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Bulk Density and Fuel Loads of Ponderosa Pine and White Fir Forest Floors: Impacts of Leaf Morphology

Abstract

Fire suppression has produced large forest floor fuel loads (ground fuels) in many western coniferous forests. Combustion of the forest floor can produce significant ecological effects due to potentially high fuel loads and proximity to living tissues. Forest floor consumption is estimated from depth changes after burning using species-specific data for bulk density. To quantify forest floor bulk density and fuel loads, 40 white fir and 61 ponderosa pine forest floor samples were randomly collected from Giant Forest. Sequoia National Park. Multivariate ANOVA determined there was a significant difference in both bulk density and fuel load for species and strata. Multiple regression analysis related mean bulk density (Mg ha^{-1} cm^{-1}) of a given stratum to stratum depth and total depth of the forest floor. Bulk density increased non-linearly with profile depth and varied from 5.35–34.97 Mg ha^{-1} cm^{-1} (0.053–0.35 g cm^{-3}) and 1.84–13.92 Mg ha^{-1} cm^{-1} (0.018–0.139 g cm^{-3}) for white fir and ponderosa pine. Bulk density of the lowest stratum in white fir forest floors is approximately four times greater than ponderosa pine. Forest floor fuel load varied from 6.35–146.02 Mg ha^{-1} and 3.68–125.19 Mg ha^{-1}, for white fir and ponderosa pine. Forest floor bulk density and fuel load were non-linearly related to depth for both species but negatively related to total depth for ponderosa pine. Leaf morphology and litter quality of the two species probably affected the bulk density of their forest floors.

Introduction

Prescribed fire is one of the best methods to reduce fuel hazards in coniferous forests (van Wagtendonk 1996, Stephens 1998, Fulé et al. 2001) and its use is forecasted to increase in many areas of the western United States (National Wildfire Coordinating Group 2001). However, the combustion of the forest floor (O_i, O_e, and O_a layers), an organic horizon that contains newly fallen and partially decomposed plant, animal, and microbial residues (McColl and Gressel 1995) can produce significant ecological effects due to potentially high fuel loads and proximity to living tissues (Ryan 1982, Little et al. 1986, Ryan and Frandsen 1991, Sackett and Haase 1992, Graham et al. 1994, Neary et al. 1999, Stephens and Finney 2002).

Wildland fires typically have five phases including pre-ignition, flaming combustion, smoldering combustion, glowing combustion, and extinction (DeBano et al. 1998). Each phase produces different ecosystem effects because of differing energy release rates and proximity to vulnerable tissues (Stephens and Finney 2002). Pre-ignition consists of fuel heating, vaporization of water, and initial chemical decomposition of the fuel (pyrolosis). Flaming combustion is a rapid exothermic reaction that can produce temperatures up to 1400° C depending on fuel characteristics and the rate of oxidation. Smoldering combustion has slow rates of spread, low combustion efficiency, and long durations (tens of minutes to hours). Glowing combustion is the slow oxidation of char residues left over after smoldering combustion. Extinction occurs when fuels are depleted, fuel moisture contents are increased (e.g. rain) to a level where combustion is not sustained, or oxygen or heat is removed.

Forest floor fuels are mostly consumed by smoldering combustion, in either downward spreading or lateral spreading patterns, depending on forest floor characteristics (Frandsen 1987, Kauffman and Martin 1989, Frandsen 1998). Forest fuels that consist of deep litter and duff layers release only a fraction of their energy in the flaming front (Hartford and Frandsen 1992) and the impacts of slow ground fires on the belowground systems are much more severe compared to fast

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moving fires with high flame lengths (Neary et al. 1999).

Duff and litter fuel load equations have been developed for conifers in the southwestern United States, Alaska, and mixed species stands of Sierra Nevada conifers (Agee 1973; Ffolliott et al. 1968, 1976; Barney et al. 1981). Additional Sierra Nevada forest floor fuel load equations have been developed by van Wagtendonk et al. (1998), but they assume homogenous bulk density within strata.

Forest floor fuel load can be large in Sierra Nevada mixed conifer forests, and in one study where the last fire occurred in 1898 averaged 157.5 Mg ha^{-1} (Stephens and Finney 2002). Forest floor consumption during fall prescribed fires is a significant factor in white fir (*Abies concolor*), ponderosa pine (*Pinus ponderosa*), incense-cedar (*Calocedrus decurrens*), and sugar pine (*Pinus lambertiana*) mortality (Stephens and Finney 2002). Basal injury to Rocky Mountain ponderosa pine is also affected by duff depth and duff moisture content during burning (Ryan and Frandsen 1991).

