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Estimating Volume, Biomass, and Potential Emissions of Hand-Piled Fuels

Clinton S. Wright, Cameron S. Balog, and Jeffrey W. Kelly

Authors

Clinton S. Wright is a research forester and **Jeffrey W. Kelly** was a forestry technician, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, 400 North 34th Street, Suite 201, Seattle, WA 98103; **Cameron S. Balog** is a research scientist, School of Forest Resources, University of Washington, 400 North 34th Street, Suite 201, Seattle, WA 98103.

Abstract

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Dimensions, volume, and biomass were measured for 121 hand-constructed piles composed primarily of coniferous (n = 63) and shrub/hardwood (n = 58) material at sites in Washington and California. Equations using pile dimensions, shape, and type allow users to accurately estimate the biomass of hand piles. Equations for estimating true pile volume from simple geometric shapes and measurements of pile dimensions were also developed for users who require estimates of pile volume for regulatory reporting. Biomass and volume estimation equations were developed to allow users to estimate either value from pile dimensions. Hand pile biomass estimates can be used to predict fuel consumption and smoke emissions by applying proportional consumption estimates and emission factors. Equations to estimate pile volume, pile biomass, fuel consumption, and pollutant emissions from pile shape, dimensions, and quantity are programmed into a Web-based calculator for use by the management and regulatory communities.

Keywords: Hand piles, fuel, fuel treatment, biomass, emissions, smoke management.

Contents

Introduction

Understory growth is present in excess of historical natural levels and may contribute to more extreme wildland fire behavior and elevated fire hazard in many dry forests. Anomalously high amounts of understory biomass may cause potentially more extreme fire behavior than was common historically, leading to fires that are potentially more intense, severe, dangerous, and difficult to control. Thinning of the forest understory, midstory, and overstory coupled with reduction or removal of this biomass is being implemented in forests throughout the Western United States as one approach for mitigating elevated fire potential and preventing catastrophic surface and crown fire events (Agee 1996, Agee et al. 2000, Graham et al. 1999).

Federal land management policies, such as the National Fire Plan and the Healthy Forest Restoration Act of 2003 (HFRA 2003) direct managers of forests and woodlands that are at risk of catastrophic wildland fire to modify fuels to reduce risk and restore ecosystem pattern and process. Mechanical treatments such as thinning, brush cutting, and mastication are being used to reshape dry forests and woodlands with the intention of reducing their susceptibility to catastrophic fires. Substantial increases in dead and down surface fuels related to management activity (i.e., activity fuels) are one consequence of mechanical treatments. Surface fuel treatment following thinning or brush cutting is necessary to effectively mitigate wildland fire risk.

Traditionally, broadcast prescribed burning was one of the main treatment methods for reducing or removing understory vegetation and activity fuels. However, with increases in prescribed fire complexity and risk associated with elevated fuel levels, proximity to the wildland/urban interface, and air quality regulations (i.e., Federal Clean Air Act and State Smoke Management Plans), the use of conventional broadcast burning as a fuel treatment is now more difficult in some circumstances.

Heavy accumulations of activity fuels were historically piled by using heavy equipment following clearcut and partial-cut harvest operations. Machines, however, can cause soil compaction and may be less practical for piling the surface fuels that are created from thinning where the overstory is left in place. Piling by hand followed by burning is being used more frequently in many forest and woodland types to remove or reduce the residue created by mechanical manipulation of excessive understory (and sometimes overstory) growth (fig. 1). Past pile characterization research (Hardy 1996; Johnson 1984; Little 1982; McNab 1980, 1981; McNab and Saucier 1980) dealt only with large, crane-constructed and tractor-built piles and windrows. Machine-constructed piles have different physical properties than hand-constructed piles owing in part to the inclusion of larger fuel particles (tree boles and large limbs) and mineral soil. In hand-piling operations, in contrast, smaller nonmerchantable material is commonly thinned and piled on site without the aid of machinery and contains needles,

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Ernesto Alvarado

Figure 1—Typical hand-piled fuels after thinning in sample area near Naches, Washington.

twigs, and small-diameter branches and boles. In areas with a major shrub component, cutting and hand piling is also used for reducing heavy surface fuels. Compositional and structural differences between hand and machine piles result in different relationships between pile volume and pile biomass and in different combustion environments (table 1).

Hand piling and burning mitigates some of the concerns about environmental impacts, safety, and air quality and is a viable alternative for treating a variety of areas.

