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Physical Properties of Woody Fuel Particles of Sierra Nevada Conifers

Jan W. van Wagtendonk[1], James M. Benedict[2], and Walter M. Sydoriak[3]

[1]*U.S. Geological Survey, Yosemite Field Station, El Portal, California 95318 USA*
Tel. 1 209 379-1885; Fax 1 209 379-1886

[2]*National Park Service, Santa Monica Mountains National Recreation Area, Agoura Hills, California 91301 USA*

[3]*National Park Service, Bandelier National Monument, Los Alamos, New Mexico 87544 USA*

Abstract. A study of the physical properties of Sierra Nevada conifer fuel particles showed that average diameter, squared quadratic mean diameter, surface-area-to-volume ratio, and specific gravity varied significantly by species for all four timelag fuel diameter size classes. The nonhorizontal angle was not significantly affected by size class, and the developmental stage of the overstory did not affect any of the properties. These values are used to calculate fuel weight and predict fire behavior. Regional variation in physical properties can result in fuel weight estimates for the Sierra Nevada that differ from under 40.8 percent to over 8.3 percent from those calculated from Rocky Mountain values. These differences made small changes in predicted fire behavior.

Keywords: Physical fuel properties, conifers, Sierra Nevada

Introduction

With the renewed emphasis on ecosystem management, land managers are under increasing pressure to deal with unnaturally high accumulations of fuels that have resulted from logging activities or years of fire suppression. The use of prescribed fire to reduce fuels requires reliable estimates of fuel weight in order to safely accomplish the burn and to evaluate its effectiveness in meeting management objectives (USDI, NPS 1992). Fuel weight assessment is also a component of the National Fire Danger Rating System (Deeming et al. 1977) and the prediction system used by fire behavior analysts (Rothermel 1983, Burgan and Rothermel 1984).

The planar intercept method of inventorying downed woody material developed by Brown (1974) is the primary procedure used for appraising fuel complexes. It is also the basis for photo series for quantifying natural forest residues (Blonski and Schramel 1981). This method uses physical fuel properties of conifer species found in the Rocky Mountains to estimate fuel weight. Since physical properties for a species could vary significantly by region of the country, it is unknown whether values derived from studies in other parts of the West could be used directly for calculating fuel weight in the Sierra Nevada.

Fuel weight is estimated by counting fuel particle intersections by size classes that correspond to fuel moisture timelag classes (Brown 1974). Timelag is the amount of time necessary for a fuel particle to reach 63 percent of its equilibrium moisture content (Lancaster 1970). One-hour timelag fuels consist of dead herbaceous plants and roundwood less than .64 cm (.25 in) in diameter, as well as the uppermost litter layer. Dead roundwood fuels from .64 cm (.25 in) to 2.54 cm (1 in) in diameter make up the 10-hour timelag fuels. One-hundred-hour timelag fuels include dead roundwood from 2.54 (1 in) to 7.62 cm (3 in) in diameter, while 1000-hour timelag fuels consist of dead roundwood greater than 7.62 cm (3 in). These largest particles are separated into sound or rotten classes based on visual determination of the degree of deterioration.

In order to convert counts into weight, the total number of intersections in each size class is multiplied by species specific constants predetermined to account for differences in particle squared quadratic mean diameter, specific gravity, and nonhorizontal angle of inclination:

$$WEIGHT = \frac{CONST \cdot n \cdot QMD \cdot SG \cdot SEC \cdot SLP}{LENGTH}$$

Where *CONST* is a constant that converts the results to specific units of weight per area (e.g., tons/acre or g/m^2), n is the number of intersections with the sampling plane, *QMD* is the squared quadratic mean diameter, *SG* is the specific gravity, *SEC* is the secant of the nonhorizontal angle, *slp* is the slope of the line, and *LENGTH* is the length of the plane. Diameter and specific gravity convert particle intersections into weight, while the secant of the nonhorizontal angle adjusts for the fact that all particles do not lie horizontally as assumed by the planar intersect theorem (Brown 1971). Acute angles of inclination are converted into their secants for use as correction factors in calculating fuel weight (Brown 1974). Fuel weight and particle surface-area-to-volume ratio are used as inputs to the fire behavior prediction system.

