Fuel Bed Characteristics of Sierra Nevada Conifers

Article *in* Western Journal of Applied Forestry · July 1998

Jan W. van Wagtendonk
National Park Service

Fuel Bed Characteristics of Sierra Nevada Conifers

Jan W. van Wagtendonk, *U.S. Geological Survey, Yosemite Field Station, El Portal, CA 95318;* **James M. Benedict,** *National Park Service, Santa Monica Mountains National Recreation Area, Agoura Hills, CA 91301; and* **Walter M. Sydoriak,** *National Park Service, Bandelier National Monument, Los Alamos, NM 87544.*

ABSTRACT. *A study of fuels in Sierra Nevada conifer forests showed that fuel bed depth and fuel bed weight significantly varied by tree species and developmental stage of the overstory. Specific values for depth and weight of woody, litter, and duff fuels are reported. There was a significant positive relationship between fuel bed depth and weight. Estimates of woody fuel weight using the planar intercept method were significantly related to sampled values. These relationships can be used to estimate fuel weights in the field. West. J. Appl. For. 13(3):73–84.*

The accumulation of hazardous fuels throughout the Sierra Nevada over the past 60 yr has become an issue of recent increased concern. In 1993, Congress directed that a study be conducted to assess what information is needed to make decisions for the future management of the Sierra Nevada ecosystems. One of the critical findings of the Sierra Nevada Ecosystem Project was that live and dead fuels in the conifer forests today are more abundant and continuous than in the past (SNEP 1996). Combined with the growing density of homes, these increases in fuels exacerbate the threat of fire to the human and natural resources in the Sierra Nevada. Accurate methods are needed to assess fuel conditions in order to develop fire protection and fuel mitigation plans. Lack of such accurate information reduces the reliability of these plans.

Prescribed fire has been proposed as one of the most effective tools for reducing fuel hazards (van Wagtendonk 1996). The use of prescribed fire requires reliable estimates of fuel weight in order to safely accomplish the burns and to evaluate their effectiveness in meeting management objectives (Reeberg 1995). In addition, fuel bed weight and depth are used in the Rothermel (1972) rate of spread equation that is central to the National Fire Danger Rating System (Deeming et al. 1977) and the fire behavior prediction system used by fire behavior analysts (Rothermel 1983). Fuel weight and depth are specified for standardized models that are used in both of these systems (Anderson 1982, Albini 1976).

Fuel weight plays a dual role in Rothermel's (1972) spread rate equation. In the numerator, it is multiplied by fuel heat content to produce a source of heat for the calculation of reaction intensity. Fuel weight is divided by fuel depth in the denominator of the equation to determine fuel bed bulk density, which acts as a heat sink. Increases in fuel weight usually cause reaction intensity to increase more than rate of spread. In fact, all else being equal, as weight increases, rate of spread may actually decrease because more fuel must be raised to ignition temperature (Burgan and Rothermel 1984). Brown (1981) identifies fuel bed bulk density as one of the most difficult properties to measure in the field.

Deeming et al. (1977) categorized woody fuels by size classes and duff fuels by depth classes that both correspond to fuel moisture timelags (Table 1). Timelag is the amount of time necessary for a fuel component to reach 63% of its equilibrium moisture content (Lancaster 1970). Deeming et al. (1977) stress that the duff designations are very rough approximations and should be used with caution. For ex-

Table 1. Timelag classes and corresponding woody fuel size classes and duff fuel depth classes (Deeming et al. 1977).

Timelag class	Woody fuel size class	Duff fuel depth class
	(cm)	
1 hr	0.00–0.64	0.00–0.64
10 hr	0.64–2.54	0.64–1.91
100 hr	2.54–7.62	1.91–10.16
1000 hr	>7.62	>10.16

NOTE: Jan W. van Wagtendonk is the corresponding author and can be reached at (209) 379-1885; Fax: (209) 379-1886; E-mail: jan_van_wagtendonk@usgs.gov. The authors thank all of the people who helped on this project. Joe Coho oversaw the data entry, and Diane Ewell spent many hours in the field collecting fuels. She was ably assisted by many volunteers including Charisse Sydoriak, Kay Beeley, Kathy Tier, and Karen Kolbeck. Liam Bickford volunteered to enter all of the data.

ample, van Wagtendonk and Sydoriak (1985) found good correlations between the moisture contents of duff and woody 1 hr and 10 hr timelag fuels, but the correlations were poor for 100 hr and were nonexistent for 1000 hr timelag fuels.

The forest floor also can be divided into litter and duff, corresponding to the O_i layer and the combined O_e and O_a layers described in the literature on forest soils (Soil Survey Staff 1993). Litter is defined as freshly cast nonwoody organic matter that still retains its morphological characteristics. Duff includes both the fermentation layer, where decomposition has begun but the particles can still be recognized, and the humus layer, where organic material is compressed and in all states of decay. As fuels, the most useful categories are probably litter and the four duff depth layers.

Land managers have traditionally used the planar intercept method developed by Brown (1974a) to inventory downed woody material. This method is also the basis for photo series for quantifying natural forest residues (Blonski and Schramel 1981). Fuel weight is estimated by counting the number of intercepts of woody fuel particles in different size classes with a sampling plane. The intercepts are then multiplied by factors derived from physical properties of woody fuels of Rocky Mountain conifer species. The planar intercept method has proven useful in areas with plentiful woody fuels resulting from management activities but has met with less success in areas with natural fuels (Brown 1981). Although van Wagtendonk et al. (1996) have determined factors based on the physical properties of woody fuel particles of Sierra Nevada conifers, there is a need for more accurate woody fuel weight estimates.

In the Sierra Nevada, the only published equations for estimating forest floor weight from depth were provided by Agee (1973). Because he sampled mixed stands of ponderosa pine (*Pinus ponderosa*) and incense-cedar (*Calocedrus decurrens*) and stands of white fir (*Abies concolor*) and giant sequoia (*Sequoiadendron giganteum*), individual species relationships could not be determined. His r^2 values, however, ranged up to 0.90 for total litter and duff for the white fir–giant sequoia mix.

Equations for estimating weights of duff fuels and total fuels have also been developed for the Southwest and the Rocky Mountains. Unfortunately, conversion factors recommended by Brown et al. (1982) were based on a limited number of studies of bulk density including ponderosa pine and lodgepole pine (*Pinus contorta*) in the northern Rocky Mountains (Brown 1970, 1974b). Several studies of ponderosa pine in the Southwest have related fuel bed weight to fuel bed depth. Eakle and Wagle (1979) used logarithmic regressions for the litter and duff layers, but r^2 values were low (0.58 and 0.65, respectively). Linear regressions through the origin were reported by Ffolliott et al. (1968, 1976), but no r^2 values were provided. Harrington (1986) also used a linear regression and reported an r^2 of 0.78. Sackett (1979), however, was unable to establish a reliable relationship for predicting fuel weight from duff depth. Woodard and Martin (1980) reported an r^2 of 0.849 for lodgepole pine in Washington.

The lack of information on fuel weight and depth of Sierra Nevada conifers reduces the reliability of fuel hazard assessments and fire behavior predictions. This study was designed to gather that information. This paper presents data for Sierra Nevada conifers on woody fuel weight by size class, litter and duff fuel weight by depth class, litter and duff depth, and fuel bed bulk density. We also compare woody fuel weights with estimates using the planar intercept method. In addition, we present regression equations for each species that can be used to estimate duff fuel weight.

Methods

Fuels were collected from stands of each of the 22 species of conifers occurring in the Sierra Nevada. Species absent or not well-represented in Yosemite National Park were sampled in adjacent national forests or in Sequoia and Kings Canyon National Parks (Figure 1). California torreya (*Torreya californica*), Pacific yew (*Taxus brevifolia*), and California juniper (*Juniperus californica*) had insufficient fuels for complete sampling. Four stands of each species were sampled representing developmental stages from young to old. Trees were approximately 2.5 to 10 cm in diam. in sapling stands, 10 to 60 cm in pole stands, 60 to 120 cm in mature stands, and greater than 120 cm in old stands. Each selected stand had an area of at least 300 m^2 with an overstory composed of 100% of the desired species and was free of recent disturbance such as fire and tree mortality from insects and diseases. Since adjacent trees could contribute to the fuels on a plot, only stands with at least 90% of fuels of the desired species were sampled.