Hand piling and burning mitigates some of the concerns about environmental impacts, safety, and air quality and is a viable alternative for treating a variety of areas. Use of hand piling mitigates soil compaction concerns and widens the prescribed burning window, allowing managers to use fire under weather and fuel moisture conditions that are inappropriate or ineffective for broadcast burning. Fire managers have more flexibility when burning piles. For example, piles can be burned under weather conditions and with reduced staffing levels that are not conducive to safe and effective broadcast burning (fig. 2). Pile burning can be more easily monitored and controlled, minimizing escape potential. Likewise, fire and fuel managers can choose to not burn all piles in an area at once, thereby distributing total smoke production over multiple days or burning periods and reducing the air quality impacts of smoke. Furthermore, piled fuels burn more efficiently than broadcast fuels, thereby reducing the quantity of smoke emitted for comparable quantities of fuel consumed (Johansen 1981, Ward et al. 1989).

Table 1—Some differences between hand- and machine-constructed piles

Characteristic	Hand piles
Woody material	Lack large logs; have a greater proportion of biomass in small size classes
Dimensions	Are smaller
Soil content	Are cleaner with less soil contamination for more efficient combustion


Eric Siemer

Figure 2—Hand pile burning during winter conditions on the Bear Valley National Wildlife Refuge, Oregon.

The Healthy Forest Restoration Act (HFRA 2003) specifies that 50 percent of funds allocated for fuel reduction should be used for treatments within the wildland/urban interface (typically referred to as the "WUI"). Use of mechanical treatment and hand piling is widespread in the WUI because of concerns about the risks and impacts associated with broadcast prescribed burning of accumulated fuels (e.g., potential for escape or private property damage, public health impacts of widespread and potentially extended-duration smoke events, etc.). Approximately 25,000 ha were treated with hand piling and burning in the Pacific Northwest (U.S. Forest Service, Region 6—Washington and Oregon) in 2005.[1] The need for land managers to mitigate risk

[1] Russell, J. 2007. Personal communication. Air Resources/Smoke Management Program Manager, U.S. Forest Service and Bureau of Land Management, Pacific Northwest Region, 333 SW First Avenue, Portland, OR 97204.

The ability to accurately quantify the mass of hand-piled fuels will allow fire and air resource managers to make more accurate estimates of potential emissions and smoke impacts.

associated with wildland fire by reducing fuel loading, while also complying with federal and state air quality regulations, provides an impetus for research that improves the accuracy of the impact of fuel reduction activities. The ability to accurately quantify the mass of hand-piled fuels will allow fire and air resource managers to make more accurate estimates of potential emissions and smoke impacts. This project improves assessments of volume and biomass of hand piles, leading to better smoke production estimates, improved burn scheduling, and compliance with the maximum allowable emissions as determined by various state smoke management plans.

Objectives

Land managers and air quality regulators need a tool to accurately and efficiently estimate the biomass and emissions from burning of hand-piled fuels as pile burning becomes a more widespread and common practice for treating high fire hazard areas with surface fuels in excess of desired levels. Our objective was to quantify the relationships between pile composition, pile size, and pile biomass by measuring and weighing hand-constructed piles. We sampled piles composed of different types of debris (i.e., conifer, shrub, and hardwood) with a variety of shapes and sizes to develop equations for estimating the volume and biomass of hand piles. We provide methods for calculating emissions from the burning of hand-piled biomass, and also compare pile loading estimates using relationships developed from this study to estimates based on relationships reported by Hardy (1996) that are implemented in CONSUME 3.0[2] (Prichard et al., n.d.) to evaluate the different outcomes that are predicted by the two models.

Methods

The field portion of this study was concentrated in forest and woodland types in the Western United States. Forested stands with hand piles were selected in Washington (Naches) and California (Whiskeytown, Porterville, and San Luis Obispo) with the assistance of local and regional fire and fuels managers (fig. 3). Sampling sites were typical of hand-piling operations. Our intention in selecting study sites and pile types was that the results of this study would have utility throughout the West where surface fuels are being treated with the use of hand piling and burning.

We had proposed to characterize three types of piles with our sampling: conifer, hardwood, and shrub. Pure hardwood-dominated piles were difficult to find and were typically mixed with shrub material. Therefore, our data represent hand-constructed

[2] CONSUME 3.0 is a software decision-support tool used by fire, fuel, and air quality managers to predict fuel consumption and emissions during prescribed and wildland fires.

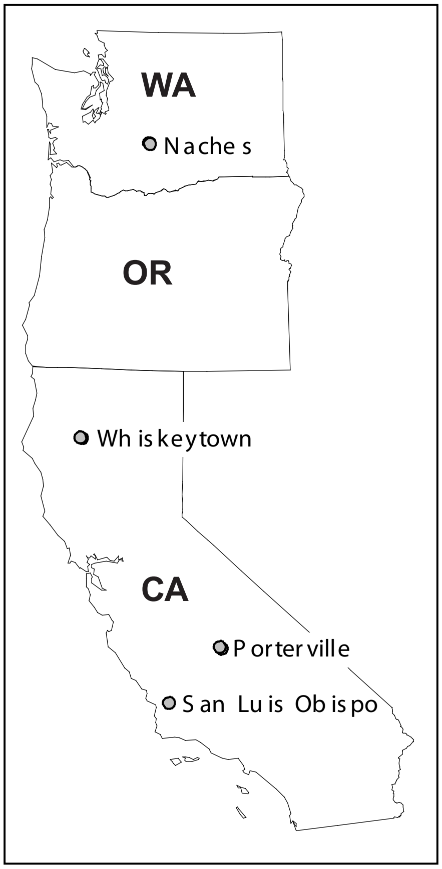

Figure 3—Approximate hand pile sample locations.

piles composed primarily of either coniferous material or various combinations of shrub and hardwood material owing to the general scarcity of pure hardwood piles.