Seasonality of the combustion of the forest floor may produce different ecosystem effects (Howe 1994, Neary et al. 1999). In eastern Oregon, spring prescribed burns in mature ponderosa pine forests with high forest floor fuel loads result in higher mortality as compared to fall burns (Swezy and Agee 1990). Burning reduces fine root dry weight by 50-75% in the upper forest floor profile after spring treatment. Because 75% of active ectomycorrhizal roots occur in organic materials that represent the first 4 cm of the soil depth in the inland northwest, loss of this layer from burning could result in high tree mortality (Harvey et al. 1986). Burning in the spring can retain a large amount of the forest floor, but when the historical fire regime is dominated by late summer and fall fires, the negative effects to other ecosystem components may be large.

In forests where summer drought occurs, fine root production moves deeper into the soil profile where water and nutrients are more available (López et al. 1998, Dicus 2000). Consequently, fall prescribed fires damage a smaller percentage of the fine root mass because roots have moved well below the level of elevated temperatures.

The flammability of western conifer needles has been investigated (Fonda et al. 1998, Fonda 2001). Species such as ponderosa pine are classified as fire resistors because of their high flammability that produced high values of flame lengths, percent fuel combusted, and rate of weight loss. Short needle conifers such as white fir are classified as fire avoiders because their needles contribute little to the fire environment of their communities (Fonda et al. 1998).

Non-uniformity of forest floor bulk density may complicate the process of estimating fuel load from a simple measurement of depth (Finney and Martin 1993). Bulk density of the forest floor may not be uniform and generally increases with depth as the forest floor decomposes.

Fire suppression has produced large forest floor fuel loads in many western coniferous forests. Careful consideration should be given to combustion of the forest floor when planning prescribed fires, and more information on the fuel properties of this system is needed. The objectives of this study are to quantify the physical properties (fuel load, bulk density) of Sierra Nevada ponderosa pine and white fir forest floor profiles. A second objective is to determine if significant differences exist between the forest floor characteristics of these 2 species.

Methods

Forest floor samples were collected in mixed conifer forests at Sequoia National Park, ~ 2200 m above sea level. Forest floor samples were collected within pure, mature, ponderosa pine and white fir stands that had not recorded a surface fire since the late 1800s (Caprio and Swetnam 1995).

Soils in the sampled areas are classified as Pachic Xerumbrepts (Huntington and Akeson 1987). Soils are moderately deep, dark, well to excessively drained acid soils formed in granitic rock residuum. Organic matter content in the surface soils range from 1-12%. Textures range from loamy coarse sands to coarse sandy loams.

Soils are overlain by an organic forest floor horizon and range in depth from 50 to > 150 cm (Huntington and Akeson 1987). Soil profiles are moist from late fall to early summer. From early summer to fall the profiles are usually dry except for the surface horizons, which may be periodically moistened by local thunder showers. The climate of this region is Mediterranean with an average annual precipitation from 1980-1997 of 104.7 cm (Stephens et al. 1999). An average of 3.4 cm of precipitation occurred in the summer months from 1980-1997 (Stephens et al. 1999).

Forest floor sample stratum depth was defined as zero at the top of the litter layer and increased downward until mineral soil dominated the stratum. This orientation was chosen because the measurement of forest floor consumption after fires occurs from the top down (Frandsen 1987, Ryan and Frandsen 1991, Frandsen 1998).

Forest floor samples were stratified by total depth of the forest floor for each 1 cm depth category for white fir, and 2 cm depth category for ponderosa pine. Forest floor material was excavated (removing 1 cm thick strata individually for white fir, 2 cm thick strata individually for ponderosa pine) within a 20 x 20 cm square frame and sample locations were selected randomly.

Forest floor samples were weighed to the nearest 0.01 g after oven drying for 48 hr at 65° C. Samples were ground in a Wiley mill to pass a 2 mm screen and mixed to ensure homogeneous subsampling before being sampled for ash-free dry weight (Kovalevsky 1987, Groeschl et al. 1993).