A lack of information on the physical properties of fuel particles of Sierra Nevada conifers reduces the reliability of fuel inventories and fire behavior predictions. Of the 22 conifer species that occur in the Sierra Nevada in California and Nevada, the physical properties of fuel particles of only *Pinus ponderosa* (ponderosa pine), *Pseudotsuga menziesii* (Douglas-fir), *Pinus contorta* (lodgepole pine), and *Abies magnifica* (red fir) have been previously studied (Brown and Roussopoulos 1974, Brown 1972, Beaufait et al. 1975, Sackett 1980, Ryan and Pickford 1978, Bevins 1978, Pitcher 1981). Except for *Abies magnifica*, these studies were not conducted in the Sierra Nevada. In order to fill this information gap, we undertook this study to quantify physical fuel particle properties of Sierra Nevada conifers.

Methods

Fuels were collected from four stands of each of 19 of the 22 species of conifer occurring in the Sierra Nevada that had sufficient fuels for sampling. Most of the stands were in Yosemite National Park; species absent or not well-represented in the park were sampled on adjacent national forests or in Sequoia and Kings Canyon National Parks (Figure 1). Four stands of each species were sampled representing sapling, pole, mature, and old developmental stages. Each selected stand was at least 21 m (70 ft) in diameter with an overstory composed of 100 percent of the desired species, and was free of recent disturbance. The forest floor was visually estimated to contain at least 90 percent of fuels of the desired species. Four 11-m (35-ft) parallel transects 3 m (10 ft) apart were established beneath each species and developmental stage combination (Brown 1974).

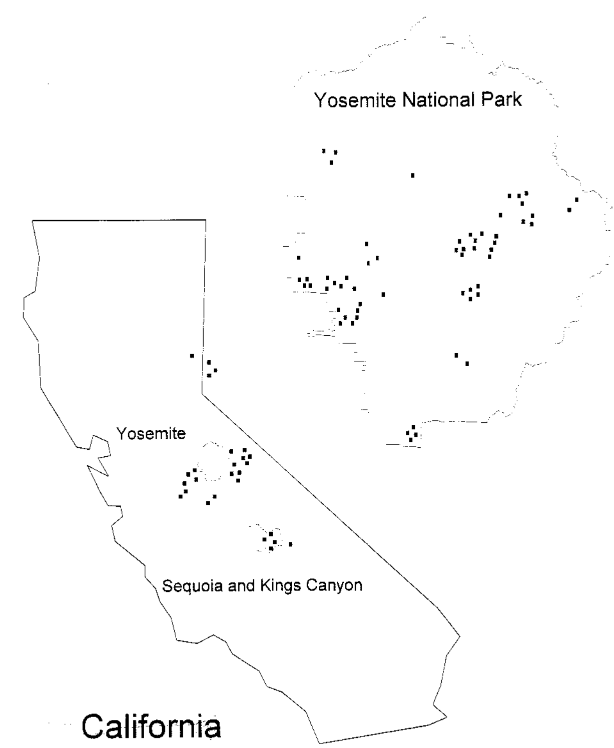

Figure 1. Sampling locations for four stands of each of 19 conifer species in the Sierra Nevada, California and Nevada.

Fuel particle intersections with the sampling plane were categorized by timelag fuel size classes. For each fuel particle that intersected the 11-m (35-ft) sampling plane, two perpendicular diameters were measured at the point of intersection to the nearest .10 cm (.039 in) using calipers. In addition, the acute angle that the intersected particle formed with a horizontal plane was measured using a protractor level to the nearest five degrees.