We measured and weighed 121 hand piles (63 conifer, 58 shrub/hardwood) of varying size in a total of seven stands at four locations. Within stands, piles were chosen by using a random walk procedure to remove bias from the pile-selection process. The pile that was closest to a point 10 m at a random azimuth from a randomly-selected starting point was chosen, with each successive pile located 10 m at a random azimuth from the last measured pile. Once located, pile volume was measured using two methods: geometric volume and surface shape volume. For estimates of geometric pile volume, we measured the dimensions required to compute the volume of one of seven specific geometric shapes (fig. 4) and applied the appropriate volume formula (table 2). For estimates of surface shape volume, we mapped the contours of the pile surface using an angle gauge and level system. A series of level lines were projected from the center to the edge of the pile in 30° increments using a string line and a bubble level. We measured the vertical offset (to the nearest 3 cm) from the level line at 15-cm intervals in the horizontal from the pile center (fig. 5). This method allowed us to compute a three-dimensional coordinate for systematically located points on the surface of the pile from which volume was estimated using a triangular irregular network (TIN) lattice constructed in ArcGIS 9.1 (ESRI 2008).[3 4] For the purposes of this study, we consider the TIN-derived volume (fig. 6) to be the best representation of the true volume of the pile.

Following dimension and surface measurements, piles were deconstructed and fuel particles were sorted into species and size class groups (<2.5, 2.5 to 7.6, and >7.6

[3] For piles located on sloping ground, the estimated height of the center of the pile was used to determine the effective ground level in pile volume calculations.

[4] Use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

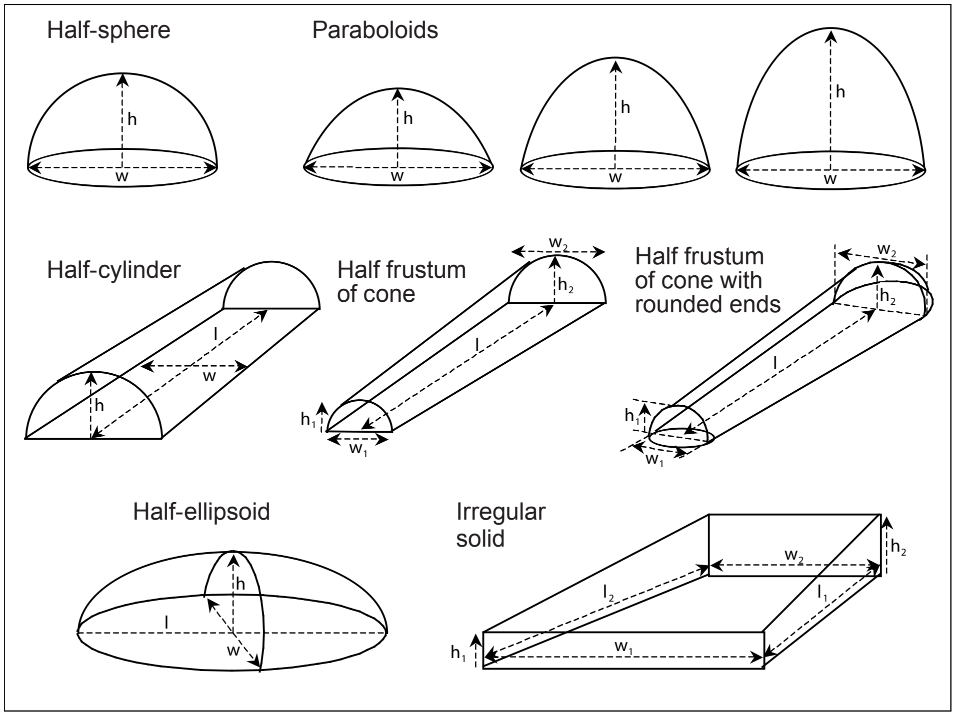

Figure 4—Geometric pile shapes and required dimensions. Redrawn from Hardy (1996).