Inorganic material in the deepest two strata (1 and 2 cm white fir, 2 and 4 cm ponderosa pine) was separated from the combustible organic material in a muffle furnace. Three, 1-2 g subsamples of the two lowest forest floor sample stratum were placed in a porcelain dish and combusted at 300°C for 1 hr and 550°C for 3 hr (Kovalevsky 1987). Residual matter was cooled in a desiccator with a drying agent until at room temperature and weighed to the nearest 0.001 g. The ash-free weight of organic matter in the deepest two strata was determined by subtracting weights of residual ash and mineral content from total sample oven-dry weight (Finney and Martin 1993). Five subsamples from stratum above 3 and 4 cm were randomly selected to determine mineral ash content of the organic material of white fir and ponderosa pine. A t-test was used to determine if significant differences ($P \leq 0.05$) existed in mineral ash content of ponderosa pine and white fir.

A multivariate ANOVA was used to determine if significant differences exist in fuel loads (Mg ha^{-1}) and bulk density (Mg ha^{-1} cm^{-1}) of ponderosa pine and white fir forest floors. Both fuel load and bulk density were used in the model as dependent variables while species (ponderosa pine and white fir) and stratum (0-2 cm, 2-4 cm, and 4-6 cm) were used as independent variables. Comparisons below 6 cm were not possible because this was the maximum depth of white fir forest floors. The SYSTAT statistical package was used to perform this analysis (SYSTAT 2000).

Multiple regression analysis was used to relate mean bulk density (Mg ha^{-1} cm^{-1}) of a given stratum to stratum depth and total depth of the forest floor. Stratum bulk density was calculated by dividing oven dry weight of organic material (with inorganic materials removed in lowest 2 stratum) by sample volume. The weight of forest floor above a given stratum (analogous to consumption, Mg ha^{-1}) was modeled as a function of strata depth and total depth of the forest floor using multiple regression. The SAS statistical package was used to obtain model coefficients (SAS Institute 1989). A significance value of $P \leq 0.05$ was used for all regression models.

Results

We sampled 40 white fir and 61 ponderosa pine profiles of various depths. Duff and litter depth varied from 2 - 6 cm in white fir profiles and 2-16 cm in ponderosa pine profiles, resulting in a total of 133 white fir and 248 ponderosa pine strata. The number of samples in the greatest depth categories was smaller because they were relatively rare. The upper third of each forest floor profile mainly consisted of whole dry needles. The middle of the profile consisted of needles that were broken into small pieces. The materials in the lower third of each profile could not be identified as leaves and occasionally included fine roots and mineral soil.

Mineral ash content of the upper white fir and ponderosa pine forest floor samples was significantly different (means of 6.5% for white fir, 3.5% for ponderosa pine). Strata fuel load and bulk density variable distributions were right skewed so they were log (base 10) transformed, which improved normality. Multivariate ANOVA determined that there was a significant difference in both bulk density and fuel load for species ($P < 0.001$) and strata ($P < 0.001$).

Forest floor fuel load varied from 6.35 – 146.02 Mg ha^{-1} for white fir, and 3.68 – 125.19 Mg ha^{-1} for ponderosa pine. Bulk density varied from 5.35 – 34.97 Mg ha^{-1} cm^{-1} (0.053 - 0.35 g cm^{-3}) for white fir, and 1.84 – 13.92 Mg ha^{-1} cm^{-1} (0.018 - 0.139 g cm^{-3}) for ponderosa pine. Bulk density of white fir and ponderosa pine forest floors increased nonlinearly with profile depth (Figures 1 and 2).

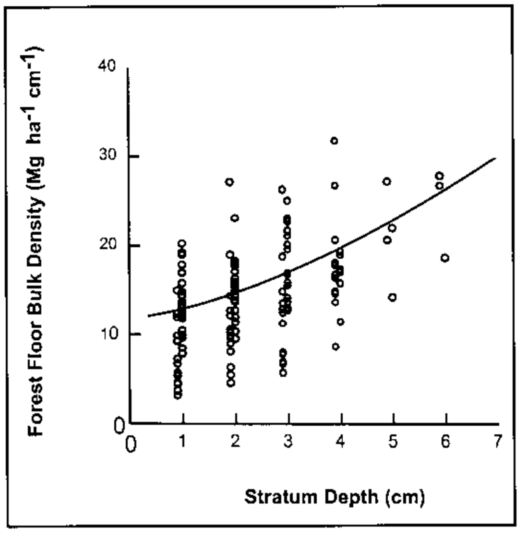

Figure 1. Bulk density of Sierra Nevada white fir forest floors in relation to stratum depth (Eq. 3).