Five 20 x 50 cm (7.87 x 19.69 in) subplots were systematically placed along each transect to collect woody fuels for a total of 20 subplots per stand. These fuels were separated into the four timelag fuel diameter classes and then sealed in plastic bags. Sound and rotten samples were bagged separately. Samples were dried in a convection oven at 65° C until weight loss stabilized. After drying, fuels of the same stand and size class were combined and up to 10 random grab samples taken for specific gravity determination. Size classes with fewer than 10 particles were completely sampled. A Kraus Jolly specific gravity balance was used to determine the weight of the sample in air and weight of the sample immersed in water (Eberbach 1979). Specific gravity was calculated using the formula:

$$SG = \frac{WT_{air}}{WT_{air} - WT_{water}}$$

where SG is the specific gravity, and WT the weight in air or in water.

Diameter was calculated for each fuel particle by averaging the two perpendicular measurements made at the point the particle intersected with the sampling plane. Squared quadratic mean diameter was calculated by squaring each particle's average diameter and taking the average of the sum for each stand and size class:

$$QMD = \frac{\Sigma d^2_{ave}}{n}$$

where QMD is the squared quadratic mean diameter, d is the average diameter, and n is the number of particles. Dividing the constant value of four by the average diameter of each fuel particle produced the surface-area-to-volume ratio:

$$SAVR = \frac{4}{d_{ave}}$$

where d is the average diameter.

Statistical analyses were performed using two-way analysis of variance for each size class with species and developmental stage as the independent factors for diameter, squared quadratic mean diameter, and surface-area-to- volume ratio. Three-way analysis of variance was used for the secant and specific gravity measurements with size class as the additional independent factor. Post hoc Schefee multiple comparisons were used to determine which means were significantly different from each other (Schefee 1959). All significance tests were at the .05 level.

Percent change in fuel weight estimates was calculated for the three smallest size classes of *Pinus contorta*, *Pinus ponderosa*, and *Pseudotsuga menziesii* by dividing the product of the squared quadratic mean diameter, specific gravity, and average secant derived in this study by the same product from Brown (1974):

$$PCT\ CHANGE = \frac{(QMD \bullet SG \bullet SEC)_{\text{this study}}}{(QMD \bullet SG \bullet SEC)_{\text{Brown}}}.$$

Effects of the weight and surface-area-to-volume changes on fire behavior parameters were tested using the BEHAVE fire behavior prediction system (Andrews 1986).

Table 1. Analysis of variance table for average diameter by fuel size class for 19 Sierra Nevada conifers.

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	Significance of F
0-.64 cm diameter size class					
Species	.445	18	.025	90.017	.000
Stage	.001	3	.000	1.286	.289
Residual	.015	54	.000		
Total	.461	75	.006		
.64-2.54cm diameter size class					
Species	.370	18	.021	7.080	.000
Stage	.023	3	.008	2.676	.056
Residual	.157	54	.003		
Total	.550	75	.007		
2.54-7.62 cm diameter size class					
Species	5.260	18	.292	6.270	.000
Stage	.295	3	.098	2.106	.110
Residual	2.517	54	.047		
Total	8.071	75	.108		
7.62+ cm diameter size class					
Species	205.972	18	13.731	52.894	.000
Stage	.639	3	.213	.821	.489
Residual	11.682	45	.260		
Total	218.294	63	3.465		

Results and Discussion

Over 20,000 fuel particles were measured including over 12,000 particles in the 0-.64 cm (0-.25 in) size class and nearly 7,000 in the .64-2.54 cm (.25-1 in) class.

Average Diameter

Species differences in average diameter were significant for all size classes while developmental stage had no significant effect (Table 1). Multiple comparisons divided the 0-.64 cm fuels into nine significantly different diameter groups with *Pinus ponderosa*, *Pinus washoensis* (Washoe pine), *Pinus flexilis* (limber pine), *Pinus jeffreyi* (Jeffrey pine), and *Pinus sabiniana* (grey pine) in the largest group. The group with smallest diameters included *Tsuga mertensiana* (mountain hemlock), *Pseudotsuga menziesii*, and *Juniperus occidentalis* (western juniper).