Four 11 m parallel transects 3 m apart were established beneath each species and developmental stage combination. Fuel particle intersections with the sampling planes were counted and categorized by size class. Woody fuel depth was recorded at three points along each transect from the highest intersected dead particle to the bottom of the litter layer (Brown 1974a). Five 20 × 50 cm subplots were systematically placed along each transect to collect woody fuels for a total of 20 subplots/stand. Twenty 10 × 10 cm subplots at the same locations were used to collect litter and duff fuels. Duff samples included incorporated cone scales, bark flakes, and fine (0.0–0.64 cm) branches Litter and total duff depth were measured at the center of the edge of each subplot adjacent to the transect line Freshly fallen litter was first separated and sealed in plastic bags. Then fuels from the four timelag fuel diameter classes and four duff depth timelag classes (Table 1) were collected and bagged. Sound and rotten samples of the larger branchwood were bagged separately. Samples were dried in a convection oven at 65°C until weight loss stabilized.

Fuel weights of the duff and woody fuel components were analyzed using two-way analysis of variance with species and developmental stage as the independent factors. Two-way analysis of variance was also used for woody fuel depth, litter depth, and duff depth with species and developmental stage as the independent variables. Post hoc Scheffé multiple

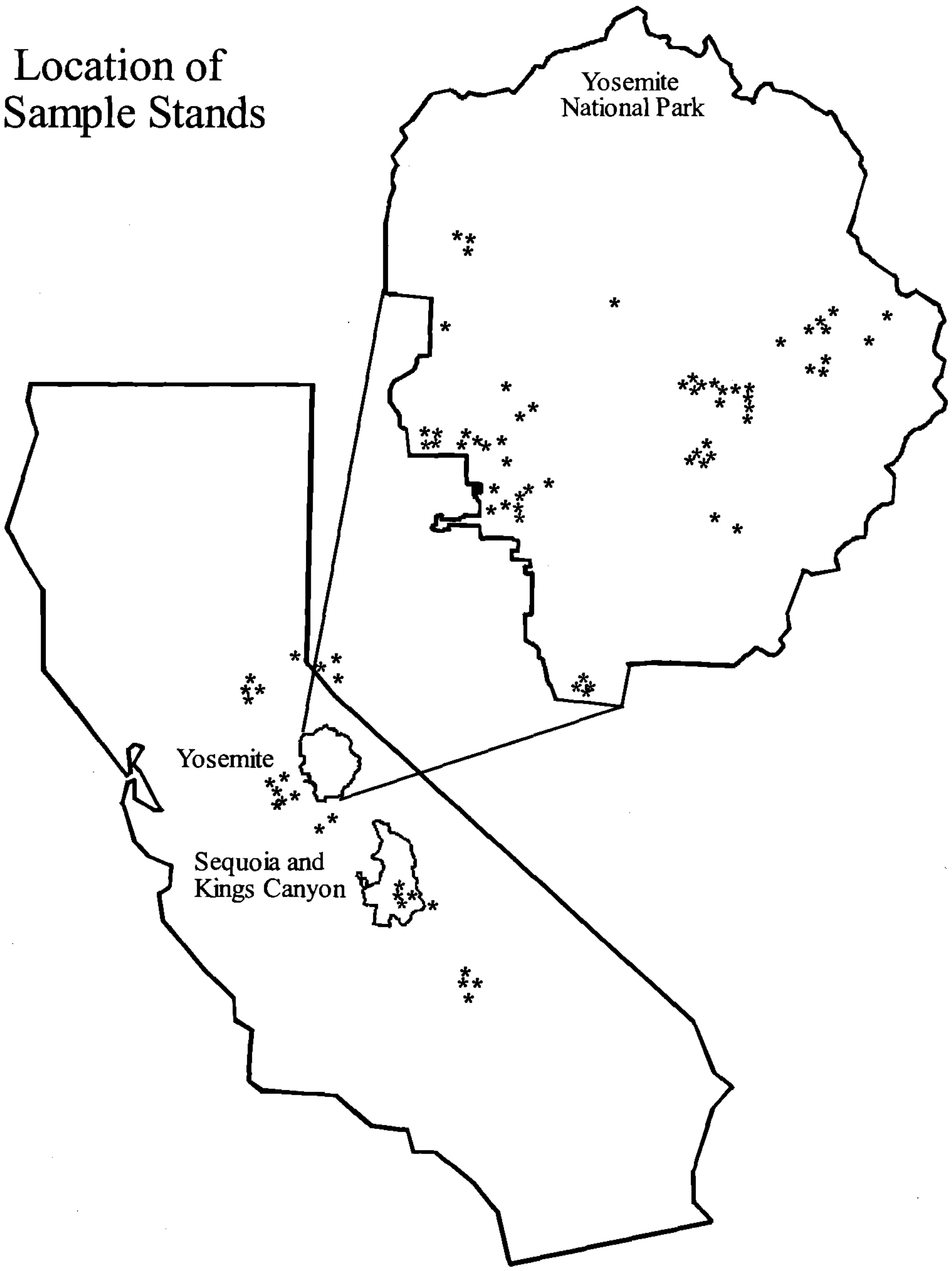

Figure 1. Sampling locations for four stands each of 22 conifer species in the Sierra Nevada, California and Nevada.

range tests were used with a one-way analysis of variance to determine which species means were significantly different from each other (Scheffé 1959). Regression analysis was used to compare woody fuel weights derived in this study with the planar intercept method using Rocky Mountain (Brown 1974a) and Sierra Nevada (van Wagtendonk et al. 1996) values. Estimates of fuel weight as a function of fuel depth were determined through regression analysis. All significance tests were at the 0.05 level.

Bulk densities for litter, duff, and litter and duff combined were calculated from their respective depth and weight values. Duff weight was the sum of the four fuel depth classes. Fuel bed bulk density calculations were based on the depth and weight of the woody fuels as well as the litter and the uppermost duff layer. This is consistent with Burgan and Rothermel (1983) and Albini (1976), who include litter and 1 hr duff fuels in their fuel models. Brown (1974a) also includes the litter layer in his fuel depth measurement. The equation for fuel bed bulk density used in this study is:

$$BULKDENSITY_{Bed} =$$

$$100 \times \frac{WEIGHT_{Woody} WEIGHT_{Litter} WEIGHT_{Onehourduff}}{DEPTH_{Woody} + DEPTH_{Onehourduff}}$$

where *BULKDENSITY* is in kg m^{-3}, *WEIGHT* is in kg m^{-2}, *DEPTH* is in cm. The depth of the 1 hr duff layer is either 0.64 cm or, in cases where the total duff depth is less than 0.64 cm, the total duff depth. Multiplying by 100 is necessary to express bulk density on a per cubic meter basis.

Results

Fuel Bed Depth

Woody fuel depth was significantly affected by species, developmental stage, and their interaction. Litter depth and duff depth were similarly affected. Woody fuel depth values for the various species ranged from 1.24 cm for foxtail pine (*Pinus balfouriana*) to 9.27 cm for giant sequoia (Table 2). Litter depth was lowest for white fir and red fir at 0.15 cm and highest for sugar pine (*P. lambertiana*) at 2.10 cm. There was considerable variation in duff depths from a high of 8.67 cm for giant sequoia to a low of 1.28 cm for western juniper.