Regression equations describing relationships between forest floor depth, fuel load, and bulk density in white fir and ponderosa pine forest floors are given in Equations 1 - 6. Fuel load equations were derived with and without a y intercept.

$$WFLD = 7.675 + 5.849*Stratum^{1.666} \qquad [1]$$

$$WFLD = 10.394*Stratum^{1.352} \qquad [2]$$

$$WFLD = 11.88 + Stratum^{1.492} \qquad [3]$$

$$PPLD = 4.016 + 3.098*Stratum^{1.297}-0.483*Totaldepth \qquad [4]$$

$$PPLD = 4.06*Stratum^{1.399}-.337*Totaldepth \qquad [5]$$

$$PPBD = 4.203*Stratum^{0.355}-0.155*Totaldepth \qquad [6]$$

Where:

Stratum = strata depth in cm

Totaldepth = total forest floor profile depth in cm

WFLD = white fir fuel load (Mg ha^{-1})

WFBD = white fir bulk density (Mg ha^{-1} cm^{-1})

PPLD = ponderosa pine fuel load (Mg ha^{-1})

PPBD = ponderosa pine bulk density (Mg ha^{-1} cm^{-1})

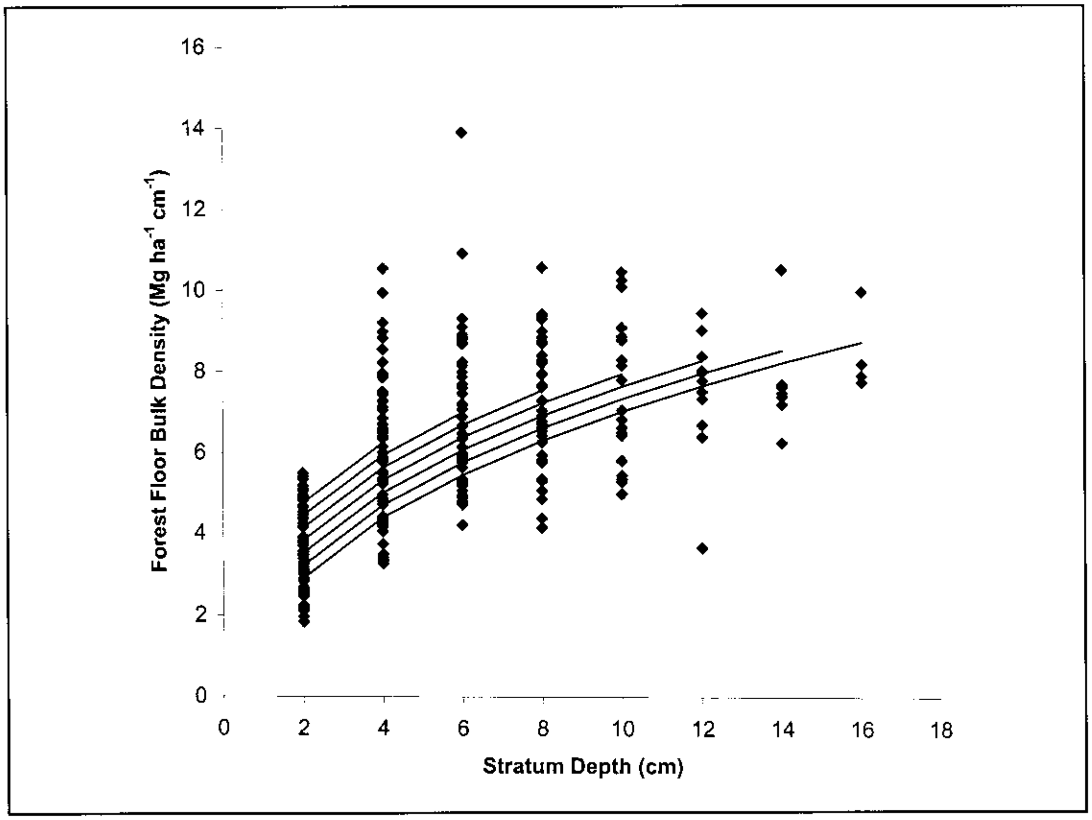

Figure 2. Bulk density of Sierra Nevada ponderosa pine forest floors in relation to stratum depth and total profile depth (Eq. 6, total forest floor depth varied from 2-16 cm).