Table 2—Volume formulas for geometric shapes[a]

Geometric shape	Volume formula
Half-sphere	$V = (\pi \times h \times w^2)/6$
Paraboloid	$V = (\pi \times h \times w^2)/8$
Half-cylinder	$V = (\pi \times w \times l \times h)/4$
Half-frustum of cone	$V = \{\pi \times l[h_1^2 + h_2^2 + (h_1 \times h_2)]\}/6$ or
	$V = \{\pi \times l[w_1^2 + w_2^2 + (w_1 \times w_2)]\}/24$
Half-frustum of cone with rounded ends	$V = \pi\{l[w_1^2 + w_2^2 + (w_1 \times w_2)] + w_1^3 + w_2^3\}/24$
Half-ellipsoid	$V = (\pi \times w \times l \times h)/6$
Irregular solid	$V = [(l_1 + l_2)(w_1 + w_2)(h_1 + h_2)]/8$

[a] See figure 4 for illustration of dimensions.

cm diameter). Species and size class groups of separated piles were weighed in the field with a precision hanging scale (nearest 0.01 kg). One moisture content subsample was collected for each species/size class category for each pile to convert field-measured weight to oven-dry weight. Each moisture content subsample included several appropriately-sized pieces for each species/size class category.

Volume, biomass, and composition data were synthesized and used to calculate physical properties, including packing ratio (the ratio of solid wood volume to total pile volume) and bulk density (the ratio of total pile biomass to total pile volume).

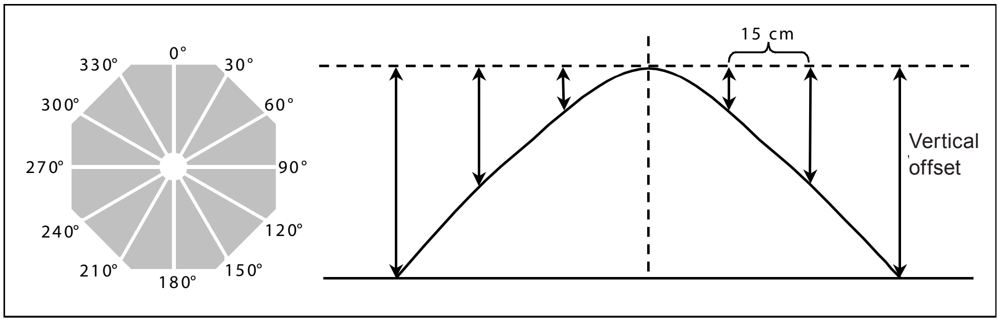

Figure 5—Overhead plan view (left) and cross-section view (right) of pile surface measurement methodology.

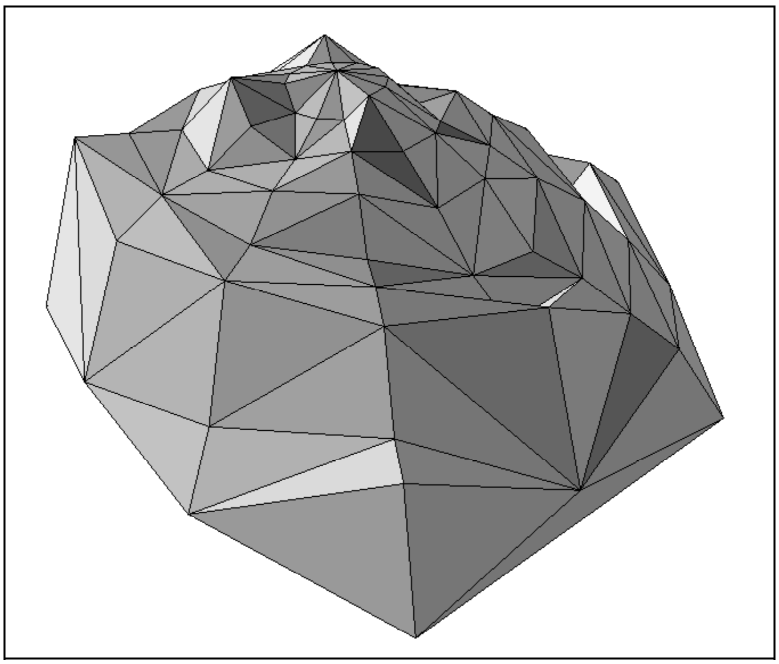

Figure 6—Example triangular irregular network lattice for a typical pile at the Naches, Washington, field site. This pile was 0.73 m high and 1.86 m wide; the “true” volume of this pile was 1.08 m^3.

Estimates of the volume of solid wood were derived by dividing the total mass of fuel particles of a given species by the wood density (Chojnacky 1984, Countryman and Philpot 1970, Dohr 1958, USDA FS 1999, Gray 1982, Jacobsen et al. 2008, Schniewind and Gammon 1983, Zhou et al. 2005). For those species for which published wood density values were unavailable, the wood density of species with similar wood qualities was substituted (e.g., *Arbutus menziesii* for *Arctostaphylos* spp.).