Multiple comparisons divided the woody fuel depths into six subsets with singleleaf pinyon (*P. monophylla*) and foxtail pine unique to the shallowest subset and Douglas-fir (*Pseudotsuga menziesii*), giant sequoia, and red fir (*Abies magnifica*) unique to the deepest subset. Litter depth means were grouped into four subsets: the first subset included all the species with mean litter depths less than the 0.70 cm of limber pine (*Pinus flexilis*); Jeffrey pine (*P. jeffreyi*) was included in the second and third subsets; and ponderosa pine and Douglas-fir were unique to the fourth. There were seven homogeneous subsets for duff depth, with foxtail pine and western juniper in the shallowest subset and giant sequoia the deepest.

The effect of developmental stage can be seen in Figure 2: growth of stands from sapling to pole, mature, and old stages generally resulted in increased depth. There was a slight drop in litter depth between the pole and mature stages and in woody fuel depth between the mature and old stages.

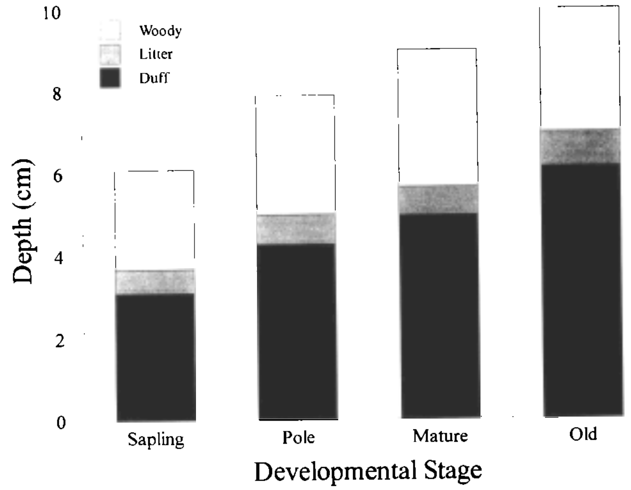

Figure 2. Average fuel bed depth by developmental stage for 19 Sierra Nevada conifers.

Fuel Bed Weight

Litter and Duff Fuel Weight.—Species, developmental stage, and their interaction had significant effects on the weight of litter and duff fuel components. Litter weights varied from a low of 0.127 kg m^{-2} for white fir to a high of 0.742 kg m^{-2} for sugar pine (Table 3). Foothill pine (*Pinus sabiniana*) had the lowest weight (0.207 kg m^{-2}) in the 0.00–0.64 cm duff depth class while mountain hemlock (*Tsuga mertensiana*) had the highest (0.927 kg m^{-2}) In the 0.64–1.91 depth class, foothill pine weighed the least (0.706 kg m^{-2}) and white fir the most (2.675 kg m^{-2}) Limber pine had particularly deep duff layers with 9.193 kg m^{-2} in the 1.191–10.16 cm depth class and 4.582 kg m^{-2} in the greater than 10.16 cm class. There was very little western juniper duff with only 0.733 kg m^{-2} in the 1.91 cm depth class and no fuel in the greater than 10.16 cm class Foxtail pine and western white pine (*Pinus monticola*) fuels in the deepest class also were missing.

Species means for litter weight were divided into five homogeneous subsets. Out of the 14 species in the group with the lightest litter, western juniper, white fir, western white pine, and red fir were unique. Sugar pine was the only unique member of the heaviest group. The multiple comparisons for

Table 2. Fuel bed depth for 19 Sierra Nevada conifers.

Species	Woody fuel depth	Litter depth	Duff depth	Litter and duff depth
	(cm)			
Douglas-fir	6.51	0.33	4.40	4.73
Foothill pine	4.50	1.35	3.23	4.58
Foxtail pine	1.24	0.19	1.60	1.79
Giant sequoia	9.27	0.37	8.67	9.04
Incense-cedar	5.84	0.20	4.87	5.07
Jeffrey pine	2.82	1.11	5.40	6.51
Knobcone pine	3.62	1.70	2.80	4.50
Limber pine	3.73	0.70	6.97	7.67
Lodgepole pine	2.35	0.44	3.54	3.98
Mountain hemlock	3.52	0.36	6.05	6.41
Ponderosa pine	4.34	1.87	7.88	9.75
Red fir	6.21	0.15	4.88	5.03
Singleleaf pinyon	2.67	0.49	3.26	3.75
Sugar pine	5.52	2.10	5.97	8.07
Washoe pine	3.00	0.65	3.66	4.31
Western juniper	1.90	0.11	1.28	1.39
Western white pine	1.43	0.25	1.81	2.06
White fir	3.98	0.15	6.46	6.61
Whitebark pine	2.19	0.49	4.93	5.42
All species	3.93	0.68	4.61	5.29

Table 3. Average weight of litter and duff fuels of 19 Sierra Nevada conifers.

Species	Litter	Duff depth class (cm)				
		0.00–0.64	0.64–1.91	1.91–10.16	>10.16	Total
	(kg m^{-2})					
Douglas-fir	0.308	0.638	1.493	3.876	0.054	6.062
Foothill pine	0.338	0.207	0.706	3.001	0.395	4.309
Foxtail pine	0.178	0.754	1.604	1.291	—	3.649
Giant sequoia	0.452	0.677	1.997	8.942	2.477	14.092
Incense-cedar	0.268	0.736	1.746	5.651	0.232	8.365
Jeffrey pine	0.376	0.345	1.275	6.169	1.177	8.965
Knobcone pine	0.586	0.244	0.985	3.180	0.428	4.836
Limber pine	0.744	0.602	1.630	9.193	4.582	16.006
Lodgepole pine	0.416	0.786	1.623	3.343	0.042	5.793
Mountain hemlock	0.431	0.927	2.125	6.309	1.522	10.883
Ponderosa pine	0.562	0.257	1.016	7.354	2.682	11.309
Red fir	0.155	0.884	2.106	5.226	0.583	8.799
Singleleaf pinyon	0.567	0.866	2.063	4.328	0.624	7.881
Sugar pine	0.742	0.322	1.220	6.603	0.574	8.720
Washoe pine	0.351	0.356	1.244	4.702	0.286	6.588
Western juniper	0.079	0.617	0.934	0.733	—	2.285
Western white pine	0.128	0.387	1.084	1.089	—	2.560
White fir	0.127	0.736	2.675	6.428	0.134	7.973
Whitebark pine	0.269	0.663	1.448	4.591	2.419	9.121
All species	0.370	0.579	1.525	4.843	1.022	7.999

duff weights identified seven subsets for the 0.00–0.64 cm and 0.64–1.91 cm depth classes. Means for the greater than 10.16 cm class were grouped into two subsets with all species but limber pine in the first set and the seven species with the least duff in the second class. Figure 3 shows the effect of developmental stage on litter and duff weight. As stands develop to older stages, weights in each of the litter and duff components increased.

Woody Fuel Weight.—Woody fuel weight in the three smallest size classes and sound fuels greater than 7.62 cm in diam. were all significantly affected by species, developmental stage, and their interaction. Rotten fuels greater than 7.62 cm in diameter did not vary significantly. Red fir had the largest quantities of woody fuel in the 0.00–0.64 cm and 0 64–2.54 cm size classes, while giant sequoia dominated the

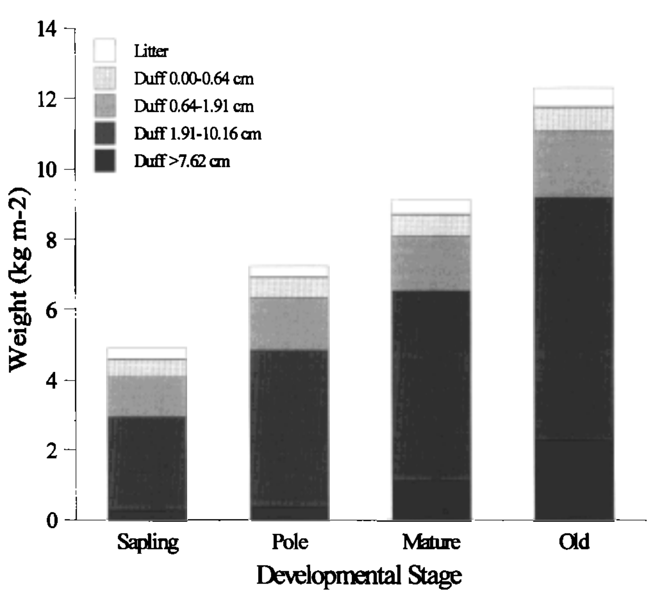

Figure 3. Average litter and duff weight by developmental stage for 19 Sierra Nevada conifers.