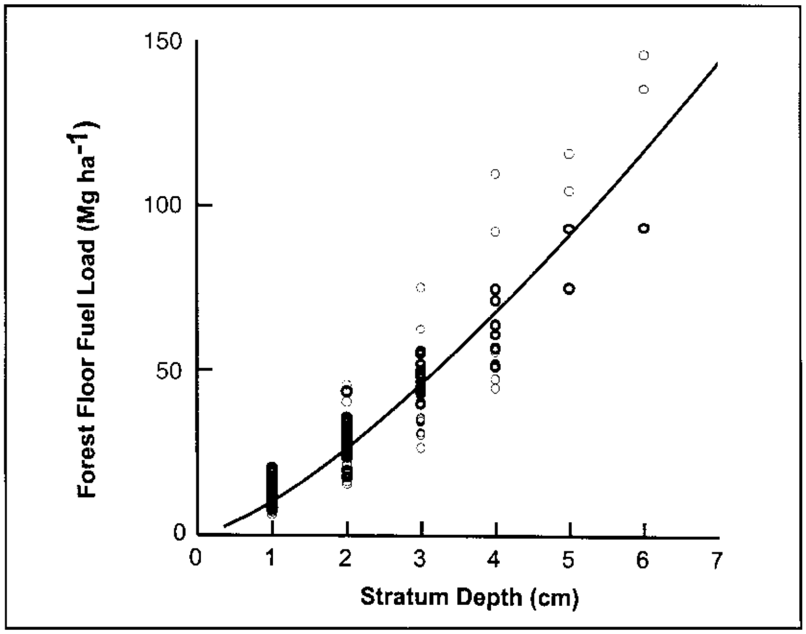

Figure 3. Fuel load of Sierra Nevada white fir forest floors in relation to profile depth (Eq. 2).

Figures 1 and 2 display the original bulk density data and outputs from equations (3) and (6) for white fir and ponderosa pine. Forest floor fuel load and the results from equations (2) and (5) for white fir and ponderosa pine are given in Figures 3 and 4. Fuel load equations without a y intercept (Equations 2 and 5) are preferred because of similar values of r^2 as compared to equations (1) and (4) (r^2 of 0.85 and 0.94 versus 0.86 and 0.94) with the additional benefit of estimating zero load at zero depth.

Bulk density of the lowest ponderosa pine stratum is approximately 8 Mg ha^{-1} cm^{-1} (0.08 g cm^{-3}) regardless of the total forest floor depth (Figure 2). The lowest stratum in white fir forest floors has a bulk density ~4 times greater (30 Mg ha^{-1} cm^{-1}or 0.3 g cm^{-3}).

Discussion

The significance ($P \leq 0.05$) of the regression coefficients suggests that bulk density for both white fir and ponderosa pine increased nonlinearly with stratum depth. The most likely explanation involves the covariance of an age-gradient with forest floor depth. Older litter decomposes and is compacted in deeper layers. However, the exponent for ponderosa pine < 1 (0.355) whereas for white fir it was > 1 (1.492). This relationship indicates a decreasing rate of compactness with increasing depth for ponderosa pine versus an increasing rate of compactness for white fir.

Multiple regression analysis determined that total depth had a significant negative relationship with bulk density and load for ponderosa pine but was not significant for white fir (Equations 1-6). When strata depth is held constant in ponderosa pine forest floors, the relationship between bulk density and load of the overlying material is negatively related to the total depth of the forest floor. A possible explanation may involve a much slower rate of annual litter deposition in white fir stands than ponderosa pine. If the range between maximum and minimum rates of litter accretion to a white fir forest floor is small, the 1 cm sampling scheme may not have enough resolution to reflect the changes in forest floor bulk density related to total depth.

The leaf morphology of the two species probably affected the bulk density of their respective forest floors. White fir has short individual needles (3-4 cm) that allows for higher initial compaction whereas ponderosa pine has long needles (10-14 cm) grouped three per fascicle that would be compacted by subsequent litter fall and the weight of overlying snow. The fascicle in ponderosa pine binds one end of the leaf and its three long

