small sequential ignitions that take place until a barrier, such as moisture content, is met. Propagation of smoldering combustion in duff relies on the balance between the energy required to vaporize and drive off water, and the energy released in the combustion process. Given that water requires a large amount of energy to evaporate, moisture content is a significant heat sink in the combustion process (Wein 1983). The properties of duff that influence water holding abilities therefore affect smoldering behavior of the material. Several characteristics of duff – bulk density, mineral content, and moisture content – have been identified as the primary determinants of duff consumption in pine species (Frandsen 1987, Varner et al. 2005). The likelihood that sustained smoldering combustion will take place decreases as any of these properties increase (Hartford 1989). Bulk density and combustion are positively correlated until a threshold where greater bulk densities decrease the likelihood of burning. Densely packed or deep duff may reduce the oxygen concentration and extinguish smoldering combustion. Higher bulk densities have been found to 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 smoldering 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 1983) due to interception of precipitation within drip lines and greater accumulation of fuels under tree crowns. Predicting forest floor consumption from measurable attributes is vital in order to limit the deleterious effects of prolonged smoldering combustion and to achieve management duff reduction goals. The objective of this study is to better define the consumption threshold for duff mounds in a laboratory combustion experiment based on measurable attributes including (1) moisture content, (2) mineral content, and (3) bulk density.

Methods

Study Site Description

This study was conducted in a long-unburned ponderosa pine stand at Whiskeytown National Recreation Area (WNRA) in the southeastern Klamath Mountains, located 13km west of Redding, California, USA (40° 61'N, 122° 66'W). The study area is approximately 6ha and moderately sloping (10-15%) to the north with a prevailing north wind. The elevation is approximately 1650m. The study area is located mid slope, approximately 250m below the summit of Shasta Bally mountain. Soils are well-developed and well-drained, resulting from either andesitic mudflow or granitic/granodiorite parent materials (Fry and Stephens 2006). Average annual rainfall is approximately 105cm.

The stand is dominated by an overstory of relict ponderosa pine, with patchy groundcover dominated by shrub tanoak (*Lithocarpus densiflorus)*, and a thick organic 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* Dougl.) was also present in the overstory. The stand last burned in 1925. Few trees in the stand have either exposed or healed over fire scars, most show no evidence of previous fire history which indicates frequent, low-intensity fires in the past and a lack of sustained smoldering at the base of trees. The area was classified as a closed long-needle pine fuel type (fuel model 9) for fire behavior purposes (Anderson 1982).

<u>Data Collection</u>

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

Experimental 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 November 16 and December 8, 2009 at the Rocky Mountain Research Station, Fire Sciences Laboratory in Missoula, MT.

Duff was wetted prior to 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 cut to a standardized 10 x 10cm size, divided into upper and lower duff by cutting with a butcher's knife, 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 x 10cm 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 4cm deep to ensure full contact with the ignition coil, and no more than 8cm deep due to the depth of the burn box (10cm) 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 2.5cm thick ceramic board that restricted heat loss during the smoldering process, as expected in a duff mound. Ceramic board is non-burning (melting point of 1760^{o}C) and provides an insulating layer between sample material and the 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 Premier Sphagnum commercial peat moss placed in contact with one of the lateral sample edges. Peat was packed to approximately the same depth and bulk density as the duff sample using a flat piece of aluminum slightly smaller than the opening of the burn box. The smoldering spread rate of peat is approximately 3cm/h, which is at the lower end of forest duff spread rates (Frandsen 1987). The 10 x 10cm dimensions of the burn box are therefore sufficient for assessment of the duff burning process, considering the slow rate of spread during the smoldering process in duff and peat (Hungerford et al. 1995).

It has been recognized that duff is primarily consumed by smoldering 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 smoldering 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^2)/short duration (13 min) treatment described by Hawkes (1993). A glowing resistance coil ignited the peat moss which served as an ignition transfer medium. Smoldering 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 smoldering (up to 10min), simulating ignition by a lateral combustion zone similar to field conditions.

Once smoldering peat fire reached the duff material, samples were then observed to determine if unaided smoldering combustion continued. Sample response was recorded as either burned (≤60% consumption), or unburned (>60% consumption). The 60% consumption threshold has been used in previous ignition studies (Reardon et al. 2007), as few outcomes border this threshold. Percent consumption was calculated as 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. Bulk density, mineral content, moisture content, along with success or failure to burn were recorded for each test.

Bulk density was obtained for each sample of upper and lower duff by removing a 10 x 10cm piece from the remainder of the 25 x 25cm 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 standardized length and width of each subsample. Samples were placed in a drying oven at 100^{o}C for 24h to determine dry weight. Bulk density is calculated as the weight of dry organic matter per unit volume. A 1 x 10cm slice of each sample burned was oven-dried to determine moisture content at the time of the burn, then burned in a muffle furnace to obtain initial mineral content. Mineral content was calculated as the ratio of mineral (ash) mass to total oven-dry weight. This measurement was determined by placing oven-dried samples in a muffle furnace at 450^{o}C for 24h. Mineral content and bulk density display naturally variability horizontal and vertical origin of duff and are fixed properties of each sample. Moisture content was adjusted to observe the transition through the ignition limit. Moisture contents were initially prepared over a relatively broad range to capture the ignition limit. Subsequent tests targeted moisture contents based on these preliminary results.

<u>Experimental Design</u>

The following hypotheses were tested based on study objectives, to identify factors and possible interactions which determine percent consumption of duff including: (1) moisture content, (3) mineral content, and (3) bulk density. We hypothesize that there is a significant relationship between moisture content, mineral content and bulk density on percent consumption. As these variables increase, we would expect the percent consumption to decrease, and eventually be unattainable, in both upper and lower duff. All three factors were obtained from each experimental burn. Significance of factors was assessed at alpha=0.05. A total of 100 burn tests were conducted, 50 upper duff and 50 lower duff. Initial regression analysis showed factor effects differed significantly by layer, so further analysis examined upper and lower duff independently.

Multiple regression is commonly used to study the relationship between several independent variables and a dependent variable. In the current study, percent consumption is the dependent variable and the duff properties listed above were independent variables. Multiple regression was used to express a predictive relationship of percent 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, their effect on consumption potential assessed through the multiple regression model. The assumption of linearity for multiple regression was assessed with scatter plots of all variables of interest. Normal probability plots were reviewed for distribution of the residuals, in addition to the *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 the independent variables.

Results

Duff Properties

Duff mound size (length and width) averaged 15cm and 38cm respectively (40% slope). The results show that throughout the stand, upper duff had a narrow range of mineral content of 1.37 to 10.88% (mean=4.19%, SD=2.02) (Figure 1a). Lower duff had more variability than upper duff with mineral content ranging from 4.32 to 80.38% (mean=25.01%, SD=21.71) (Figure 1a) and bulk density range of 0.07 to 0.28g/cm^3 (mean=.15g/cm^3, SD =.05) (Figure 1b). Upper duff bulk density ranged from 0.04 to 0.18 g/cm^3 (mean=.08g/cm^3, SD=.03) (Figure 1b). 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 a 'burn' resulted in 80.07% consumption on average and samples classified as 'no burn' resulted in 22.82% consumption on average. Multiple linear regression showed that moisture content had a highly significant (p=0.0017) effect on consumption (Table 1). Increasing moisture content decreased the likelihood of sustained combustion. Results from experimental burning show that upper duff samples do not sustain smoldering combustion above 57% moisture content (Figure 2a). Moisture content explained only 18% of the variance in combustion. Sustained smoldering in upper duff is variable at moisture contents between 0-57%. 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 0-20% was 61.45%, samples from 20-40% moisture content were consumed 56.92% on average, and samples from 40-60% moisture contents were 45.70%

consumed on average. There is a trend of decreasing percent consumption as moisture class increases. 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 percent 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 below 11%) had opposing burn outcomes, the remainder of the samples seemed to have an equally likely chance of burning regardless of mineral content (Figure 2b). Similarly, samples at both high and low bulk densities had a likelihood of burning (Figure 2c). A report of model selection steps can be found in Table 1. The prediction model (F=11.096) (p=0.0017) for percent consumption is highly significant, but poorly predictive.