2.54–7.62 cm and greater than 7.62 cm sound classes (Table 4). Ponderosa pine had the least amount of woody fuel in the 0.00–0.64 cm class as did knobcone pine (*Pinus attenuata*) in the 0.64–2.54 cm class. Several species had no woody fuels in the three largest size classes.

Eight homogeneous subsets of means were identified for the small woody fuels in the 0.00–0.64 cm class. The 0.64–2.54 cm class was divided into five subsets with the heaviest containing only red fir and Douglas-fir. Species means were grouped into two overlapping subsets for the 2.54–7.62 size class, and giant sequoia was the only species that did not occur in the lightest subset. The mean comparisons did not divide the sound and rotten classes of fuels greater than 7.62 cm into subsets.

The increase in woody fuel weight with advancing developmental stage can be seen in Figure 4. The three smallest size classes increased between each of the developmental stages. Large sound fuels decreased slightly between the pole and mature stages, as did large rotten fuels between the pole, mature, and old stages.

Bulk Density.—Average duff bulk density ranged from 34.86 kg m^{-3} for the 0.00–0.64 cm depth layer for foothill pine to 981.82 kg m^{-3} for the greater than 10.16 cm layer for Douglas-fir (Table 5). Bulk density within the duff layer generally increased with depth. Red fir, singleleaf pinyon, and sugar pine showed decreases in the greater than 10.16 cm depth class, however, while western juniper and white fir decreased in the 1.91–10.16 cm class.

Litter bulk densities varied from a low of 32.88 kg m^{-3} for foothill pine to a high of 145.98 kg m^{-3} for singleleaf pinyon (Table 6). Foothill pine had the lowest values for the duff layer, the combined litter and duff layers, and the total fuel bed. Singleleaf pinyon had the highest bulk densities for duff (234.16 kg m^{-3}) and litter and duff combined (205.80 kg m^{-3}). Limber pine had the highest value for total fuel bed bulk density (40.21 kg m^{-3}).

Table 4. Average weight of woody fuel components of 19 Sierra Nevada conifers.

Species	Woody fuel component (cm)					
	0.0–0.64	0.64–2.54	2.54–7.62	>7.62 sound	>7.62 rotten	Total
	(kg m^{-2})					
Douglas-fir	0.370	0.473	0.153	0.039	—	1.036
Foothill pine	0.064	0.093	0.067	—	—	0.224
Foxtail pine	0.185	0.140	—	—	—	0.325
Giant sequoia	0.130	0.403	0.758	1.045	—	2.336
Incense-cedar	0.245	0.282	0.139	0.318	—	0.984
Jeffrey pine	0.025	0.196	0.073	—	—	0.294
Knobcone pine	0.069	0.075	0.091	—	—	0.235
Limber pine	0.150	0.215	0.456	0.494	—	1.315
Lodgepole pine	0.084	0.142	0.175	0.038	—	0.439
Mountain hemlock	0.217	0.248	0.184	0.181	—	0.830
Ponderosa pine	0.013	0.215	0.260	0.428	0.079	0.995
Red fir	0.527	0.683	0.507	0.139	0.140	1.996
Singleleaf pinyon	0.217	0.112	—	—	—	0.329
Sugar pine	0.143	0.178	0.389	0.086	0.008	0.804
Washoe pine	0.018	0.107	0.028	0.023	—	0.176
Western juniper	0.037	0.110	0.079	—	—	0.226
Western white pine	0.089	0.162	0.087	—	—	0.338
White fir	0.290	0.370	0.195	0.175	0.003	1.033
Whitebark pine	0.099	0.101	0.085	0.124	0.131	0.540
All species	0.156	0.227	0.196	0.161	0.019	0.759

Estimating Fuel Bed Weight

Fuel bed weights can be estimated by predicting litter and duff weight from litter and duff depth or by determining the relationship between calculated woody weight values from the planar intercept method with woody fuel weights from this study.

Estimating Litter and Duff Weight.—Since regressions through the origin had consistently higher r^2 values than regressions with intercepts, the analysis was performed without intercepts. These r^2 values measure the proportion of the variability in weight about the origin explained by the regression, however, and cannot be directly compared to r^2 values for models that include an intercept.

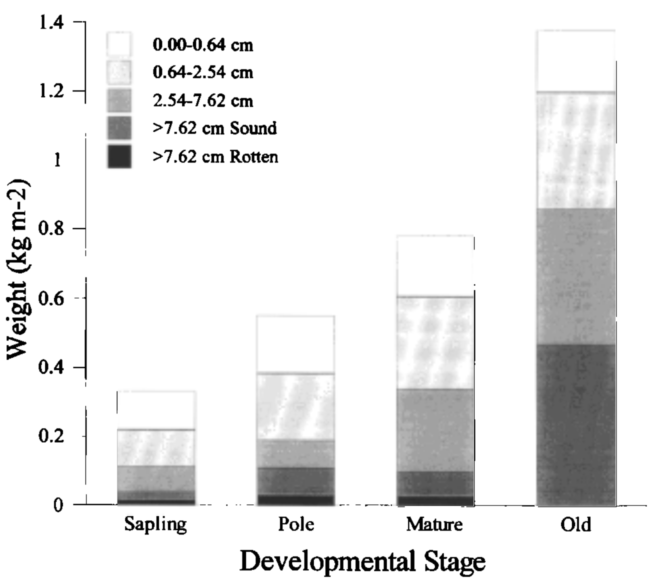

Figure 4. Average woody fuel weight by developmental stage for 19 Sierra Nevada conifers.

There was considerable variation among species for the litter layer regressions. Incense-cedar had the highest slope coefficient of 1.276, while foothill pine had the lowest at 0.111 (Table 7). The r^2 values ranged from 0.905 for lodgepole pine to 0.355 for foothill pine. The r^2 values for duff were higher and more consistent than those of the litter, ranging from 0.978 for whitebark pine (*Pinus albicaulis*) to 0.643 for western white pine. The largest regression coefficient for duff was 2.592 for singleleaf pinyon, and the smallest was 1.319 for Douglas-fir. When litter and duff were combined, the regression coefficients for individual species ranged from 1.189 for sugar pine to 2.478 for singleleaf pinyon, reflecting the influence of the heavier duff layer. The r^2 values ranged from 0.797 for western white pine to 0.972 for whitebark pine. When all species were combined, the r^2 value for the litter layer was 0.494 and the duff layer was 0.881. The equation for the regression through the origin for total litter and duff weight as a function of total litter and duff depth was:

$$WEIGHT = 1.624 \times DEPTH$$
$$r^2 = 0.937$$

where *WEIGHT* is in kg m^{-2} and *DEPTH* is in cm. Figure 5 is a plot of the regression of all 1,520 plots. As can be seen in the figure, the largest proportion of the data points appeared near the origin.