Ordinary least-squares regression was used to develop equations: (1) to estimate true volume from dimension measurements and shape assignments (i.e., from geometric volume), and (2) to estimate biomass from true volume for different pile types (i.e., conifer and shrub/hardwood). T-tests were used to test for differences in pile physical properties (packing ratio and bulk density) and differences in regression slopes and intercepts between pile types and shapes (Zar 1984). We evaluated the bias of our equations as the average of the absolute value of the relative difference between the modeled and measured true volume for each pile and assigned a negative or positive direction to the bias based on the number of over- or under-predictions. We also evaluated precision as the standard deviation of the relative difference between the modeled and measured true volume for each pile.

The equations developed by this analysis have been encoded in a Web-based calculator that allows users to accurately estimate volume and biomass of hand-constructed piles for use in determining potential emissions impacts from burning.

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Results and Discussion

Pile Data

Summary data for sampled hand-constructed piles appear in table 3, and individual pile data are reported in the appendix (tables 7 and 8). In general, hand piles are of modest size (overall mean volume of 3.01 m^3; overall mean biomass 156.63 kg); the largest pile we measured was 14.47 m^3, and the heaviest pile weighed 672.14 kg. Packing ratio ranged from 0.01 to 0.40, and bulk density ranged from 7.59 to 152.45 kg/m^3. The packing ratios of the hand piles we measured encompass the range of typical values noted by Hardy (1996) for machine piles (0.10 to 0.25). The median packing ratio for conifer hand piles is centered on the range of typical values for machine piles (conifer median packing ratio = 0.18), but the median packing ratio for shrub hand piles is lower than is typical for either conifer-dominated hand piles or machine piles (shrub/hardwood median packing ratio = 0.05). Of the 121 hand piles measured, the packing ratio of 58 piles was less than 0.10, the packing ratio of 53 piles was between 0.10 and 0.25, and the packing ratio of 10 piles was greater than 0.25.

Table 3—Summary hand pile data[a]

	All piles (n = 121)	Conifer (n = 63)	Shrub (n = 58)
	Mean ± standard error		
Geometric volume (m^3)	3.23 ± 0.26	2.61 ± 0.19	3.90 ± 0.49
True volume (m^3)	3.01 ± 0.19	2.45 ± 0.18	3.63 ± 0.33
Biomass (kg)	156.63 ± 10.42	177.34 ± 12.10	134.13 ± 16.95
Bulk density (kg/m^3)	56.45 ± 2.86	76.79 ± 3.37	34.36 ± 2.43
Packing ratio (m^3/m^3)	0.12 ± 0.01	0.19 ± 0.01	0.05 ± 0.00
Mass <2.5 cm (percentage of total)	40.3 ± 2.4	24.9 ± 1.5	57.0 ± 3.7
Mass 2.5-7.6 cm (percentage of total)	30.3 ± 1.8	28.1 ± 2.0	32.8 ± 3.0
Mass >7.6 cm (percentage of total)	29.4 ± 2.4	47.0 ± 2.9	10.3 ± 2.0

[a] Shrub and hardwood categories were combined for all analyses.

Pile shape—

Most piles were classified as either paraboloids (n = 64) or half-ellipsoids (n = 44). Only a few half-cylinders (n = 4), half-frustums of a cone (n = 6), and irregular solids (n = 3) were observed among the 121 piles sampled in the field (fig. 7). This may be a result of how material is piled when done by hand in contrast to machine piling where windrows, which have a half-cylinder shape, are common. During hand piling, material is dragged from a relatively small radius (compared to machine piles) around the pile location toward a center point yielding piles that have round or oval plan-view shapes.

The distribution of points in fig. 7a suggested that the relationship between geometric volume and true volume may have been different for piles of different shape (paraboloids vs. half-ellipsoid+half-cylinders+half-frustums of a cone+irregular solids) and might be best modeled by using two different equations. T-tests, however, revealed that the slope ($t = 1.915$; $p = 0.058$) and intercept ($t = 1.579$; $p = 0.117$) terms of the resulting regressions were not significantly different, so we opted to pool the data and develop one equation for all pile shapes.