Upper consumption equation:

$$\% \text{ Consumption} = 65.328 - 0.4092 * \text{Moisture Content} \quad (1)$$

(Moisture Content 95% CI: Lower= -0.6562, Upper= -0.1622)

Logistic regression was used to obtain an odds ratio of sustained smoldering for upper and lower duff (Table 2). The upper duff moisture content odds ratio represents a decreased chance that duff samples will sustain smoldering 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 smoldering by $[1 - 0.952^5]$ or 0.218 (21.8%).

Laboratory burning: Lower duff

Lower duff samples classified as a 'burn' resulted in 91.28% consumption on average and samples classified as 'no burn' resulted in 23.33% consumption on average. 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. As expected, increasing moisture content decreased percent consumption. A similar relationship was found for mineral content. Results from experimental burning show that lower duff samples did not sustain smoldering combustion above 102% moisture content (Figure 3a). Samples with moisture content from 128.66 to 223.78% (mean=164.07) resulted in 22.53% consumption on average. Sustained smoldering in lower duff is variable at moisture contents between 0-102%. The results indicate an upper threshold for mineral content; no samples with more than 55% mineral content resulted in a burn (Figure 3b). Samples with mineral content 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 percent consumption of lower duff and were therefore not included in the model (Figure 3c). It should be noted that of the lower duff samples that were able to sustain smoldering combustion, over half of the samples were 90-100% consumed.

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 percent consumption is highly significant. The proportion of the variation in the data that can be explained by the model, or r^2, is 0.5722. Moisture content explained 45.0% of the variance in percent combustion in the model and mineral content explained 37.3%.

Lower duff consumption equation:

$$\% \text{ Consumption} = 130.7991 - 0.5472 * \text{Moisture Content} - 1.0959 * \text{Mineral Content} \quad (2)$$

(Moisture Content 95% CI: Lower= -0.7037, Upper= -0.3907)
(Mineral Content 95% CI: Lower= -1.4401, Upper= -0.7516)

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

Frandsen (1987) investigated how moisture content and mineral content affected smoldering combustion, producing a linear estimate of the smoldering limits of peat moss. Adding inorganic material to his samples reduced the moisture limit that had previously permitted smoldering. Results from this study show a similar trend in the lower duff. Figure 4 shows a linear estimate of the 50% probability of consumption threshold with mineral content plotted against moisture content. Elevated levels of these variables lead to a failure to consume. Samples with high moisture contents (above 102%) did not burn. Similarly, smoldering was not sustained in samples with high mineral content (above 55%). There was a linear decrease in the moisture limit with increasing mineral content between extremes. Successful ignitions and consumption take place when moisture and mineral contents are below the 50% probability line. Results from regression analysis indicate a relationship between moisture content and mineral content similar to Frandsen's (1987) findings.

Discussion

Results from previous studies using both forest floor duff and peat moss have shown that the probability of sustained smoldering 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 sustained smoldering 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 percent consumption for both upper and lower duff; as moisture content approaches 57% or 102% respectively, the percent 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. 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 smoldering 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 smoldering 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 smoldering combustion in upper duff may be more greatly affected by low bulk densities, while 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. He reported that peat moss with less than 10% mineral content would not smolder if moisture content was 110% or greater. This finding held true in the current study for lower duff (Figure 4). The mineral content of upper duff had a very narrow range, 1.37-10.88%, which may explain the lack of a significant relationship as values were below the mineral threshold for burning. This study supports Frandsen's findings that increasing moisture content and mineral content decreases the probability of smoldering combustion for lower duff.

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 below 30% moisture content. Wade et al. (1980) state that the upper organic layer will ignite at less than 65% moisture content, then burn progressively wetter layers up to 150% moisture content in longleaf pine forests. 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 upper duff moisture content threshold for combustion to be 57%. No samples above this moisture content were classified as a burn.

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 below 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 less than 150% (Norum 1977, Brown et al. 1985). The combustion limit found in this study was 102% for lower duff, which corresponds well with similar studies of peat moss combustion thresholds.

Contrary to what we had predicted, bulk density was not found to be a significant factor influencing duff consumption. Hartford (1989) 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 percent consumption for this range of field values.

Results from data collected by Garlough of ambient duff moisture on the study site during sampling were inserted to the upper duff consumption model (n=176). Upper duff moisture contents ranged 8.34-44.47% (mean=23.88%) and lower duff moisture contents ranged 9.74-39.19% (mean=22.85%). Based on this range of findings and the predictions of the upper duff consumption equation, burning under these conditions would have resulted in between 47.13% and 61.92% consumption. Similarly, lower duff moisture content findings predicted consumption between 71.38% and 87.50% for this range of moisture contents (calculated with Garlough's average lower duff mineral content of 34.65%). Given a rain event totaling over 47cm within one week of this reported moisture content, such levels of duff mound consumption seem surprisingly high.

Most models of fire-induced mortality predict that survivability increases with tree size, yet some studies of pine ecosystem restoration burns have shown otherwise (Wein 1983). Pine mortality increased with size of tree in dry burns in areas with deep forest floor accumulations

(Swezy and Agee 1991, Stephens and Finney 2002, Varner et al. 2007). 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). Enhancing the understanding of properties relate to smoldering combustion in ponderosa pine duff mounds was the focus of this study.

Reducing the fuel hazard caused by duff mounds is essential to successful restoration burning in fire-dependent old-growth forests. Such fires are an important part of a naturally occurring fire cycle and serve a purpose in reducing fuel loadings and maintaining or creating a mosaic of ecological changes on the landscape. The predictive models in the present study are a tool for the evaluation of ground fire potential. Findings from this work show that consumption in upper duff is constrained by moisture content, and in lower duff is limited by moisture content and mineral content. Results provide a method for evaluating consumption potential in ponderosa pine duff mounds from a northern California old growth stand.

Table 1. Results of multiple regression analysis of upper duff burn response

Model	Factor	P-value	R^2	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	-

*Significant at 0.05 level.