Estimating Woody Fuel Weight.—For all species combined, the average total woody fuel weight in the 0.00–0.64 cm, 0.64–2.54 cm, and 2.54–7.62 cm size classes was 0.574 kg m^{-2} (Table 8). Calculated total woody fuel weight in the same classes using the planar intercept method with fuel particle values from the Rocky Mountains (Brown 1974a) was 0.630 kg m^{-2}. Calculations based on recently derived fuel particle values for the Sierra

Table 5. Average bulk density of duff fuels of 19 Sierra Nevada conifers

Species	Duff depth class (cm) 0.00–0.64	0.64–1.91	1.91–10.16	>10.16	Total duff
	($kg\ m^{-2}$)				
Douglas-fir	103.68	138.93	263.91	981.82	152.53
Foothill pine	34.86	130.86	237.12	435.77	130.61
Foxtail pine	153.76	313.22	448.21	—	210.67
Giant sequoia	105.91	163.02	161.61	240.90	162.00
Incense-cedar	117.20	153.58	203.68	378.65	180.93
Jeffrey pine	54.48	119.20	239.89	607.25	168.48
Knobcone pine	44.71	134.14	370.76	392.53	219.71
Limber pine	112.03	164.86	337.91	532.85	223.80
Lodgepole pine	124.40	188.60	279.51	—	162.59
Mountain hemlock	145.00	193.72	190.56	340.03	183.98
Ponderosa pine	40.83	83.85	214.23	545.15	154.86
Red fir	150.58	209.81	206.29	156.24	182.42
Singleleaf pinyon	136.09	296.81	464.39	362.07	234.16
Sugar pine	50.35	108.06	368.30	184.69	160.96
Washoe pine	60.29	151.52	266.73	936.51	172.79
Western juniper	150.03	254.60	239.21	—	178.06
Western white pine	66.07	225.94	298.19	—	138.71
White fir	115.04	212.82	172.72	198.22	183.03
Whitebark pine	115.88	191.78	233.48	329.96	176.82
All species	98.34	176.40	259.31	580.82	177.37

Nevada (van Wagtendonk et al. 1996) yielded a total woody fuel weight of 0.563 kg m^{-2} for the same classes. Using each of the three methods, red fir had the heaviest combined woody fuel weight, while Washoe pine (*Pinus washoensis*) had the lightest woody fuel weight.

When the calculated weights from the planar intercept method are used to predict the sampled weights, both the Rocky Mountain fuel particle values and the Sierra Nevada values produced significant regressions through the origin (Figure 6). The equations are:

$$WEIGHT = 0.935 \times CALCULATED_{RockyMountains}$$

$$r^2 = 0.790$$

$$WEIGHT = 0.858 \times CALCULATED_{SierraNevada}$$

$$r^2 = 0.795$$

where *WEIGHT* is the predicted weight in kg m^{-2} based on the samples, and *CALCULATED* is the weight in kg m^{-2} from the planar intercept method. The r^2 values of the two regres-

Table 6. Average bulk density of fuel beds of 19 Sierra Nevada conifers. The fuel bed bulk density includes woody, litter, and 1 hr timelag duff fuels.

Species	Litter	Duff	Litter and duff	Fuel bed
	($kg\ m^{-3}$)			
Douglas-fir	101.333	152.533	143.464	20.629
Foothill pine	32.876	130.605	85.890	12.407
Foxtail pine	89.909	210.665	187.976	33.395
Giant sequoia	140.511	162.000	160.416	31.823
Incense-cedar	144.775	180.928	185.041	20.744
Jeffrey pine	32.633	168.482	139.352	21.107
Knobcone pine	38.253	219.711	113.822	20.325
Limber pine	99.570	223.803	189.771	40.209
Lodgepole pine	94.371	162.586	151.174	32.948
Mountain hemlock	114.857	183.977	177.352	32.250
Ponderosa pine	36.010	154.863	118.003	23.479
Red fir	120.049	182.423	172.139	35.581
Singleleaf pinyon	145.981	234.164	205.797	30.846
Sugar pine	40.763	160.960	117.153	28.243
Washoe pine	56.404	172.785	145.048	16.571
Western juniper	70.532	178.064	147.378	20.934
Western white pine	49.357	138.705	122.948	27.295
White fir	78.424	183.030	179.786	24.831
Whitebark pine	59.440	176.817	154.970	27.233
All species	81.199	177.372	152.417	26.361

Table 7. Regression statistics for litter, duff, and litter and duff weight (kg m–2) as a function of their respective depths (cm) for 19 Sierra Nevada conifers Each regression went through the origin, was based on 80 observations, and was significant at the 0.05 level.

	Litter		Duff		Litter and duff	
Species	Coefficient	r^2	Coefficient	r^2	Coefficient	r^2
Douglas-fir	0.864	0.796	1.319	0.901	1.295	0.910
Foothill pine	0.111	0.355	1.448	0.746	1.220	0.804
Foxtail pine	0.886	0.650	2.504	0.914	2.360	0.907
Giant sequoia	0.990	0.548	1.648	0.914	1.632	0.920
Incense-cedar	1.276	0.709	1.675	0.865	1.664	0.866
Jeffrey pine	0.358	0.823	1.707	0.864	1.496	0.874
Knobcone pine	0.339	0.636	1.646	0.896	1.274	0.902
Limber pine	0.889	0.789	2.337	0.946	2.255	0.955
Lodgepole pine	0.951	0.905	1.671	0.904	1.612	0.912
Mountain hemlock	1.102	0.883	1.876	0.913	1.848	0.917
Ponderosa pine	0.276	0.669	1.402	0.912	1.233	0.921
Red fir	0.530	0.446	1.727	0.932	1.722	0.937
Singleleaf pinyon	0.906	0.845	2.592	0.883	2.478	0.900
Sugar pine	0.304	0.623	1.396	0.880	1.189	0.897
Washoe pine	0.600	0.570	1.870	0.863	1.719	0.862
Western juniper	0.832	0.780	1.798	0.932	1.763	0.924
Western white pine	0.542	0.319	1.422	0.643	1.485	0.797
White fir	1.050	0.888	1.518	0.918	1.572	0.922
Whitebark pine	0.540	0.878	1.895	0.978	1.802	0.972
All species	0.363	0.494	1.750	0.881	1.624	0.937

sions show that there is a slight improvement when using Sierra Nevada values over values from the Rocky Mountains (Figure 6).

Discussion

Fuel Bed Depth

Most woody fuel depths were slightly shallower than the 6.10 cm specified in standard fuel models for short-needled conifers and long-needled conifers as described by Albini (1976). Giant sequoia, Douglas-fir, and red fir exceeded this value; while incense-cedar and sugar pine were within 0.30 cm of the standard value. These species, along with foothill pine, ponderosa pine, and white fir, grow at low- to mid-elevations and typically drop more branches and twigs than the higher elevation species. An exception is knobcone pine, which grows on the lower ridgetops in a stand-replacing fire regime where woody fuels seldom get a chance to accumulate. Differences between Sierra Nevada fuel bed depth values and those in the standardized fuel models could result in significant overpredictions of fire spread and intensity.

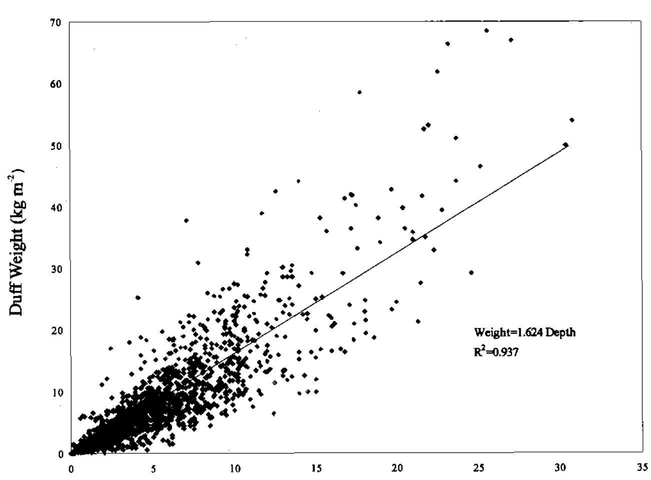

Figure 5. Regression lines for duff weight as a function of duff depth for all 19 Sierra Nevada conifer species combined.