Two large overlapping groups were formed for the .64-2.54 cm size class. *Ponderosa pine*, *Juniperus occidentallis*, and *Pinus monophylla* (single-leaf pinyon) were too large for the first group, while *Pinus monticola* (western white pine) was excluded from the second group. In the 2.54-7.62 cm diameter size class there were four significantly different groups with *Pinus ponderosa* and *Pinus jeffreyi* unique to the larger group and *Pinus attenuata* (knobcone pine) to the smaller group. Seven groups were formed in the 7.62+ cm class with *Sequoiadendron giganteum* (giant sequoia), *Pinus lambertiana* (sugar pine), and *Abies magnifica* in the largest group and *Juniperus occidentallis*, *Pinus attenuata*, *Calocedrus decurrens* (incense-cedar), and *Pseudotsuga menziesii* in the smallest group.

The largest diameters for the two smaller size classes were for *Pinus ponderosa* with .46 cm (.18 in) and 1.19 cm (.47 in) respectively (Table 2). This corresponds to similar findings by Ryan and Pickford (1978) of .46 cm (.18 in) and 1.22 cm (.48 in) for the same species. Brown and Roussopoulos (1974) reported naturally fallen *Pinus ponderosa* particle diameters of .46 cm (.18 in) and 1.14 cm (.45 in). In the .64-2.54 cm (.24-1 in) size class, they found diameters for *Pinus contorta* of 1.40 cm (.55 in) and for *Pseudotsuga menziesii* of 1.30 cm (.51 in). Their diameter estimate for *Pinus ponderosa* in the 2.54-7.62 cm (1-3 in) class was 4.24 cm (1.67 in), identical to the one obtained in this study. No previous studies included particles in the 7.62+ cm (3+ in) class.

Previously reported values for *Pseudotsuga menziesii* and *Pinus contorta* diameters were less than those in this study for all size classes except as noted above in both the Brown and Roussopoulos (1974) and Ryan and Pickford (1978) studies. *Abies magnifica*, on the other hand, had only slightly greater values than those reported here (Pitcher 1981). The smallest diameter in the 0- .64 cm (0-.25 in) class was .18 cm (.07 in) for *Tsuga mertensiana*. Bevins (1978) reported that *Tsuga heterophylla* (western hemlock), a similar species, had an average diameter of .15 cm (.06 in) in that class. The fine branching habit of

Table 2. Average diameter by fuel size class for 19 Sierra Nevada conifers.

Species	Fuel Size Class (cm)			
	0-.64	.64-2.54	2.54-7.62	7.62+
	cm			
Abies concolor	0.26	1.07	3.41	10.97
Abies magnifica	0.29	1.10	3.92	12.78
Calocedrus decurrens	0.27	1.01	4.07	8.67
Juniperus occidentalis	0.24	1.17	3.72	7.85
Pinus albicaulis	0.34	1.04	3.87	9.63
Pinus attenuata	0.30	1.05	3.16	8.51
Pinus balfouriana	0.31	0.96	3.37	—
Pinus contorta	0.30	1.12	3.73	11.75
Pinus flexilis	0.43	1.13	3.87	10.98
Pinus jeffreyi	0.38	1.04	4.26	9.88
Pinus lambertiana	0.33	1.12	3.75	12.78
Pinus monophylla	0.27	1.16	3.50	11.40
Pinus monticola	0.25	0.90	3.22	—
Pinus ponderosa	0.46	1.19	4.23	10.28
Pinus sabiniana	0.38	1.04	3.57	—
Pinus washoensis	0.45	1.06	3.53	10.72
Pseudotsuga menziesii	0.21	1.11	3.49	8.70
Seguoiadendron giganteum	0.35	1.05	3.98	14.57
Tsuga mertensiana	0.18	1.14	3.62	10.77
All Species	0.28	1.09	3.84	11.33

Tsuga, particularly in comparison to *Pinus ponderosa*, explain such extremes.