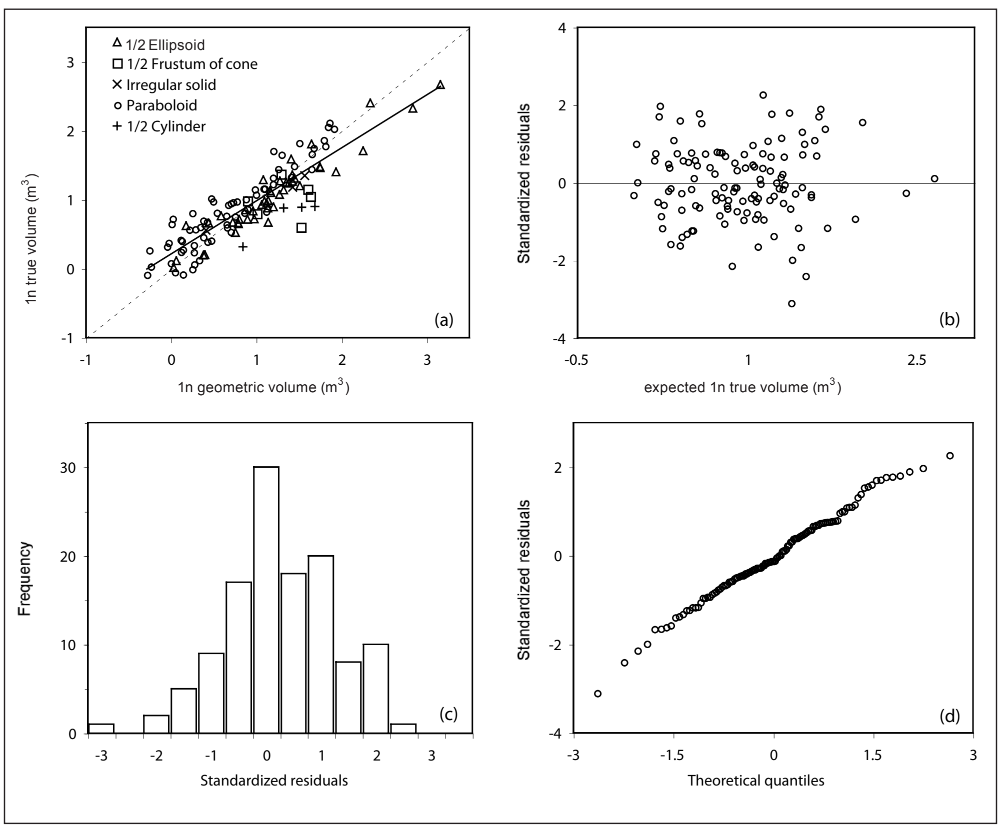

Figure 7—Relationship between the natural logarithm (1n) of geometric volume and the natural log of true volume (a). Data points above and below the dashed 1:1 line indicate instances in which the geometric volume under- or over-predicts the true volume, respectively. Note that most piles were classified as either paraboloids or half-ellipsoids. Residual diagnostic plots, including standardized residuals against expected natural logarithm of true volume (b), frequency distribution (c), and against theoretical quantiles of the normal distribution (d).

Pile volume—
Geometric pile volume underestimated true pile volume for very small piles (<2.5 m^3), and overestimated true pile volume for larger piles (fig. 7a); however, the relationship between pile volume determined using pile dimensions and geometric formulas (geometric volume) and true pile volume was not linear. Natural log transformation of both the geometric and true pile volumes linearized the relationship and made the distribution of the residuals normal and homoscedastic (fig. 7b-d). Retransforming predictions from logarithmic to arithmetic units can produce bias. Calculation and application of a correction factor has been suggested as a method to reduce the bias (Baskerville 1971). We evaluated bias for predicted values with and without the correction factor specified by Sprugel (1983)[5] and found the differences to be small, and the uncorrected predictions to be slightly less biased and more precise. The equation for predicting true volume from geometric volume (fig. 8a and table 4) is implemented without the correction factor in the Web calculator.

The equation for predicting true pile volume from geometric volume is appropriate for a range of pile sizes owing to the relatively wide span in our data; however, extrapolation beyond the range of the data should be done with caution, particularly for very large piles (>25 m^3). Our regression does not pass through the origin, so to accommodate very small piles, we chose to encode a straight proportional reduction of

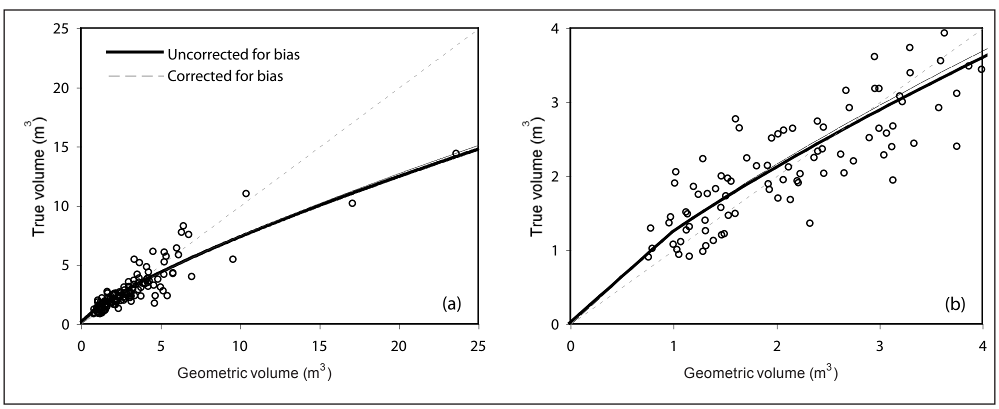

Figure 8—The relationship between geometric pile volume and true pile volume is nonlinear. Equations, both corrected and uncorrected for logarithmic retransformation bias, are plotted for comparison. The dashed diagonal line indicates a 1:1 relationship for reference. Shown are plots of all data points and the modeled equations (a), and for clarity, a view of the data and modeled equations for piles less than 4 m^3 (b). Note that the regression lines show a linear extrapolation through the origin for geometric volumes <1 m^3.