Litter fuel depth appeared to be a function of needle morphology. Conifers with medium to long needles had the deepest litter layers, while those with single short needles or scales had the shallowest litter layers. Long needles tend to form more porous fuel beds than short and flat needles as evidenced by the mean litter and duff weights (Table 3). The thin litter layers for the short-needled high-elevation whitebark pine, lodgepole pine, and western white pine could indicate that low growth potential has an effect on needle production and litter depth.

Studies in other regions show similar relationships with growing conditions. In Arizona, Eakle and Wagle (1979) reported a litter depth for ponderosa pine of 1.46 cm, while Brown (1970) found litter depths for ponderosa pine in wetter, more mesic Montana to average just over 2 cm. Lodgepole pine duff depths in Wyoming were 2.34 cm (Brown 1974b), while in the Cascade Mountains of Washington they averaged 5.02 cm (Woodard and Martin 1980)

Differences in duff depth also appear to be related to growing conditions. Ponderosa pine, white fir, and giant sequoia, the three species with the deepest duff layers, all grow in productive low- to mid-elevations; in the absence of fire, they tend to accumulate large quantities of organic material. Deep duff layers were also recorded for limber pine, a species that grows in cold conditions at high elevations These trees grow to considerable age, and fire is a rare event, giving duff ample time to accumulate. Although this is also the case for whitebark pine and foxtail pine, these species did not show a similar response. Some species, such as western juniper and foxtail pine, grow on rocky expanses of exposed granite where winds and other factors preclude the build up of fuels.

Table 8. Woody fuel weight for the combined 0.00–0 64 cm, 0.64–2.54 cm, and 2 54–7 62 cm size classes from this study and calculated from the planar intersect method using values from the Rocky Mountains (Brown 1974a) and from the Sierra Nevada (van Wagtendonk et al. 1996)

Species	Woody fuel weight		
	This study	Rocky Mountains	Sierra Nevada
	(kg m^{-2})		
Douglas-fir	0.997	1.145	0.955
Foothill pine	0.224	0.292	0.212
Foxtail pine	0.325	0.300	0.259
Giant sequoia	1.292	1.186	1.202
Incense-cedar	0.666	0.847	0.771
Jeffrey pine	0.294	0.347	0.306
Knobcone pine	0.235	0.240	0.171
Limber pine	0.821	0.698	0.786
Lodgepole pine	0.401	0.579	0.484
Mountain hemlock	0.649	0.863	0.761
Ponderosa pine	0.488	0.479	0.505
Red fir	1.717	1.718	1.521
Singleleaf pinyon	0.329	0.381	0.375
Sugar pine	0.710	0.704	0.669
Washoe pine	0.153	0.233	0.179
Western juniper	0.227	0.239	0.259
Western white pine	0.339	0.354	0.209
White fir	0.855	1.037	0.809
Whitebark pine	0.286	0.334	0.274
All Species	0.579	0.630	0.563

Previously, most studies that reported depths for species that occur in the Sierra Nevada combined the litter and duff layers. In general, these values were less than the ones found in this study. For instance, combined depths for ponderosa pine in the Southwest were one-third of those from this study (Ffolliott et al. 1968, 1979, Eakle and Wagle 1979). Kittredge (1955) measured litter and duff depth in the Sierra Nevada and found values for white fir, red fir, sugar pine, and ponderosa pine to be two-thirds to one-half those found here. It is possible that 40 yr of additional accumulation without fire has allowed fuels throughout the Sierra Nevada to increase. Kittredge (1955) also conducted the only previous study of knobcone pine litter and duff depth. In the southern California coast ranges, he found values that were similar to those reported here. Since knobcone pine is a short-lived fire-dependent species, there might not be enough time for fuels to accumulate to high levels. If fire is not allowed in knobcone pine stands, considerable dead and down woody fuels accumulate as the stands die and fall apart.

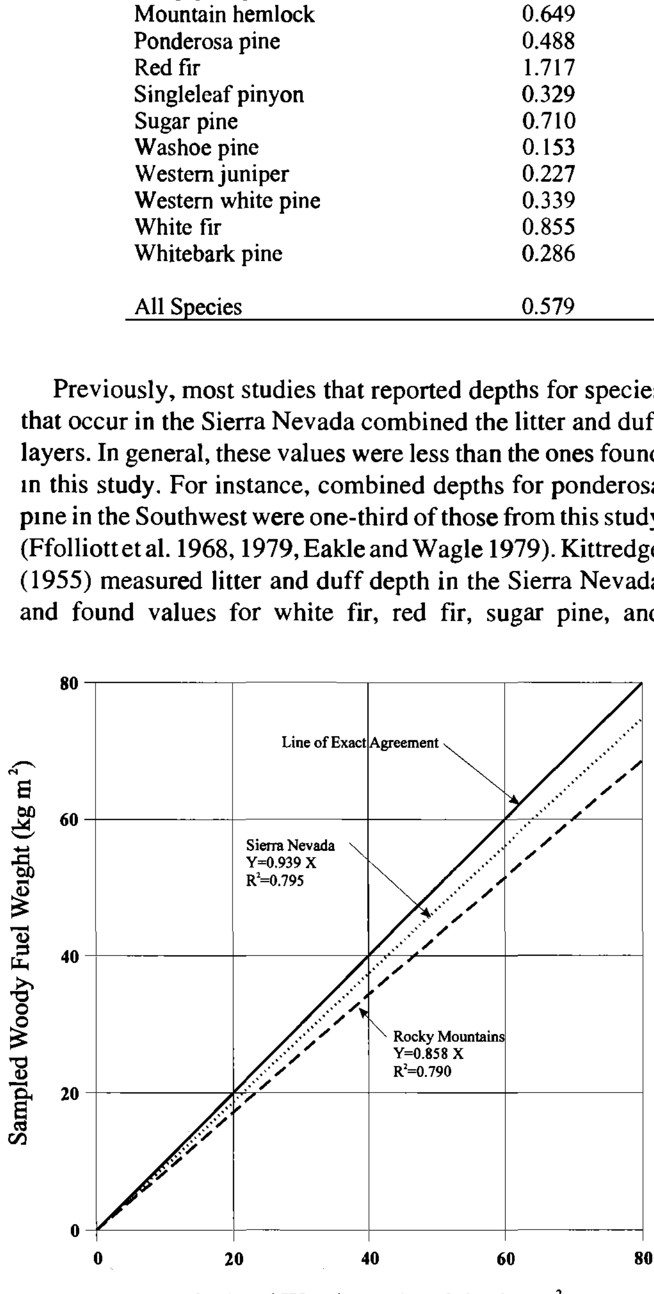

Figure 6. Regression lines for woody fuel weight derived by direct sampling in this study as a function of weights calculated using the planar intercept method with values from the Rocky Mountains (Brown 1974a) and the Sierra Nevada (van Wagtendonk et al. 1996).

Fuel Bed Weight

Litter and duff weight differences also appeared to be related to needle morphology and growing conditions. Conifers with single short needles growing at mid- to high-elevations, such as white fir and red fir, tended to have heavier litter weights. Mid- to low-elevation conifers with fascicles of multiple medium to long needles, such as sugar pine, knobcone pine, and ponderosa pine, had heavier litter loads. Growing conditions and tree size could be affecting litter weights of species with scalelike leaves; the lowest litter weight was recorded by the high-elevation western juniper, while the mid-elevation giant sequoia had a moderately high litter weight. Other species, however, defy simple explanations. For instance, whitebark pine and limber pine grow in similar conditions and have similar needle morphologies; yet their litter weights are at the two extremes.

The litter weight values determined in this study were similar to those of previous studies of Sierra Nevada conifer species. In the Sierra Nevada, van Wagtendonk (1974) reported litter weights of 0.442 kg m^{-2} for ponderosa pine and 0.292 kg m^{-2} for incense-cedar. Agee et al. (1978) found slightly lower values for ponderosa pine, sugar pine, and giant sequoia in the southern Sierra Nevada Their litter weight for white fir was twice that reported here, but they attributed that to a heavy crop of deciduous cone scales, which were not included as litter in this study. Ponderosa pine litter in the drier Southwest averaged 0.224 kg m^{-2} (Sackett 1979), while in the northern Rocky Mountains its average was 0.324 kg m^{-2} (Brown 1970).