Squared Quadratic Mean Diameter

Since squared quadratic mean diameter is calculated from the average diameter, the analysis of variance results were similar: it was significantly affected by species but not by developmental stage. The multiple comparisons also showed a similar pattern with *Pinus ponderosa* in the group with the largest diameters and *Pseudotsuga menziesii* among the smallest (Table 3).

For *Pinus ponderosa*, differences between reported studies are small. For instance, the squared quadratic mean diameter for 0-.64 cm (0-.25 in) particles was identical to that in Ryan and Pickford (1978), .013 cm^2 (.002 in^2) more than that in Brown and Roussopoulos (1974), and .013 cm^2 (.002 in^2) less than reported by Sackett (1980). Similarly, the values for .64-2.54 cm (.25-1 in) fuels were within .162 cm^2 (.025 in^2) of each other, and for 2.54-7.62 cm (1-3 in) fuels, within 1.019 cm^2 (.158 in^2).

Variation between studies was greater for *Pseudotsuga menziesii*, particularly in the larger size classes. For instance, for 2.54-7.62 cm (1-3 in) fuels, Brown and Roussopoulos (1974) found a value 6.45 cm^2 (1.00 in^2) higher than the 12.04 cm (1.87 in) diameter reported here, while Sackett (1980) showed a 8.23 cm^2 (1.28 in^2) larger value. Such differences would result in 35 percent and 41 percent overestimations, respectively.

Pinus contorta had little variation in comparison to the results in Ryan and Pickford (1978) and Brown and Roussopoulos (1974). Small differences were found for *Abies magnifica* between this study and that of Pitcher (1981) and between *Tsuga mertensiana* and *Tsuga heterophylla* (Bevins 1978), although all mean fuel size classes tended to be smaller in this study.

Surface-Area-to-Volume Ratio

In a pattern similar to diameter, the surface-area-to-volume ratio was significantly affected by species but not development stage for all size classes. Multiple comparisons showed that *Pinus ponderosa* generally had significantly larger ratios while *Tsuga mertensiana*, *Pinus monticola*, *Pinus attenuata*, and *Juniperus occidentalis* had the smallest ratios (Table 4).

Other studies did not report this ratio, but the same relationships between species would exist since diameter is divided into a constant to obtain the ratio. Since the fire behavior and fire danger systems combine surface-area-to-volume ratios for needles with those of smallest woody particle size class, a comparison could not be made with those values. For the larger size classes, the average values found in this study were larger than those used in the fuel models. Both models in the two systems use 3.58 cm^{-1} (109 ft^{-1}) for 10-hour fuels compared to the average of 4.20 cm^{-1} (128.02 ft^{-1}) calculated in this study (Albini 1976, Cohen and Deeming 1985). Our value for 100-hour fuels was 1.13 cm^{-1} (34.44 ft^{-1}) while both systems use .98 cm^{-1} (30 ft^{-1}). All NFDRS models that have a 1,000-hour fuels component use a surface-area-to-volume ratio of .26

Table 3. Average squared quadratic mean diameter by fuel size class for 19 Sierra Nevada conifers.

Species	Fuel Size Class (cm)			
	0-.64	.64-2.54	2.54-7.62	7.62+
	cm^2			
Abies concolor	0.08	1.32	11.56	162.56
Abies magnifica	0.10	1.32	16.24	219.93
Calocedrus decurrens	0.09	1.23	20.79	74.30
Juniperus occidentalis	0.08	1.61	13.92	61.62
Pinus albicaulis	0.13	1.21	14.75	92.74
Pinus attenuata	0.10	1.25	9.68	70.39
Pinus balfouriana	0.12	0.92	12.82	—
Pinus contorta	0.10	1.44	13.39	138.06
Pinus flexilis	0.21	1.28	17.72	115.78
Pinus jeffreyi	0.15	1.25	17.31	135.49
Pinus lambertiana	0.12	1.46	13.61	169.52
Pinus monophylla	0.09	1.41	11.56	129.96
Pinus monticola	0.08	0.79	9.92	—
Pinus ponderosa	0.23	1.56	19.36	101.81
Pinus sabiniana	0.14	0.94	12.91	—
Pinus washoensis	0.22	1.37	13.47	122.77
Pseudotsuga menziesii	0.06	1.37	12.04	75.69
Seguoiadendron giganteum	0.14	1.28	17.06	167.70
Tsuga mertensiana	0.05	1.46	13.61	115.99
All Species	0.12	1.28	14.52	127.24

Table 4. Average surface area-to-volume ratio by fuel size class for 19 Sierra Nevada conifers.