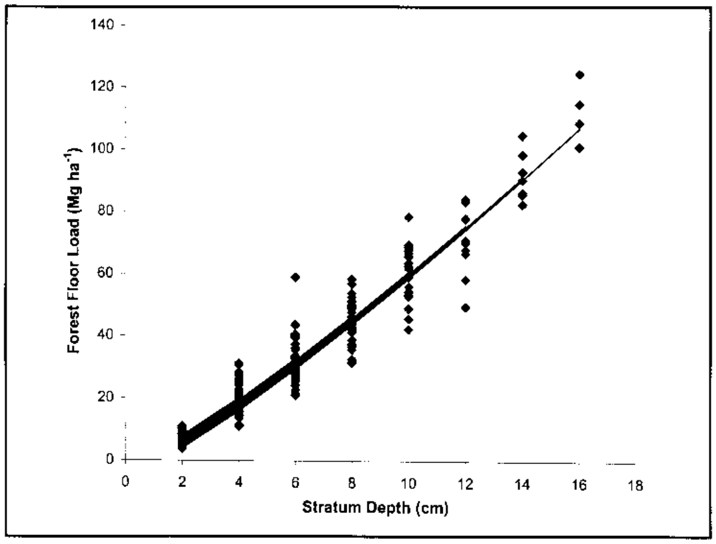

Figure 4. Fuel load of Sierra Nevada ponderosa pine forest floors in relation to stratum depth and total profile depth (Eq. 5, forest floor depth varied from 2-16 cm).

needles protrude out in different directions resulting in a structure that is initially more difficult to compact.

Litter quality differences between the two species also contributes to their differing forest floor bulk densities. Sierra Nevada pine litter decomposes at a slower rate when compared to white fir (Stohlgren 1988), which would further exacerbate the differences in bulk density. White fir forest floors have higher initial bulk density because of leaf morphology and faster litter decomposition would further increase bulk density. Ponderosa pine leaf morphology and litter quality could produce lower bulk density at similar stratum depths.

Maximum forest floor fuel loads for ponderosa pine and white fir were similar (150 Mg ha^{-1} white fir, 125 Mg ha^{-1} ponderosa pine), but the depth of their forest floor profiles differ by a factor of 2.5 (Figures 3 and 4). The more compact white fir profile would release and gain moisture at a slower rate when compared to ponderosa pine. Flaming combustion (DeBano et al. 1998) would produce larger flame lengths in ponderosa pine forest floors because of their lower bulk density.

The spatial arrangement and types of fuels have a strong influence on fire spread, especially when burning conditions are not extreme (Turner and Romme 1994). The flammability of adjacent fuel complexes affects the likelihood that any particular patch in the landscape might burn (Knight 1987). Species composition and fuel characteristics may not foster the spread of a fire once ignited (Despain 1985, Knight 1987), which occurred in Sierra Nevada Jeffrey pine (*Pinus jeffreyi*) forests that were adjacent to forests dominated by short needle red fir (*Abies magnifica*) and lodgepole pine (*Pinus contorta* var. *murrayana*) (Stephens 2001).

All fires except one recorded in the red fir-lodgepole pine forest were also recorded in the adjacent Jeffrey pine forest but an additional 20 fires were uniquely recorded in the more flammable Jeffrey pine (Stephens 2001). Bulk density of the long needle (10-14 cm, 3 needle per fascicle) Jeffrey pine (similar to ponderosa pine) forest floor are lower than the other short needle (3-5 cm) conifers (similar to white fir). Forest floors with lower bulk density will dry at faster rates and will become available for combustion for longer periods during the year. It is possible that some fires would burn in the Jeffrey pine forest but would be extinguished at the ecotone boundary because of changes in forest floor fuel characteristics. The burning characteristics of Jeffrey pine needles indicate that surface fires would be well supported, in contrast to short needle conifer species that would not support a frequent fire regime (Fonda et al. 1998).

Prescribed fire plans commonly specify a minimum forest floor depth and percent cover that should remain after fire (Finney and Martin 1993). Obtaining these desired conditions is difficult in the fall, but is possible when burning is done in the spring. Forest floors without dead and down woody fuels (1, 10, 100, and 1000 hr timelage fuels) will combust completely at moisture contents below 30% (on a dry weight basis) but will not combust at greater than 120% moisture content (Sandberg 1980). Most forest floors have moisture contents < 20% at the end of the fall season in Mediterranean climates (Stephens and Finney 2002) but are > 100 % moisture in the spring (Stocks 1970).

Surface fuels with diameters < 2.5 cm dry quickly in the late spring and early summer and can become available for combustion whereas the forest floor moisture contents are still above the extinction point (DeBano et al. 1998). Complicating spring prescribed burning in many areas are more severe effects to below and above ground systems including soils (Neary et al. 1999), plants (Howe 1994, López et al. 1998), and wildlife (Smith 2000), particularly in areas where historical fires occurred in the late summer and fall.

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Literature Cited

Agee, J. K. 1973. Prescribed fire effects on physical and hydrological properties of mixed-conifer forest floor and soil. Water Research Center Report 143, University of California, Davis, California.