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

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

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

Table 3. Results of multiple regression analysis of lower duff burn response

Model	Factor	P-value	R^2	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
	Bulk Density	0.2300	-	-114.7343	-
Interaction					
	Moisture	0.1548	0.0523	-0.4752	81.2486
	Mineral	0.6975	-	-1.4120	-
	Moisture x Mineral	0.0559	-	0.0579	-
	Moisture	0.0544	0.0826	-1.4646	115.2798
	Bulk Density	0.0956	-	-578.5775	-
	Moisture x BD	0.0629	-	15.4776	-
	Mineral	0.8100	0.0020	-3.2359	82.8680
	Bulk Density	0.8038	-	-180.7157	-
	Mineral x BD	0.7895	-	40.5321	-

*Significant at 0.05 level

Figure 1a. Box plots of sample layer mineral content

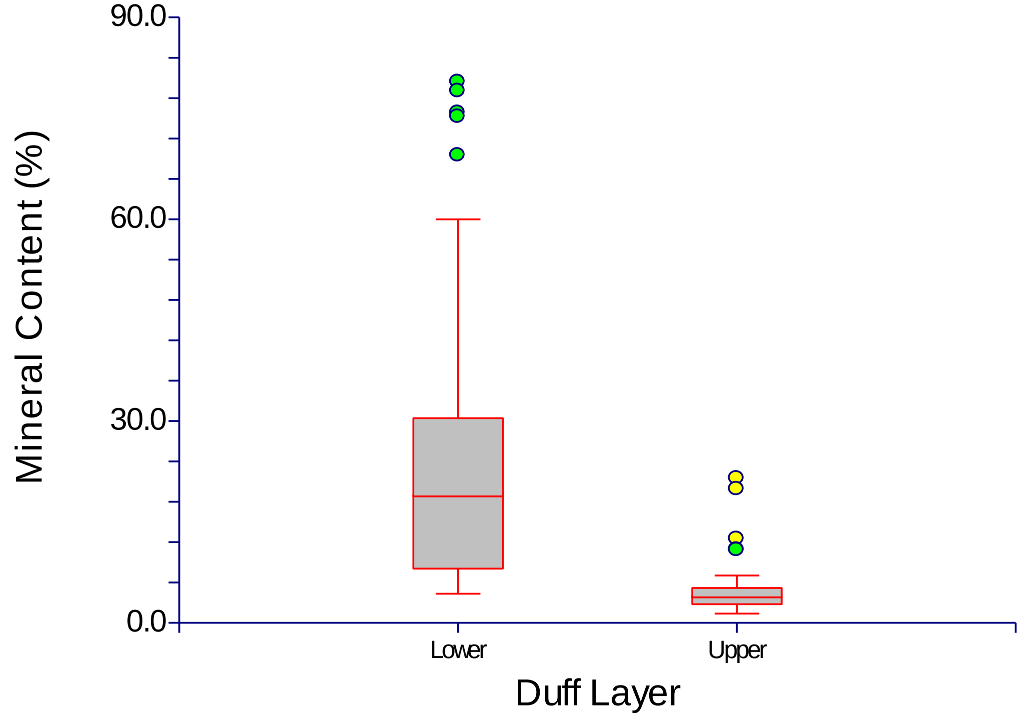
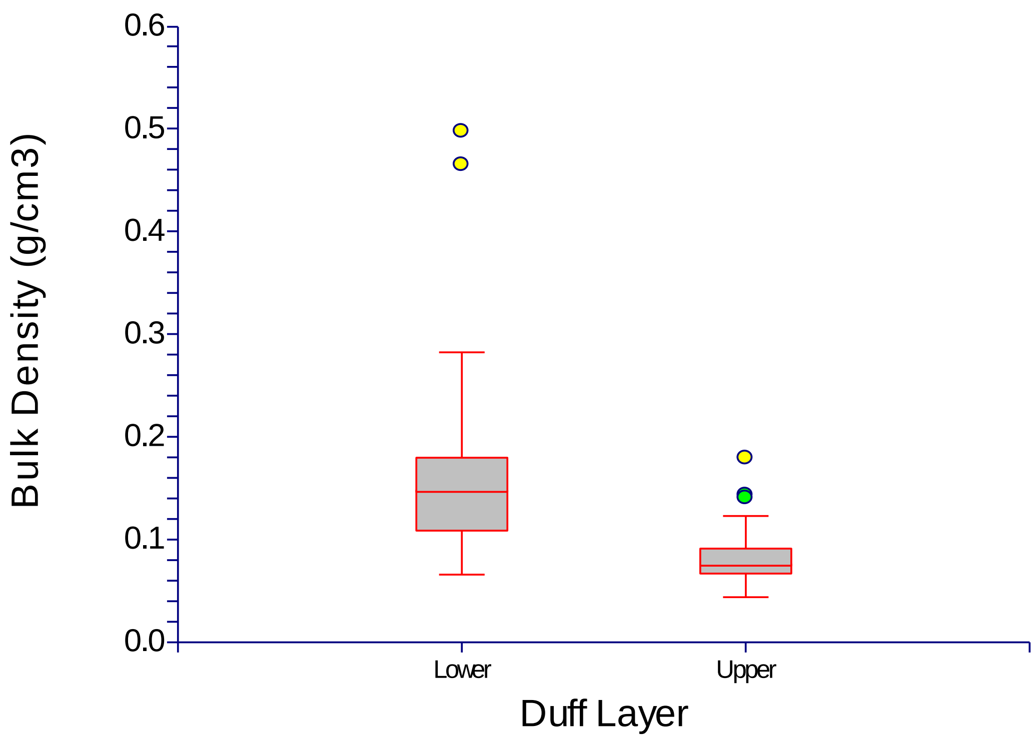