Species	Fuel Size Class (cm)			
	0-.64	.64-2.54	2.54-7.62	7.62+
	cm^{-1}			
Abies concolor	19.22	4.20	1.23	0.39
Abies magnifica	18.04	4.13	1.11	0.35
Calocedrus decurrens	18.19	4.43	1.08	0.46
Juniperus occidentalis	21.78	3.93	1.15	0.51
Pinus albicaulis	13.56	4.30	1.11	0.41
Pinus attenuata	15.65	4.35	1.31	0.47
Pinus balfouriana	15.93	4.60	1.13	—
Pinus contorta	15.51	4.12	1.16	0.37
Pinus flexilis	10.55	3.97	1.13	0.38
Pinus jeffreyi	12.17	4.37	1.04	0.43
Pinus lambertiana	14.46	4.15	1.13	0.34
Pinus monophylla	17.44	4.00	1.20	0.35
Pinus monticola	19.42	4.83	1.26	—
Pinus ponderosa	9.85	3.80	1.06	0.41
Pinus sabiniana	11.73	4.37	1.19	—
Pinus washoensis	9.84	4.27	1.15	0.39
Pseudotsuga menziesii	24.46	4.10	1.21	0.46
Seguoiadendron giganteum	12.45	4.33	1.09	0.31
Tsuga mertensiana	28.84	4.04	1.19	0.40
All Species	17.72	4.20	1.13	0.38

cm^{-1} (8 ft^{-1}), compared to .38 cm^{-1} (11.58 ft^{-1}) calculated for this study.

Nonhorizontal Angle

Species significantly affected the secant of the nonhorizontal angle but developmental stage and diameter size class did not (Table 5). Multiple comparisons showed that no two groups were significantly different from each other.

The average secant of the acute angle to the horizontal for the 7.62+ cm (3+ in) size class for all species was 2.67 (Table 6). Average secants for the three smaller size classes all fell within the range from 1.00 to 1.06 which is considerably lower than the 1.13 used for all species in Brown (1974) or the 1.21 to 1.28 range reported by Brown and Roussopoulos (1974) for naturally fallen branches in the Rocky Mountains.

Table 5. Analysis of variance table for average secant of acute angles of inclination of nonhorizontal fuel particles for 19 Sierra Nevada conifers.

Source	Sums of Squares	Degrees of Freedom	Mean Square	F	Significance of F
Species	.089	18	.005	1.704	.038
Stage	.009	3	.003	1.057	.368
Size Class	.006	3	.002	.697	.555
Residual	.777	253	.003		
Total	.884	277	.003		

Specific Gravity

Specific gravity of the sound fuels was significantly affected by species and size class but not by developmental stage (Table 7). In addition, species was not significant for the 7.62+ cm (3+ in) rotten fuels. Multiple comparisons showed that *Juniperus occidentalis* and *Tsuga mertensiana* generally had the highest specific gravities while several species were part of the lower groups. The largest size class had significantly lower specific gravity values than the other three classes, and the smallest two classes had significantly higher values.

The average specific gravity for rotten fuels was .36. Values for all size classes ranged from .32 for 7.62 cm+ (3+ in) *Abies concolor* to .67 for 0-.64 cm (0-.25 in) *Juniperus occidentalis* and *Tsuga mertensiana* (Table 8). Specific gravities found in this study for *Pinus ponderosa*, *Pinus contorta*, and *Pseudotsuga menziesii* were comparable to those from previous studies. Brown (1972) found lower values from the Rocky Mountains, while Beaufait et al. (1975) reported slightly higher values. Sackett (1980) had lower values for the Southwest while Ryan and Pickford (1978) indicated higher specific gravities from the Northwest.