[5] Sprugel (1983) calculated the logarithmic transformation correction factor (CF) as:

$$CF = \exp\left\{\left[\sum(\ln y_i - \widehat{\ln y_i})^2 / (N-2)\right] / 2\right\},$$

where $\ln y_i$ is the natural logarithm of the dependent variable, and $\widehat{\ln y_i}$ is the corresponding predicted value calculated from the equation.

the modeled true volume of piles < 1 m^3, which is approximately equal to the smallest pile we measured (fig. 8b and table 4). We feel justified adjusting the extrapolation for very small piles as we know that true pile volume approaches zero as geometric volume approaches zero. This adjustment eliminates nonsensical extrapolation values (i.e., positive modeled true volume when pile volume is zero) related to the nonzero intercept term in the regression equation as pile sizes approach zero.

The larger the pile, the more the geometric method of calculating volume appears to overestimate true volume (fig. 8). This could have important implications for prescribed burning of piles in states such as Utah, where up to 850 m^3 (30,000 ft^3) of piled debris (i.e., the volume of numerous small piles that sum to 850 m^3) constitutes a small prescribed burn that does not require special permitting or approval provided adequate smoke dispersion conditions exist. The ability to correct for this overestimation could allow land managers to accomplish more fuel treatment under current guidelines without the added burden of special permitting.

Pile composition—

Conifer and shrub/hardwood piles had different physical characteristics (table 3). Piles composed primarily of coniferous material had significantly higher bulk density ($t = 10.199$; $p < 0.001$) and packing ratio ($t = 14.145$; $p < 0.001$) than piles composed primarily of shrub and hardwood material, in large part owing to the greater percentage of large (>7.6 cm diameter) woody particles in the conifer piles (table 3). Based on these differences in composition, separate equations were developed for describing the relationships between true pile volume and biomass (table 4, fig. 9). The dependent and independent variables (pile weight and true volume) for both the conifer and shrub/hardwood hand-pile data were natural log-transformed making the distribution of the residuals normal and homoscedastic. The resulting regressions described 59 and

Conifer and shrub/hardwood piles had different physical characteristics.

Table 4—Prediction equations for estimating true volume and oven-dry biomass of hand piles

Equation[a]	Adjusted R^2	Root MSE[b]	Percentage bias	Precision
1. If GV < 1, TV = exp(0.2106) × GV				
2. If GV ≥ 1, TV = exp(0.2106 + 0.7691 × ln[GV])	0.79	0.253	0.206	0.270
3. If conifer, W = exp(4.4281 + 0.8028 × ln[TV)])	0.59	0.353	0.292	0.438
4. If shrub/hardwood, W = exp(3.0393 + 1.3129 × ln[TV])	0.64	0.534	0.468	0.647

[a] TV = true volume (m^3); GV = geometric volume (m^3); W = weight (kg); ln = natural logarithm (base e).
[b] MSE = Mean squared error.

64 percent of the variability in the data for the conifer and shrub piles, respectively. As with the geometric-to-true volume regression, we calculated a correction factor to account for the bias that results from retransforming from logarithmic to arithmetic units, and as with the volume-to-volume regressions, the uncorrected predictions were slightly less biased and slightly more precise.

Coefficients of the conifer and shrub/hardwood piles were significantly different for slope ($t = 3.282$; $p = 0.001$) and intercept ($t = 7.806$; $p < 0.001$), indicating that pile composition was important, and that the relationship between volume and biomass was different for hand piles composed of primarily conifer and primarily shrub/hardwood material (fig. 9a).

Errors Related to Characterizing Piled Fuels

Our data indicate that the use of shapes and volume formulas tends to overestimate the true volume of the pile, except for very small piles (<2.5 m^3).