Figure 1b. Box plots of sample layer bulk density



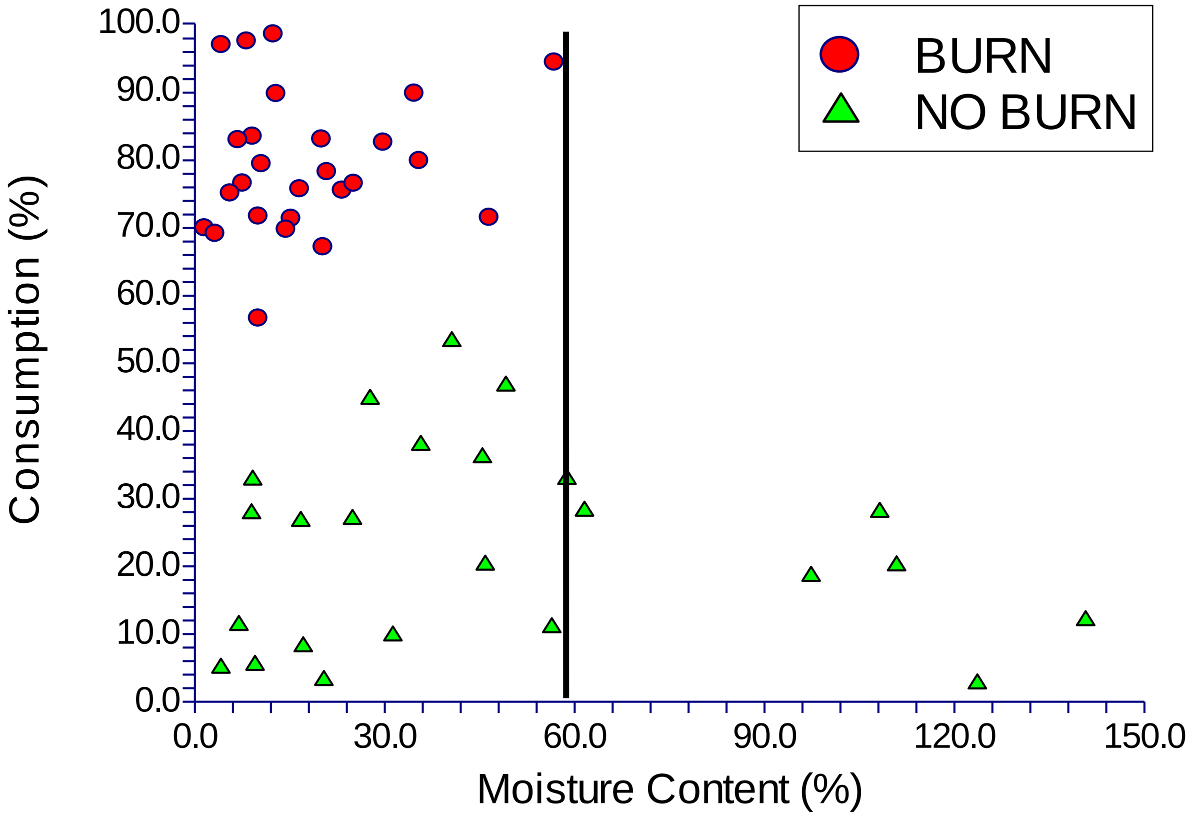


Figure 2a. Scatter plot of upper duff burn outcomes

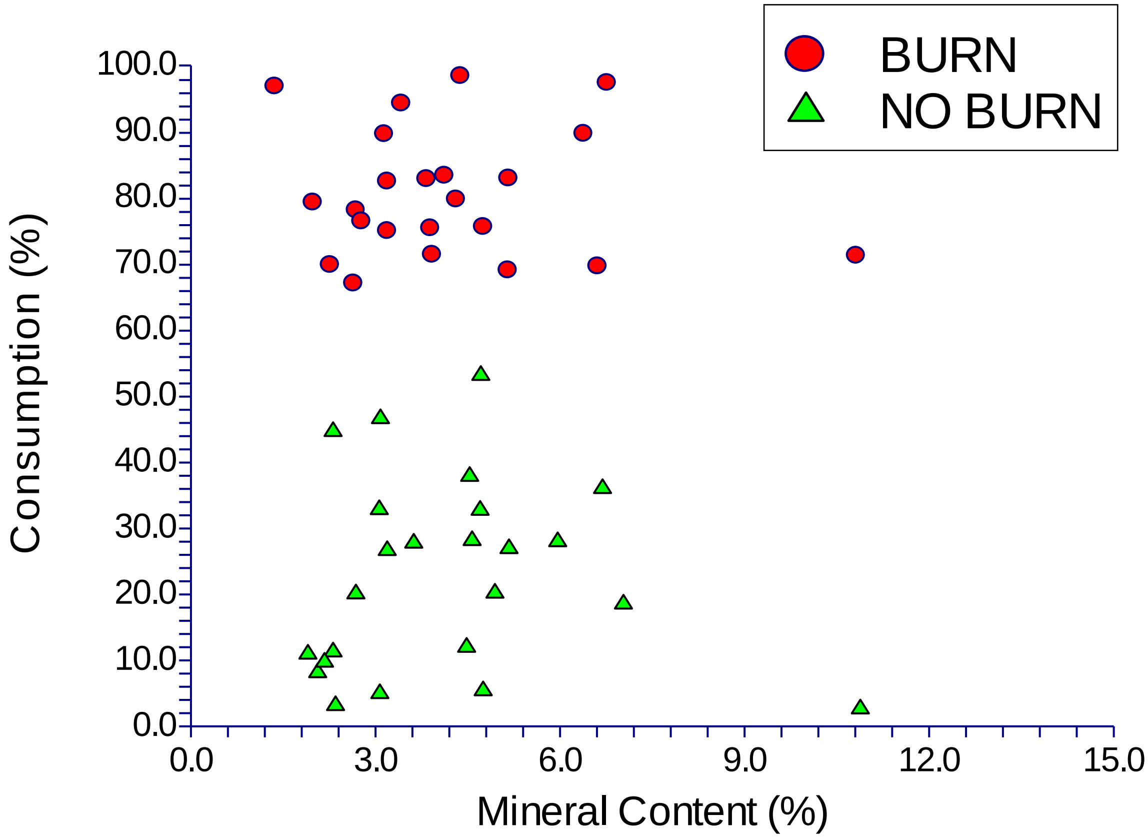


Figure 2b. Scatter plot of upper duff burn outcomes

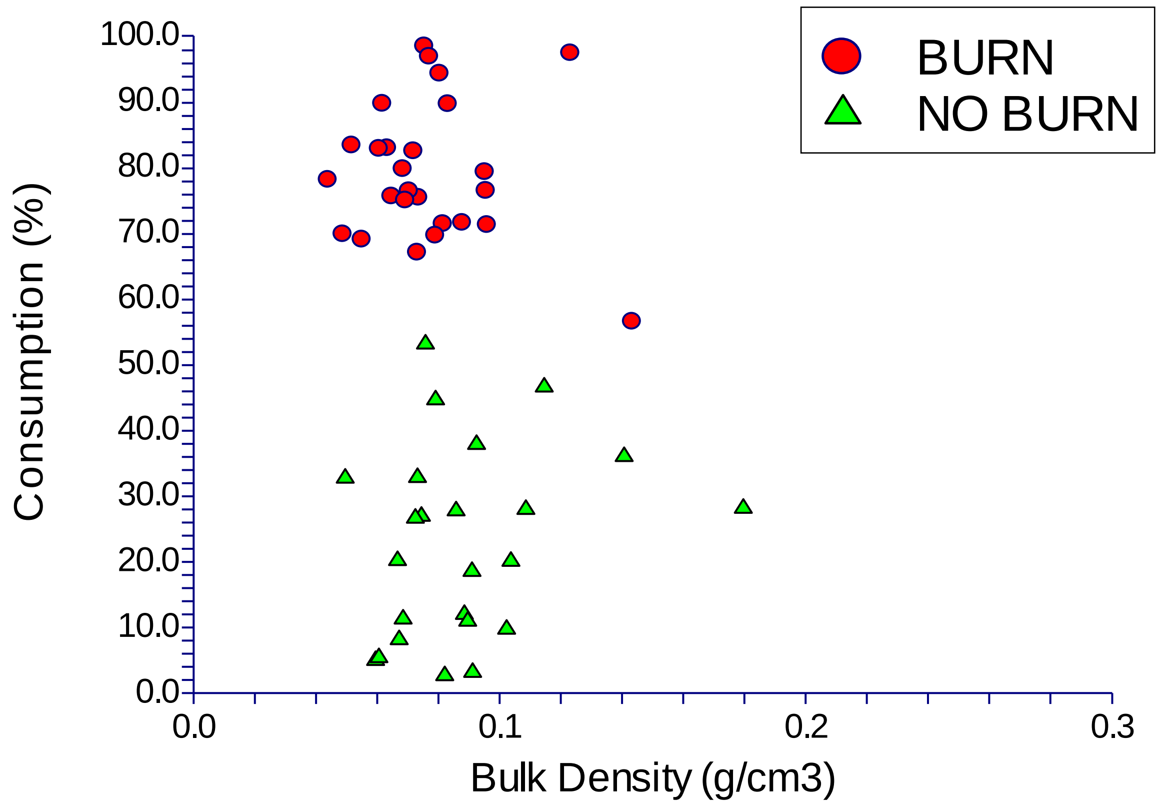


Figure 2c. Scatter plot of upper duff burn outcomes

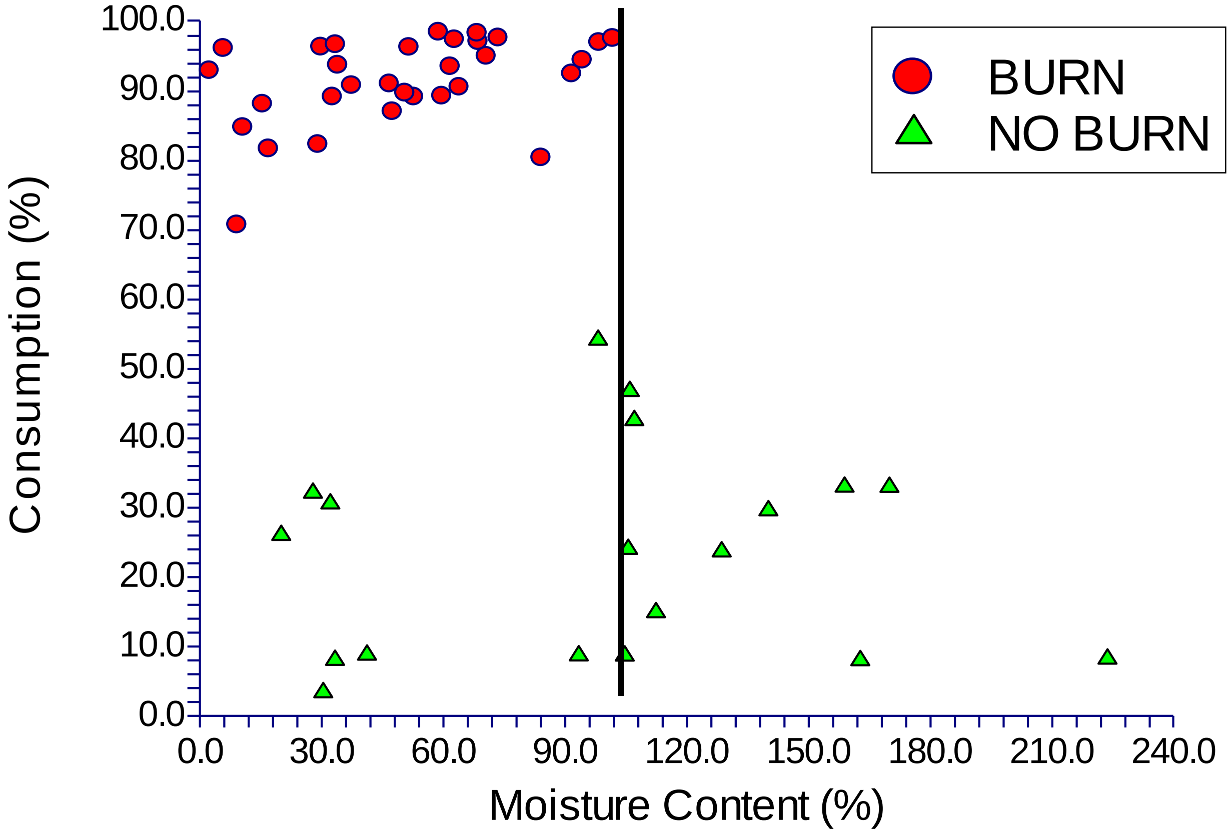


Figure 3a. Scatter plot of lower duff burn outcomes

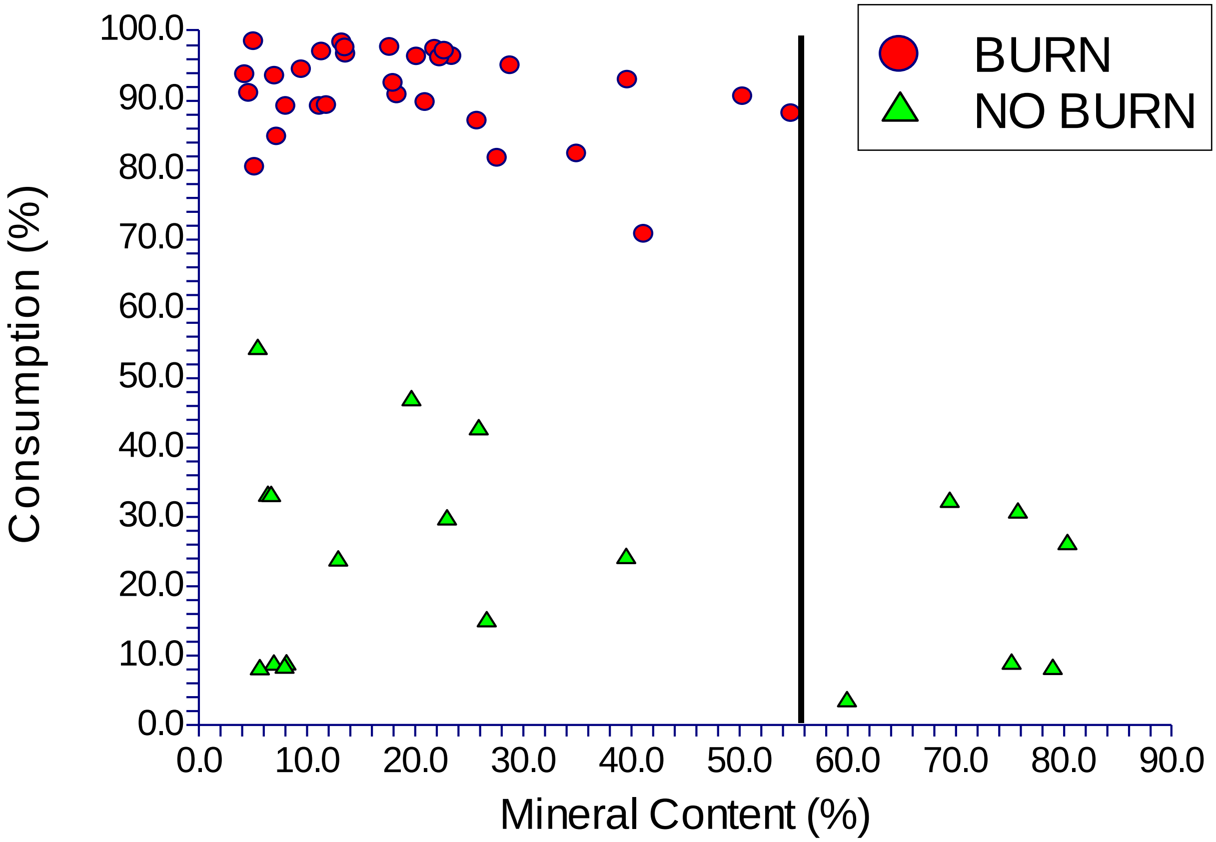


Figure 3b. Scatter plot of lower duff burn outcomes

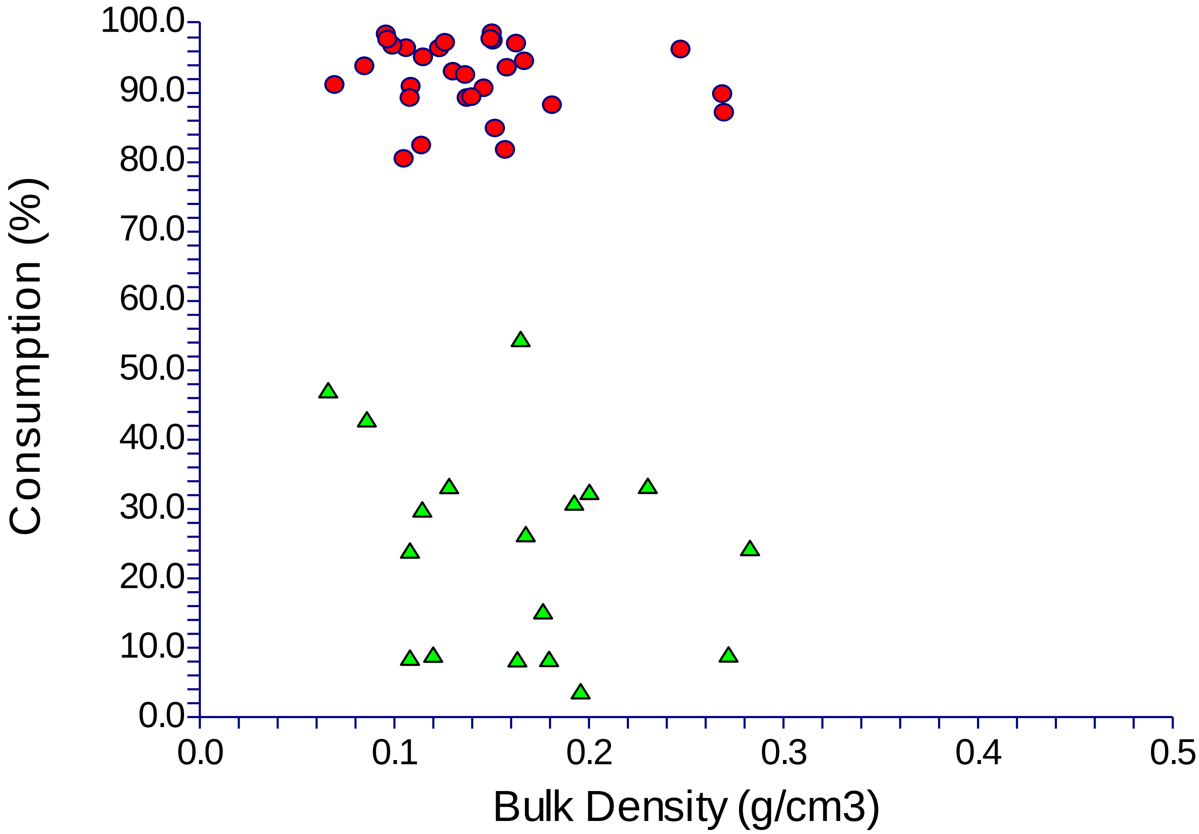


Figure 3c. Scatter plot of lower duff burn outcomes

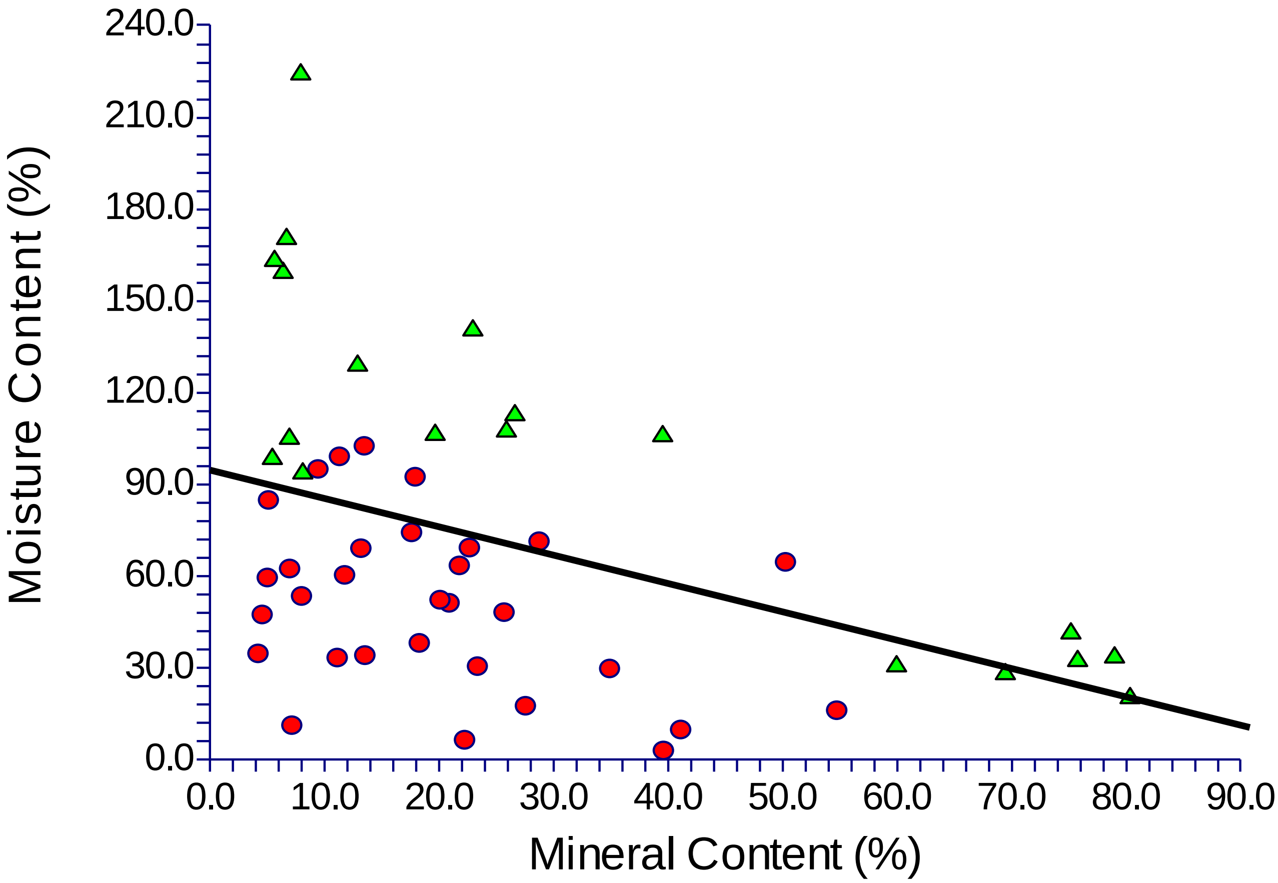


Figure 4. Scatter plot of lower duff consumption

References

Anderson HE (1982) Aids to determining fuel models for estimating fire behavior. USDA Forest Service, General Technical Report INT-122. pp 22.