Table 6. Average secant of acute angles of inclination of nonhorizontal particles by fuel size class for 19 Sierra Nevada conifers.

Species	Fuel Size Class (cm)			
	0-.64	.64-2.54	2.54-7.62	7.62+
	Secant			
Abies concolor	1.03	1.02	1.02	1.01
Abies magnifica	1.03	1.02	1.01	1.00
Calocedrus decurrens	1.02	1.02	1.03	1.06
Juniperus occidentalis	1.03	1.04	1.04	1.04
Pinus albicaulis	1.02	1.02	1.02	1.02
Pinus attenuata	1.03	1.02	1.00	1.02
Pinus balfouriana	1.02	1.02	1.01	—
Pinus contorta	1.02	1.02	1.01	1.05
Pinus flexilis	1.02	1.02	1.01	1.01
Pinus jeffreyi	1.03	1.03	1.04	1.05
Pinus lambertiana	1.04	1.04	1.03	1.03
Pinus monophylla	1.02	1.01	1.01	1.05
Pinus monticola	1.03	1.02	1.06	—
Pinus ponderosa	1.02	1.03	1.02	1.01
Pinus sabiniana	1.05	1.03	1.02	—
Pinus washoensis	1.02	1.02	1.01	1.05
Pseudotsuga menziesii	1.03	1.02	1.03	1.04
Seguoiadendron giganteum	1.02	1.02	1.02	1.01
Tsuga mertensiana	1.04	1.02	1.02	1.00
All Species	1.03	1.02	1.02	1.02

Fuel Weight Estimates

Average squared quadratic mean diameter, average secant, and specific gravity are used to adjust intersection

Table 7. Analysis of variance table for specific gravity for 19 Sierra Nevada conifers.

Source	Sums of Squares	Degrees of Freedom	Mean Square	F	Significance of F
Species	.595	18	.033	6.882	.000
Stage	.009	3	.003	.600	.616
Size Class	.642	3	.214	44.539	.000
Residual	1.216	253	.005		
Total	2.524	277	.009		

counts to estimate fuel weight. A comparison of the effect of values derived in this study to values in Brown (1974) show that considerable overestimation and underestimation can occur (Table 9). For instance, the product of those values for 0-.64 cm (0-.25 in) *Pinus ponderosa* fuels is 8.3 percent more than the one derived by Brown (1974). For .64-2.54 cm (.25-1 in) *Pinus contorta*, the fuel weight estimate is 40.8 percent less than derived by Brown (1974). The variation for other size classes of these two species was within those extremes. Estimates for all size classes of *Pseudotsuga menziesii* were less than those in Brown (1974) ranging from 12.4 to 25.0 percent less.

It is interesting to note that there were compensating variations between the factors. While the average secants measured in this study were consistently 10 percent less than those in Brown (1974), specific gravity was generally 10 percent more. Squared quadratic mean diameter varied between species with *Pinus ponderosa* having larger diameters than those reported in Brown (1974), and *Pinus contorta* and *Pseudotsuga menziesii* having smaller diameters.

Table 8. Average specific gravity by fuel size class for 19 Sierra Nevada conifers.