Barney, R. J., C. D. Bevins, and L. S. Bradshaw. 1981. Forest floor fuel loads, depths, and bulk densities in four interior Alaskan cover types. USDA Forest Service Research Note INT-304. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Caprio, A. C., and T. W. Swetnam. 1995. Historic fire regimes along an elevational gradient on the west slope of the Sierra Nevada. Pages 173-179 *In* J. K. Brown, R. W. Mutch, C. W. Spoon, and R. H. Wakimoto (technical coordinators), Proceedings of the symposium on fire in wilderness and park management. USDA Forest Service General Technical Report INT-320. Intermountain Forest and Range Experiment Station, Ogden, Utah.

DeBano, L. F., Neary, D. G., and P. F. Ffolliott. 1998. Fire Effects on Ecosystems. Wiley, New York.

Despain, D. G. 1985. Ecological implications of ignition sources in park and wilderness fire management programs. Pages 93-97 *In* J. E. Lotan, B. M. Kilgore, W. C. Fischer, and R. W. Mutch (technical coordinators), Proceedings of the symposium and workshop on wilderness fire. USDA Forest Service General Technical Report INT-182. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Dicus, C. A. 2000. The relationship of biomass allocation and nutrient dynamics in loblolly and slash pine. Ph.D. Dissertation, Louisiana State University, Baton Rouge, LA.

Ffolliott, P. F., W. P. Clary, and J. R. Davis. 1968. Some characteristics of the forest floor under ponderosa pine in Arizona. USDA Forest Service Research Note RM-127. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Ffolliott, P. F., W. P. Clary, and M. B. Baker. 1976. Characteristics of the forest floor on sandstone and alluvial soils in Arizona's ponderosa pine type. USDA Forest Service Research Note RM-308. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Finney, M. A. and R. E. Martin. 1993. Fuel load, bulk density, and depth of forest floors in coast redwood stands. Forest Science 39:1-5.

Fonda, R. W. 2001. Burning characteristics of needles from eight pine species. Forest Science 47:390-396.

Fonda, R. W., L. A. Belanger, and L. L. Burley. 1998. Burning characteristics of western conifer needles. Northwest Science 72:1-9.

Frandsen, W. H. 1987. The influences of moisture and mineral soil on the combustion limits of smoldering forest duff. Canadian Journal of Forest Research 17:1540-1544.

Frandsen, W. H. 1998. Heat flow measurements from smoldering porous fuel. International Journal of Wildland Fire 8:137-145.

Fulé, P. Z., A. E. M. Waltz, W. W. Covington, and T. A. Heinlein. 2001. Measuring forest restoration effectiveness in hazardous fuels reduction. Journal of Forestry 99:24-29.

Graham, R. T, A. E. Harvey, M. F. Jurgensen, T. B. Jain, J. R. Tonn, and D. S. Page-Dumroese. 1994. Managing course woody debris in the forests of the Rocky Mountains. USDA Forest Service Research Paper INT-477. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Groeschl, D. A., J. E. Johnson, and D. W. Smith. 1993. Wildfire effects on forest floor and surface soil in a table mountain pine-pitch pine forest. International Journal of Wildland Fire 3:149-154.

Hartford, R. A., and W. H. Frandsen. 1992. When it's hot, it's hot ... or maybe it's not (surface flaming may not portend extensive soil heating). International Journal of Wildland Fire 2:139-144.

Harvey, A. E., M. F. Jurgensen, M. J. Larsen, and J. A. Schlieter. 1986. Distribution of active ectomycorrhizal short roots in forest soils of the inland northwest: effects of site and disturbance. USDA Forest Service Research Paper INT-374. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Howe, H. F. 1994. Response of early- and late-flowering plants to fire season in experimental prairies. Ecological Applications 4:121-133.

Huntington, G. L., and M. A. Akeson. 1987. Pedologic investigations in support of acid rain studies, Sequoia National Park, California. Unpublished report on contract CA 8005-2-0002. Department of land, air, and water resources, University of California, Davis. Report on file at research office, Sequoia-Kings Canyon National Parks, Three Rivers, California.

Kauffman, J. D., and R. E. Martin. 1989. Fire behavior, fuel consumption, and forest floor changes following prescribed understory fires in a Sierra mixed conifer forest. Canadian Journal of Forest Research 19: 455-462.