Brown JK, Marsden MA, Ryan KC, Reinhardt ED (1985) Predicting duff and woody fuel consumed by prescribed fire in the Northern Rocky Mountains. USDA Forest Service, Research Paper INT-337. pp 23.

Busse MD, Simon SA, Riegel GM (2000) Tree-growth and understory responses to low-severity prescribed burning in thinned pinus ponderosa forests of central Oregon. *Forest Science* **46**, 258-286.

Finney MA, Martin RE (1992) Modeling effects of prescribed fire on young-growth coast redwood trees. *Canadian Journal of Forest Research* **23**, 1125-1135.

Frandsen WH (1991) Burning rate of smoldering peat. *Northwest Science* **65**, 166-172.

Frandsen WH (1987) The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Canadian Journal of Forest Research* **17,** 1540-1544.

Fry DL, Stephens SL (2006) Influence of humans and climate on the fire history of a ponderosa pine-mixed conifer forest in the southeastern Klamath Mountains, California. *Forest Ecology and Management* **223,** 428-438.

Hartford RA, Frandsen WH (1992) When it's hot, it's hot…or maybe it's not! *International Journal of Wildland Fire* **2,** 139-144.

Hartford RA (1989) Smoldering combustion limits in peat as influenced by moisture, mineral content and organic bulk density. In 'Proceedings of the 10th Conference on Fire and Forest Meteorology Ottawa, Ontario'. (Eds DC Maciver, H Auld, R Whitewood) pp 282-286. (Forestry Canada, Netawawa Forestry Institute: Chalk River, ON.)

Hawkes BC (1993) Factors that influence peat consumption under dependent burning conditions: a laboratory study. PhD Thesis, University of Montana, Missoula.

Hiers KJ, Gordon DR, Mitchell RJ, O'Brien JJ (2005) Duff consumption and southern pine mortality. *Joint Fire Science Project* 01-1-3-11.