Species	Fuel Size Class (cm)			
	0-.64	.64-2.54	2.54-7.62	7.62+
	specific gravity			
Abies concolor	0.53	0.54	0.57	0.32
Abies magnifica	0.57	0.56	0.47	0.38
Calocedrus decurrens	0.59	0.54	0.55	0.41
Juniperus occidentalis	0.67	0.65	0.62	—
Pinus albicaulis	0.55	0.49	0.48	0.42
Pinus attenuata	0.59	0.55	0.39	—
Pinus balfouriana	0.59	0.61	—	—
Pinus contorta	0.53	0.48	0.54	0.58
Pinus flexilis	0.57	0.57	0.54	0.63
Pinus jeffreyi	0.53	0.55	0.55	—
Pinus lambertiana	0.59	0.59	0.52	0.43
Pinus monophylla	0.65	0.64	—	—
Pinus monticola	0.56	0.56	0.49	—
Pinus ponderosa	0.55	0.56	0.48	0.40
Pinus sabiniana	0.64	0.61	0.43	—
Pinus washoensis	0.53	0.52	0.44	0.35
Pseudotsuga menziesii	0.60	0.61	0.59	0.35
Seguoiadendron giganteum	0.57	0.57	0.56	0.54
Tsuga mertensiana	0.67	0.65	0.62	0.66
All Species	0.58	0.57	0.53	0.47

Table 9. Squared quadratic mean diameter (QMD), secant (SEC), specific gravity (SG), their product, and percent change between Brown (1974) and this study by fuel size class for *Pinus contorta, Pinus ponderosa,* and *Pseudotsuga menziesii.*

0-.64 cm size class	QMD	SEC	SG	Product	Percent
Brown (1974)					
Pinus contorta	0.13	1.13	0.48	0.07	-
Pinus ponderosa	0.22	1.13	0.48	0.12	-
Pseudotsuga menziesii	0.08	1.13	0.48	0.04	-
This study					
Pinus contorta	0.10	1.02	0.53	0.05	-18.60
Pinus ponderosa	0.23	1.02	0.55	0.13	8.30
Pseudotsuga menziesii	0.05	1.03	0.60	0.03	-25.00
.64-2.54 cm size class	**QMD**	**SEC**	**SG**	**Product**	**Percent**
Brown (1974)					
Pinus contorta	2.22	1.13	0.48	1.20	-
Pinus ponderosa	1.54	1.13	0.48	0.84	-
Pseudotsuga menziesii	1.96	1.13	0.48	1.06	-
This study					
Pinus contorta	1.44	1.02	0.48	0.71	-40.80
Pinus ponderosa	1.56	1.02	0.56	0.89	6.00
Pseudotsuga menziesii	1.37	1.02	0.61	0.85	-19.80
2.54-7.62 cm size class	**QMD**	**SEC**	**SG**	**Product**	**Percent**
Brown (1974)					
Pinus contorta	18.52	1.13	0.40	8.37	-
Pinus ponderosa	20.13	1.13	0.40	9.10	-
Pseudotsuga menziesii	18.52	1.13	0.40	8.37	-
This study					
Pinus contorta	13.39	1.01	0.54	7.30	-12.80
Pinus ponderosa	19.36	1.02	0.48	9.48	4.20
Pseudotsuga menziesii	12.04	1.03	0.59	7.32	-12.40

When the percent changes in fuel weight are made to fuel model 8 for *Pseudotsuga menziesii* and *Pinus contorta*, only small changes in fire behavior occur. Using the low standard environmental conditions in Burgan and Rothermel (1984), The *Pseudotsuga menziesii* model produced identical predictions for rate of spread and flame length and was only 1 kw/m greater in fire intensity. For *Pinus contorta*, rate of spread was equal while flame length increased from .3 m to .4 m and fire line intensity from 23 kw/m to 27 kw/m. Rate of spread and flame length were the same for *Pinus ponderosa*, while fire line intensity dropped from 170 kw/m to 161 kw/m. These small changes are attributed to the dual role that fuel weight plays in the Rothermel (1972) fire spread equation. Not only does fuel weight contribute to reaction intensity in the numerator of the equation, but it acts as a heat sink in the denominator.

Conclusion

Although there were significant differences in the physical properties of Sierra Nevada conifer fuel particles as compared to previous studies, these differences were, in most cases, small and compensating. Regional variation can, however, result in fuel weight estimates that differ by up to 41.5 percent. Managers who use the planar intersect method to inventory fuels should use the best available data to assure that fuel weight estimates are accurate. The values presented here will improve fuel weight estimates for Sierra Nevada conifer forests and make small changes to fire behavior predictions.

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