Knight, D. H. 1987. Parasites, lightning, and the vegetation mosaic in wilderness landscapes. Pages 59-83 *In* M. G. Turner (editor), Landscape Heterogeneity and Disturbance. Springer-Verlag, New York.

Kovalevsky, A. L. 1987. Biogeochemical Exploration for Mineral Deposits. VNU Science Press, Utrecht, The Netherlands.

Little, S. N., R. D. Ottmar, and J. L. Ohmann. 1986. Predicting duff consumption from prescribed burns on conifer clearcuts in western Oregon and western Washington. USDA Forest Service Research Paper PNW-362. Pacific Northwest Forest and Range Experiment Station, Seattle, Washington.

López, B., S. Sabaté, and C. Gracia. 1998. Fine roots dynamics in a Mediterranean forest: effects of drought and stem density. Tree Physiology 18:601-606.

McColl, J. G., and N. Gressel. 1995. Forest floor organic matter: characterization and modern methods of analysis. Pages 13-31 *In* W. W. McFee, and J. M. Kelly (editors), Carbon Forms and Functions in Forest Soils. Soil Science Society of America, Madison, Wisconsin.

Neary, D. G., C. C. Klopatek, L. F. DeBano, and P. F. Ffolliott. 1999. Fire effects on belowground sustainability: a review and synthesis. Forest Ecology and Management 122:51-71.

National Wildfire Coordinating Group. 2001. Review and update of the 1995 federal wildland fire management policy. Interagency Fire Center, Boise, Idaho.

Ryan, K. C. 1982. Evaluating potential tree mortality from prescribed burning. Pages 167-179 *In* D. M. Baumgartner (editor). Site preparation and fuels management on steppe terrain. Washington State University cooperative extension, Pullman, Washington.

Ryan, K. C., and W. H. Frandsen. 1991. Basal injury from smoldering fires in mature Pinus ponderosa Laws. International Journal of Wildland Fire 1:107-118.

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Sacket, S. S., and S. M. Haase. 1992. Measuring soil and tree temperatures during prescribed fires with thermocouple probes. USDA Forest Service General Technical Report PSW-131. Pacific Southwest Forest and Range Experiment Station, Albany, California.

Sandberg, D. V. 1980. Duff reduction by prescribed underburning in Douglas-fir. USDA Forest Service Research Paper PNW-272. Pacific Northwest Forest and Range Experiment Station, Seattle, Washington.

SAS Institute. 1989. SAS/STAT users guide, version 6, 4th edition, Vol. 2. SAS Institute Incorporated, Cary, North Carolina.

Smith, J. K. 2000. Wildland fire in ecosystems: effects of fire on fauna. USDA Forest Service General Technical Report RMRS-42 vol. 1. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Stephens, S. L. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed conifer forests. Forest Ecology and Management 105:21-34.

Stephens, S. L. 2001. Fire history of adjacent Jeffrey pine and upper montane forests in the Eastern Sierra Nevada. International Journal of Wildland Fire 10:161-176.

Stephens, S. L., D. Dulitz, and R. E. Martin. 1999. Giant sequoia regeneration in group selection openings of the southern Sierra Nevada. Forest Ecology and Management 120:89-95.

Stephens, S. L., and M. A. Finney. 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.

Stocks, B. J. 1970. Moisture in the forest floor-its distribution and movement. Publication 1271. Department of Fisheries and Forestry, Canadian Forestry Service, Ottawa, Ontario.

Stohlgren, T. J. 1988. Litter dynamics in two Sierra mixed conifer forests. I. Litterfall and decomposition rates. Canadian Journal of Forest Research 18:1127-1135.

Swezy, D. M., and J. K. Agee. 1990. Prescribed-fire effects on fine-root and tree mortality in old-growth ponderosa pine. Canadian Journal of Forest Research 21:626-634.

SYSTAT 2000. SYSTAT: The system for statistics, version 10. SPSS, Inc. Evanston, Illinois.

Turner, M. G., and W. H. Romme. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology 9:59-77.

van Wagtendonk, J. W. 1996. Use of a deterministic fire growth model to test fuel treatments. Pages1155-1165 *In* Sierra Nevada Ecosystem Project, final report to congress, volume II, Assessments and scientific basis for management options. Wildland Research Center, University of California, Davis, California.

van Wagtendonk, J. W., J. M. Benedict, and W. S. Sydoriak. 1998. Fuel bed characteristics of Sierra Nevada conifers. Western Journal of Applied Forestry 13: 73-84.