Hungerford R, Frandsen W, Ryan KC (1995) Ignition and burning characteristics of organic soils. In 'Fire in wetlands: a management perspective. Proceedings of the Tall Timbers Fire Ecology Conference, No. 19' (Eds SI Cerulean, RT Engstrom) (Tall Timbers Research Station: Tallahassee, FL.)

Keane RE, Ryan KC, Veblen TT, Allen CD, Logan J, Hawkes B (2002) Cascading effects of fire exclusion in Rocky Mountain ecosystems: A literature review. USDA Forest Service, General Technical Report RMRS-91.

Leisch SO (1983) Smoldering combustion in horizontal dust layers. PhD Thesis, Michigan State University, East Lansing.

Leonzo CM, Keyes CR (2007) Second-growth encroachment in relictual forest ecosystems at Whiskeytown National Recreation Area, California. Report on file at Whiskeytown National Recreation Area Headquarters, P.O. Box 188, Whiskeytown, California 96095.

Miyanishi K, Johnson EA (2002) Process and patterns of duff consumption in the mixedwood boreal forest. *Canadian Journal of Forest Research* **32,** 1285-1295.

Miyanishi K (2001) Duff consumption. In 'Forest fires: behavior and ecological effects.' (Eds EA Johnson, K Miyanishi) pp 437-475. (Academic Press: San Diego, CA.)

Norum RA (1977) Preliminary guidelines for prescribed burning under standing timber in western larch/Douglas-fir forests. USDA Forest Service, Research Note INT-229.

Ohlemiller TJ (1995) Smoldering combustion. In 'SFPE Handbook of Fire Protection Engineering. 2nd Edition.' (Eds PP DiNenno, D Drysdale, J Hall) pp 171-179. (National Fire Protection Association: Quincy, MA.)

Potts DF, Zuuring HR, Hillhouse M (1983) Spatial analysis of duff moisture and structural variability. In 'Proceedings of the 7th Conference on Fire and Forest Meteorology.' Ft. Collins, CO pp 18-21. (American Meteorological Society: Boston, MA.)

Reardon J, Hungerford R, Ryan KC (2007) Factors affecting sustained smouldering in organic soils from pocosin and pond pine woodland wetlands. *International Journal of Wildland Fire* **16**, 107-118.

Ryan KC, Frandsen WH (1991) Basal injury from smoldering fires in mature pinus ponderosa laws. *International Journal of Wildland Fire* **1**, 107-118.

Sandberg DV (1980) Duff reduction by prescribed underburning in Douglas-fir. USDA Forest Service, Research Paper, PNW-272.

Stephens SL, Finney MA (2002) Prescribed fire mortality of Sierra Nevada mixed conifer tree species: Effects of crown damage and forest floor combustion. *Forest Ecology and Management* **162**, 261-271.

Swezy DM, Agee JK (1991) Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. *Canadian Journal of Forest Research* **21**, 626-634.

Varner JM, Hiers JK, Ottmar RD, Gordon DR, Putz FE, Wade DD (2007) Overstory tree mortality resulting from reintroducing fire to long-unburned longleaf pine forests: the importance of duff moisture. *Canadian Journal of Forest Resources* **37**, 1349-1358.

Varner JM, Gordon DR, Putz FE, Hiers JK (2005) Restoring fire to long-unburned pinus palustris ecosystems: Novel fire effects and consequences for long-unburned ecosystems. *Restoration Ecology* **13**, 536-544.

Wade D, Ewel J, Hofstetter R (1980) Fire in south Florida ecosystems. USDA Forest Service, General Technical Report SE-17.

Wein RW (1983) Fire behavior and ecological effects in organic terrain. In 'The role of fire in northern circumpolar ecosystems—scientific committee on problems of the environment.' (Eds RW Wein, DA Maclean) pp 81-96. (John Wiley and Sons LTD: Chichester, England)

CONCLUDING REMARKS

Crown fires, fire whirls, blow-ups, conflagrations - amidst these rousing phenomena, garnering attention to smoldering duff mounds is a challenge in the dynamic field of fire research. The deleterious effects of duff mound consumption may take several years to become apparent whereas extreme fire behavior leaves immediate and prominent scars. Yet if the goal of burning is to protect large trees and improve forest health, then this rather benign subject deserves some attention.

Relatively little is known about duff mounds as a unique fuel type, other than that excessive duff mound consumption often leads to injury and mortality for large trees. Prolonged smoldering combustion in duff mounds at the base of trees causes cambial injury and fine root mortality, but it is unclear which of these processes ultimately leads to tree death. Previous studies have shown that tree death can be predicted by the amount of cambial injury, but we have yet to determine how tree survival is affected by the combination of cambial death and fine root mortality.

Fine roots in duff mounds remain a somewhat mysterious phenomenon. Theories of tree injury and mortality are linked to rootlets, yet we have very little understanding of how fine root mortality may lead to tree death, the conditions under which fine roots grow within duff mounds, or to what extent trees can survive fine root death. Fine roots are extremely difficult to study unobtrusively in the field and would require an almost unreasonable amount of laboratory work to study in depth. Future research will, however, need to determine which of these second order fire effects - cambial injury or fine root mortality – most contributes to tree death so we can more effectively and efficiently protect large trees when burning in long-unburned stands.

Until this relationship can be established, informed burning decisions must be based on what we do know. The current state of knowledge concerning duff mound consumption indicates the importance of moisture content within upper and lower duff layers, and the importance of mineral content in the lower duff layer. In a recent study of old-growth ponderosa pine duff mounds, we found the upper and lower duff layers to differ significantly among those factors known to influence consumption, including moisture content and mineral content, as well as among the physical properties of depth, bulk density and composition. Although bulk density is commonly thought to be a limiting factor in duff consumption, our study found that the natural range of bulk densities for the upper and lower duff layers fell below the consumption threshold. As a result, we recommend that trees be sampled trees for moisture content of both upper and lower duff layers, and mineral content of lower duff, prior to burning.

We recognize that fire managers have busy schedules leading up to a prescribed burn with concerns over homes, property lines, and air quality. Monitoring weather patterns or days since rain may save time in estimating fuel moistures in an area to be burned. However, our study also revealed the importance of collecting duff mound moisture content data from the field even after extreme rain events. Just six days after an historic rain event totaling 47cm, our field measurements showed that duff moisture content averaged just 23.9% for the upper duff layer, and 22.9% for the lower duff layer. These moisture contents are far below the consumption thresholds we found in the lab, meaning that duff mound consumption would exceed 50% at these moisture contents. This is a rather surprising finding that would have likely resulted in undue tree mortality, had a burn taken place based on weather data alone.

That result points to another area in need of further research: duff mound moisture dynamics. Can the low duff moisture contents we observed after heavy rains be attributed to a hydrophobic nature, whereby rainfall and stemflow are easily shed? Or, to a hydroconductive nature, whereby water rapidly infiltrates the duff and passes through to the mineral soil? What is the relationship of soil characteristics to these moisture dynamics? Temporal study of duff moisture content through the course of a fire season would be challenging but would offer a great deal of insight into duff mound wetting and drying cycles.

Duff mounds may not represent the most exciting topic in fire research, but a better understanding of them can go a long way in preserving our valuable old trees in long-unburned stands.

BIBLIOGRAPHY

Anderson HE (1982) Aids to determining fuel models for estimating fire behavior. USDA Forest Service, General Technical Report INT-122. pp 22.

Brown JK, Marsden MA, Ryan KC, Reinhardt ED (1985) Predicting duff and woody fuel consumed by prescribed fire in the Northern Rocky Mountains. USDA Forest Service, Research Paper INT-337. pp 23.