In the absence of fire, duff accumulation is the result of the difference between duff production and decomposition. Models of forest floor buildup in the Sierra Nevada have shown maximum total accumulation to be reached after about 100 yr without fire (Agee 1973, van Wagtendonk 1985). In climates more conducive to decomposition, the accumulation peaks sooner at a lower total amount. Conversely, in climates that are favorable for growth but not for decomposition, accumulation rates are fast and total accumulation high.

The variation in total duff weight among species was so great that no single factor can explain the differences. It does appear, however, that due to productivity levels, species in hot, dry and in cold, dry environments have lighter duff layers. For instance, western juniper, western white pine, and foxtail pine had the lowest values for duff weight, followed by foothill pine and knobcone pine. Mid-elevation conifers, such as red fir and Douglas-fir, in areas little affected by fire suppression activities generally had moderate amounts of duff. On the other hand, species with the heaviest duff layers were either mid-elevation species, such as ponderosa pine and giant sequoia, where the effects of fire suppression have been most pronounced, or high-elevation long-lived species, such as limber pine, whitebark pine, and mountain hemlock, where fires seldom occur and productivity outpaces decomposition.

The duff amounts in this study were greater than those found in previous studies in the Sierra Nevada by van Wagtendonk (1974) for incense-cedar and ponderosa pine and by Kittredge (1955) for ponderosa pine, knobcone pine, giant sequoia, white fir, and red fir. As with duff depth, the additional 20 and 40 yr of fuel accumulation without fire could explain these differences. Drier growing conditions in the Southwest could explain those lower duff weights for ponderosa pine than those found in the Sierra Nevada (Ffolliott et al. 1968, 1979, Eakle and Wagle 1979, Sackett 1979).

Woody fuel weights in the smallest three size classes were heavier in this study than those specified in standardized models (Anderson 1982, Albini 1976) generally used for Sierra Nevada conifers. The short-needled fuel model (Model 8) specifies a woody weight of 1.121 kg m^{-2} compared to the 0.855 kg m^{-2} found here for white fir. The long-needled fuel model (Model 9) uses a value of 0.796 kg m^{-2}; ponderosa pine in this study had a weight of 0.488 kg m^{-2}. If, however, the weight of the litter and uppermost duff layer are added to the woody weights, the values are 1.748 kg m^{-2} and 1.307 kg m^{-2}, respectively. These latter values are probably more realistic since litter and the uppermost duff layer usually are burned by the passing fire front.

There was considerable variation in woody fuel weight among species; red fir had 10 times more woody fuels in the three smallest size classes than did Washoe pine Branching habit and tree size appear to influence the amount of woody fuels. Species, such as red fir, white fir, and Douglas-fir, have numerous small branches that contribute to the fuel load. Giant sequoia, by its sheer size, age, and slow decay rate, can accumulate large amounts of woody fuels over time. Other species, such as Washoe pine, foothill pine, and western juniper, have particularly open crowns with small amounts of branchwood. Knobcone pine retains much of its branchwood in the crown before being burned by a stand-replacing fire

Previous studies of woody fuel weights of Sierra Nevada species have been based primarily on Brown's (1974a) planar intercept method. Parsons and DeBenedetti (1979) reported weights for woody fuels less than 7.62 cm in diam for ponderosa pine and giant sequoia that were slightly lower than those found in this study; while weights for white fir were nearly twice as high. Higher values were also found for ponderosa pine, white fir, and incense-cedar by van Wagtendonk and Sydoriak (1987). In studies of ponderosa pine in the Southwest, Sackett (1979, 1980) used plots for the 0.00–0.64 cm size class and the planar intercept method for the larger classes of woody fuels and found weights comparable to those of this study.

Fuel Bed Bulk Density

Bulk density is calculated from weight and depth of woody, litter, and duff components. Species with shallow but heavy beds, such as singleleaf pinyon, had high bulk densities; species with deep but light beds, such as foothill pine, had low bulk densities. A combination of needle morphology and growing conditions contributes to these differences. This variation in bulk density will have a profound effect on fire behavior. Up to a point, more porous fuel beds will burn with greater intensity than denser beds. The bulk densities reported here can be used to construct custom fuel models (Burgan and Rothermel 1984).

In the Sierra Nevada, Stephens (1995) found bulk densities for ponderosa pine and white fir to increase with depth Ponderosa pine varied from 22.40 kg m^{-3} for the litter layer to 264.00 kg m^{-3} for the deepest duff layer. For white fir, he recorded a minimum of 52.00 kg m^{-3} and a maximum of 338.20 kg m^{-3} for the same layers. These values are similar to those found in this study.

Forest floor bulk densities from this study also compared well with studies in other regions. The only Sierra Nevada species to have bulk densities previously reported are ponderosa pine, Douglas-fir, and lodgepole pine. In the Southwest, ponderosa pine bulk densities varied from 61.13 kg m^{-3} for the combined litter and duff layers (Ffolliott et al. 1976) to 211.07 kg m^{-3} with the addition of woody fuels (Harrington 1986). The most comparable values are for the combined litter and duff layers, however, and values there ranged up to 151.01 kg m^{-3} (Eakle and Wagle 1979). These compare favorably with the 118.00 kg m^{-3} found in this study for the combined ponderosa pine litter and duff.

In the northern Rocky Mountains, Brown (1970) recorded a bulk density of 76.89 kg m^{-3} for ponderosa pine combined litter and duff. In ponderosa pine stands with grass and shrub understories, however, Brown (1981) found median bulk densities for litter layers ranging from 21 90 kg m^{-3} to 29.00 kg m^{-3} In the same region, Douglas-fir stands with similar understories had litter bulk densities from 25.30 kg m^{-3} to 58 10 kg m^{-3} (Brown 1981).

Two studies of lodgepole pine in Washington and Wyoming found bulk densities slightly less than those reported here (Woodard and Martin 1980, Brown 1970). Calculated forest floor bulk densities from the weight and depth figures in Kittredge (1955) for ponderosa pine, white fir, and red fir were similar to the ones found here. The calculated bulk density for knobcone pine growing in southern California was half that of the Sierra Nevada stands.

Estimated Litter and Duff Weight

The equations presented here will allow reliable predictions of litter and duff weight to be made based on depth. By using this easily measurable fuel characteristic, the time consuming collection and weighing of large amounts of duff fuels are avoided. These equations should replace the ones by Agee (1973) that were for mixed stands of ponderosa pine and incense-cedar and for white fir and giant sequoia. They are also more appropriate to use for ponderosa pine in the Sierra Nevada than the equations from the Southwest (Eakle and Wagle 1979, Ffolliott et al. 1968, 1976, Harrington 1986).

Although direct comparisons with other regression methods, such as linear and logarithmic, cannot be made, the high r^2 values indicate the validity of using regressions through the origin. In addition, the appropriateness of this approach was indicated by the large number of observations that were near zero for both weight and depth (Figure 5).

The regression equations can be used by managers and researchers interested in any single layer or combination of layers. For instance, the method used by the National Park Service to determine the effectiveness of prescribed fire treatments uses separate litter and duff measurements (Reeberg 1995). Brown et al. (1982) include the litter layer with the woody fuels but do not provide equations to convert litter depth to litter weight. The Albini (1976) fuel models include litter and the uppermost duff layer in the 1 hr timelag fuel class. User-defined custom fuel models can use any combination of litter and duff fuels to reflect local conditions (Burgan and Rothermel (1984). Although it is possible that interactions among species could alter production and decomposition rates, the equations could be used to approximate estimates of duff weight in mixed species stands. For instance, if some measure of abundance such as basal area or canopy cover is available, the equations can be applied in proportion to that measure.

Estimated Woody Fuel Weight

The popularity of the planar intercept method of inventorying woody fuels warrants the investigation into its applicability in regions other than the northern Rocky Mountains. In a study of Sierra Nevada conifers, van Wagtendonk et al. (1996) showed that regional variation in the physical properties of woody fuel particles could result in fuel weight estimates that differ from as much as 40.8% less to 8.3% more than those calculated from Rocky Mountain values. With the addition of weight and depth data from this study, these estimates can be improved even more Final adjustments can then be made to the calculated estimates so they reflect the differences between calculated and sampled fuel weight.

Conclusion

This study has shown that regional differences in fuel bed properties are real and should be taken into consideration when planning and conducting hazardous fuel treatments. Since fuel bed depth plays such an important role in fire behavior, these differences could result in overpredictions of fire intensity and rate of spread if the standardized fuel models are used. The refinements suggested here will provide the most accurate estimates of fuel bed properties possible consistent with time and funding constraints. The importance of having accurate estimates of fuel weight and depth in predicting fire behavior and measuring fire effects cannot be overstated. As land managers strive to meet the conflicting resource objectives of maintaining natural processes and reducing hazardous fuels, they will need the best available information.

Literature Cited

AGEE, J.K. 1973. Prescribed fire effects on physical and hydrologic properties of mixed-conifer forest floor and soil. Univ. Calif., Davis, Water Res. Cent. Rep. 143. 57 p.

AGEE, J.K., R.H. WAKIMOTO, AND H.H. BISWELL. 1978. Fire and fuel dynamics of Sierra Nevada conifers. For. Ecol. Manage. 1:255-265.

ALBINI, F.A. 1976. Estimating wildfire behavior and effects. USDA For. Serv. Gen. Tech. Rep. INT-30. 92 p.

ANDERSON, H.E. 1982. Aids to determining fuel models for estimating fire behavior. USDA For. Serv. Gen. Tech. Rep. INT-122. 22 p.

BLONSKI, K.J., AND J.L. SCHRAMEL. 1981. Photo series for quantifying natural forest residues: Southern Cascades, northern Sierra Nevada. USDA For. Serv. Gen. Tech. Rep. PSW-56. 145 p.

BROWN, J.K. 1970. Physical fuel properties of ponderosa pine forest floors and cheatgrass. USDA For. Serv. Res. Pap. INT-74. 16 p.

BROWN, J.K. 1974a. Handbook for inventorying downed woody material. USDA For. Serv. Gen. Tech. Rep. INT-16. 24 p.

BROWN, J.K. 1974b. Reducing fire potential in lodgepole pine by increasing timber utilization. USDA For. Serv. Res. Pap. INT-181. 6 p.

BROWN, J.K. 1981. Bulk densities of nonuniform surface fuels and their application to fire modeling. For. Sci. 27(4):667–683.

BROWN, J.K., R.D. OBERHEU, AND C.M. JOHNSON. 1982. Handbook for inventorying surface fuels and biomass in the interior west. USDA For. Serv. Gen. Tech. Rep. INT-129. 48 p.

BURGAN, R.E., AND R.C. ROTHERMEL. 1984. BEHAVE: Fire prediction and modeling system—FUEL subsystem. USDA For. Serv. Gen. Tech. Rep. INT-167. 126 p.

DEEMING, J.E., R.E. BURGAN, AND J.D. COHEN. 1977. The national fire-danger rating system—1978. USDA For. Serv. Gen. Tech. Rep. INT-39. 63 p.

EAKLE, T.W., AND R.F. WAGLE. 1979. Method for estimating ground fuels under two inches in diameter in southwestern ponderosa pine stands. USDA For. Serv. Res. Note PNW-333. 8 p.

FFOLLIOTT, P.F., W.P. CLARY, AND J.B. DAVIS. 1968. Some characteristics of the forest floor under ponderosa pine in Arizona. USDA For. Serv. Res. Note RM-127. 4 p.

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 For. Serv. Res. Note RM-308. 4 p.

HARRINGTON, M.G. 1986. Comparison of forest floor depth to loading relationships from several Arizona ponderosa pine stands. USDA For. Serv. Res. Note RM-463. 5 p.

KITTREDGE, J.K. 1955. Some characteristics of forest floors from a variety of forest types in California. J. For. 53(9):645–647.

LANCASTER, J.W. 1970. Timelag useful in fire danger rating. Fire Contr. Notes 31(3):6–8.

PARSONS, D J , AND S H DEBENEDETTI 1979 Impact of fire suppression on a mixed-conifer forest For Ecol Manage 2 21–33

REEBERG, P. 1995. The Western Region fire monitoring handbook. P. 259–261 *in* Proc. of Symp. on fire in wilderness and park management, Brown, J.K., et al. (tech. eds.). USDA For. Serv. Gen. Tech. Rep. INT-320. 283 p.

ROTHERMEL, R.C. 1972. A mathematical model for fire spread predictions in wildland fuels. USDA For. Serv. Res. Pap. INT-116. 40 p.

ROTHERMEL, R.C. 1983. How to predict the spread and intensity of forest and range fires. USDA For. Serv. Gen. Tech. Rep. INT-143. 161 p.

SACKETT, S.S. 1979. Natural fuel loadings in ponderosa pine and mixed conifer forests of the Southwest. USDA For. Serv. Res. Pap. RM-213. 10 p.

SACKETT, S.S. 1980. Reducing natural ponderosa pine fuels using prescribed fire: Two case studies. USDA For. Serv. Res. Note RM-392. 6 p.

SIERRA NEVADA ECOSYSTEM PROJECT. 1996. Sierra Nevada Ecosystem Project, Final report to Congress, Volume I, Assessment summaries and management strategies. Univ. Calif., Davis, Wildland Res. Cent. Rep. 36. 209 p.

SCHEFFÉ, H. 1959. The analysis of variance. Wiley, New York. 477 p.

SOIL SURVEY DIVISION STAFF. 1993. Soil survey manual. USDA Handb. 18. 437 p.

STEPHENS, S.L. 1995. Effects of prescribed and simulated fire and forest history of giant sequoia (*Sequoiadendron giganteum* [Lindley] Buchholz.)–mixed conifer ecosystems of the Sierra Nevada, California. Unpubl. Ph.D. diss., Univ. Calif., Berkeley. 108 p.

VAN WAGTENDONK, J W 1985 Fire suppression effects on fuels and succession in short-fire-interval ecosystems P 119–126 *in* Proc of Symp and Workshop on wilderness fire, Lotan, J E , et al (tech coords) USDA For. Serv. Gen. Tech. Rep. INT-182. 424 p.

VAN WAGTENDONK, J.W. 1974. Refined burning prescriptions for Yosemite National Park. USDI Nat. Park Serv. Occas. Pap. 21. 21 p.

VAN WAGTENDONK, J.W. 1996. Use of a deterministic fire growth model to test fuel treatments. P. 1155–1165 *in* Sierra Nevada Ecosystem Project, Final report to Congress, Volume II, Assessments and scientific basis for management options. Univ. Calif., Davis, Wildland Res. Cent. Rep. 37 1528 p.

VAN WAGTENDONK, J.W., AND C.A. SYDORIAK. 1987. Fuel accumulation rates after prescribed fires in Yosemite National Park. Proc. 9th Conf. Fire For Meteor. 9:101–105.

VAN WAGTENDONK, J.W., AND W.M. SYDORIAK. 1985. Correlation of woody and duff moisture contents. Proc. 8th Conf. Fire For. Meteor. 8:186–191

VAN WAGTENDONK, J.W., J.M. BENEDICT, AND W.M. SYDORIAK. 1996. Physical properties of woody fuel particles of Sierra Nevada conifers. Int. J. Wildl Fire 6(3):117–123.

WOODARD, P.M., AND R.E. MARTIN. 1980. Duff weight and depth in a high elevation *Pinus contorta* Dougl. forest. Can. J. For. Res. 10:7–9.