Brown JK, Reinhardt ED, Fischer WC (1991) Predicting duff and woody fuel consumption in Northern Idaho prescribed fires. *Forest Science* **37**, 1550-1566.

Busse MD, Simon SA, Riegel GM (2000) Tree-growth and understory responses to low-severity prescribed burning in thinned pinus ponderosa forests of central Oregon. *Forest Science* **46**, 258-286.

Cooper KL (1985) The occurrence of a dry lower duff layer in Western Washington and Oregon. M.S. thesis. College of Forest Resources, University of Washington, Seattle.

Ferguson SA, Ruthford JE, McKay SJ, Wright D, Wright C, Ottmar A (2002) Measuring moisture dynamics to predict fire severity in longleaf pine forests. *International Journal of Wildland Fire* **11,** 267-279.

Finney MA, Martin RE (1992) Modeling effects of prescribed fire on young-growth coast redwood trees. *Canadian Journal of Forest Research* **23**, 1125-1135.

Frandsen WH (1997) Ignition probability of organic soils. *Canadian Journal of Forest Research* **27,** 1471-1477.

Frandsen WH (1991) Burning rate of smoldering peat. *Northwest Science* **65**, 166-172.

Frandsen WH (1987) The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Canadian Journal of Forest Research* **17,** 1540-1544.

Fry DL, Stephens SL (2006) Influence of humans and climate on the fire history of a ponderosa pine-mixed conifer forest in the southeastern Klamath Mountains, California. *Forest Ecology and Management* **223,** 428-438.

Harrington MG (1987) Predicting reduction of natural fuels by prescribed burning under ponderosa pine in southeast Arizona. USDA Forest Service Research Note RM-472.

Hartford RA, Frandsen WH (1992) When it's hot, it's hot…or maybe it's not! *International Journal of Wildland Fire* **2,** 139-144.

Hartford RA (1989) Smoldering combustion limits in peat as influenced by moisture, mineral content and organic bulk density. In 'Proceedings of the 10th Conference on Fire and Forest Meteorology Ottawa, Ontario'. (Eds DC Maciver, H Auld, R Whitewood) pp 282-286. (Forestry Canada, Netawawa Forestry Institute: Chalk River, ON.)

Hawkes BC (1993) Factors that influence peat consumption under dependent burning conditions: a laboratory study. PhD Thesis, University of Montana, Missoula.

Hiers KJ, Gordon DR, Mitchell RJ, O'Brien JJ (2005) Duff consumption and southern pine mortality. *Joint Fire Science Project* 01-1-3-11.

Hiers KJ, Laine SC, Bachant JJ, Furman JH, Greene WW, Compton V (2003) Simple spatial modeling tool for prioritizing prescribed burning activities at the landscape scale. *Conservation Biology* **17**, 1571-1578.

Hood S (2009) Prescribed Burning and Big Trees: Can We Do It Without Killing the Trees? *Joint Fire Science Program*, Fire Science Brief 03-3-2-04.

Hood S, Reardon J, Smith S, Cluck D (2007) Prescribed burning to protect large diameter pine trees from wildfire – Can we do it without killing the trees we're trying to save? *Joint Fire Science Program*, Final Report 03-3-2-04.

Hungerford R, Frandsen W, Ryan KC (1995) Ignition and burning characteristics of organic soils. In 'Fire in wetlands: a management perspective. Proceedings of the Tall Timbers Fire Ecology Conference, No. 19' (Eds SI Cerulean, RT Engstrom) (Tall Timbers Research Station: Tallahassee, FL.)

Keane RE, Ryan KC, Veblen TT, Allen CD, Logan J, Hawkes B (2002) Cascading effects of fire exclusion in Rocky Mountain ecosystems: A literature review. USDA Forest Service, General Technical Report RMRS-91.

Leisch SO (1983) Smoldering combustion in horizontal dust layers. PhD Thesis, Michigan State University, East Lansing.

Leonzo CM, Keyes CR (2007) Second-growth encroachment in relictual forest ecosystems at Whiskeytown National Recreation Area, California. Report on file at Whiskeytown National Recreation Area Headquarters, P.O. Box 188, Whiskeytown, California 96095.

Miyanishi K, Johnson EA (2002) Process and patterns of duff consumption in the mixedwood boreal forest. *Canadian Journal of Forest Research* **32,** 1285-1295.

Miyanishi K (2001) Duff consumption. In 'Forest fires: behavior and ecological effects.' (Eds EA Johnson, K Miyanishi) pp 437-475. (Academic Press: San Diego, CA.)

Muraro SJ, Lawson BD (1970) Prediction of duff moisture distribution for prescribed burning. Inform. *Forest Resources Lab,* Report BC-X-49 (Victoria, B.C.)

Norum RA (1977) Preliminary guidelines for prescribed burning under standing timber in western larch/Douglas-fir forests. USDA Forest Service, Research Note INT-229.

Ohlemiller TJ (1995) Smoldering combustion. In 'SFPE Handbook of Fire Protection Engineering. 2nd Edition.' (Eds PP DiNenno, D Drysdale, J Hall) pp 171-179. (National Fire Protection Association: Quincy, MA.)

Potts DF, Ryan KC, Zuuring HR (1986) Stratified sampling for determining duff moisture content in mountainous terrain. *Western Journal of Applied Forestry* **1**, 29-30.

Potts DF, Zuuring HR, Hillhouse M (1983) Spatial analysis of duff moisture and structural variability. In 'Proceedings of the 7th Conference on Fire and Forest Meteorology.' Ft. Collins, CO pp 18-21. (American Meteorological Society: Boston, MA.)

Reardon J, Hungerford R, Ryan KC (2007) Factors affecting sustained smouldering in organic soils from pocosin and pond pine woodland wetlands. *International Journal of Wildland Fire* **16**, 107-118.

Ryan KC, Frandsen WH (1991) Basal injury from smoldering fires in mature pinus ponderosa laws. *International Journal of Wildland Fire* **1**, 107-118.

Sandberg DV (1980) Duff reduction by prescribed underburning in Douglas-fir. USDA Forest Service, Research Paper, PNW-272.

Stephens SL, Finney MA (2002) Prescribed fire mortality of Sierra Nevada mixed conifer tree species: Effects of crown damage and forest floor combustion. *Forest Ecology and Management* **162**, 261-271.

Sweeney JR, Biswell HH (1961) Quantitative studies of the removal of litter and duff by fire under controlled conditions. *Ecology* **42**, 572-575.

Swezy DM, Agee JK (1991) Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. *Canadian Journal of Forest Research* **21**, 626-634.

Van Wagner CE, (1972) Duff consumption by fire in eastern pine stands. *Canadian Journal of Forest Research* **2,** 34-39.

Varner JM, Hiers JK, Ottmar RD, Gordon DR, Putz FE, Wade DD (2007) Overstory tree mortality resulting from reintroducing fire to long-unburned longleaf pine forests: the importance of duff moisture. *Canadian Journal of Forest Resources* **37**, 1349-1358.

Varner JM, Gordon DR, Putz FE, Hiers JK (2005) Restoring fire to long-unburned pinus palustris ecosystems: Novel fire effects and consequences for long-unburned ecosystems. *Restoration Ecology* **13**, 536-544.

Wade D, Ewel J, Hofstetter R (1980) Fire in south Florida ecosystems. USDA Forest Service, General Technical Report SE-17.

Wein RW (1983) Fire behavior and ecological effects in organic terrain. In 'The role of fire in northern circumpolar ecosystems—scientific committee on problems of the environment.' (Eds RW Wein, DA Maclean) pp 81-96. (John Wiley and Sons LTD: Chichester, England)