The largest errors in characterizing piled fuels are related to estimating pile volume (Hardy 1996). Piles rarely conform perfectly to a geometric shape. Our data indicate that the use of shapes and volume formulas tends to overestimate the true volume of the pile, except for very small piles (<2.5 m^3). This is in contrast to McNab and Saucier

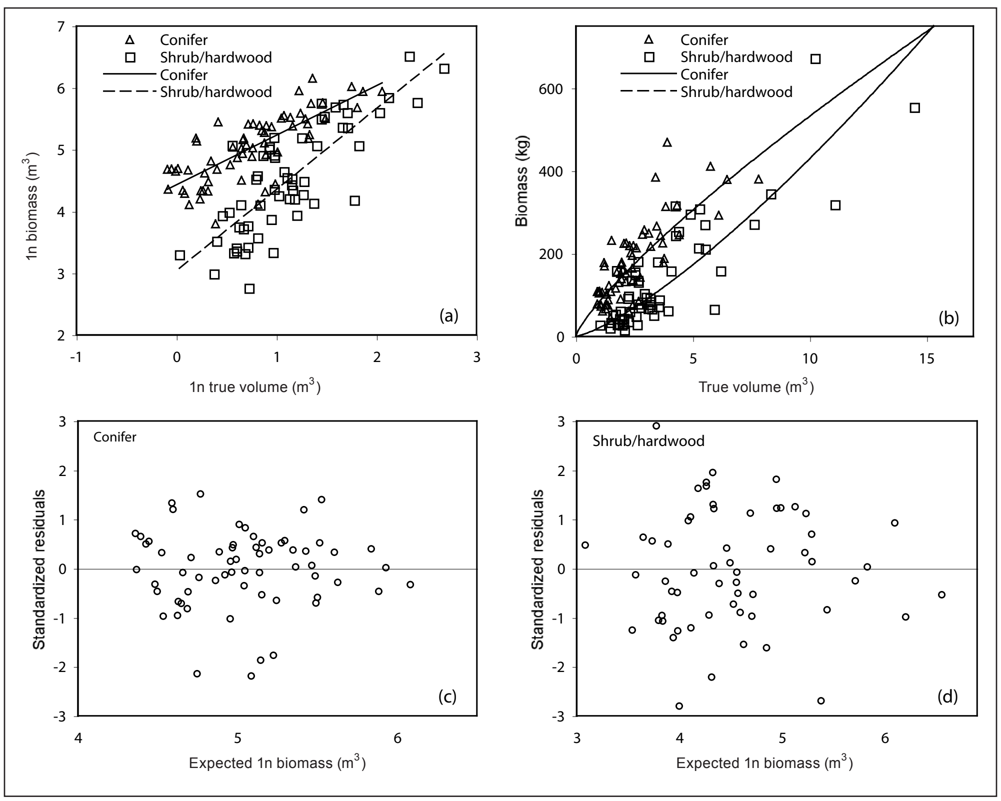

Figure 9—Relationship between the natural log of true pile volume and the natural log of pile biomass (a). The relationship between true pile volume and pile biomass is nonlinear when plotted in arithmetic units (b). Residual diagnostic plots of standardized residuals against the expected natural log of biomass for the conifer regression (c) and the shrub/hardwood regression (d).

(1980) who observed that their simple geometric method for windrowed fuels tended to underestimate the cross-sectional area and volume by approximately 19 percent.

Errors also occur when relating pile volume to pile biomass; the relationship between pile volume and mass is sensitive to estimates of the proportion of the pile volume that is actually composed of solid material (i.e., the packing ratio). Packing ratio can be quite variable (Little 1982, McNab 1980, tables 7 and 8 in this study), however, so determining the correct value for a given pile is problematic. For example, the guidelines in Hardy (1996) specify general species, particle size, and construction methods (hand-construction is not considered) to help select the correct packing ratio. However, these guidelines are for machine-constructed piles and do not describe the characteristics of hand-piled fuels; additional analysis and development of more detailed guidelines would be necessary to be able to select the correct packing ratio for hand piles.

Additional inaccuracies can be introduced when converting wood volume to wood biomass. McNab (1980) suggested a general wood density of 0.56 g/cm^3 (35 lbs/ft^3) when "species composition is not important." However, wood density varies considerably by species (USDA FS 1999): for example, ponderosa pine (*Pinus ponderosa* C. Lawson)(0.38 g/cm^3) is approximately one-third less dense than tanoak (*Lithocarpus densiflorus* [Hook. & Arn.] Rehder)(0.58 g/cm^3). Use of general wood density values or woody density values for species different than those present in a pile can affect pile biomass calculations and thus estimates of emissions from burning.

Comparison With Machine Pile Methods

In comparison to the methodological approaches that employ approximations of wood volume as a fraction of total pile volume to estimate biomass, we developed a model to estimate pile biomass directly from measurements of pile volume. Weighing of large machine-constructed piles is logistically difficult (Little 1982), hence the volume-based methods of Hardy (1996) and McNab (1980, 1981). Because hand piles were smaller, we were able to weigh them directly. At least for hand piles, the ability to model pile biomass directly from pile volume removes two potential sources of error identified above: estimating packing ratio and selecting wood density.

At least for hand piles, the ability to model pile biomass directly from pile volume removes two potential sources of error identified above: estimating packing ratio and selecting wood density.

We hypothesized that using the machine-pile-based recommendations of Hardy (1996) for hand piles could overestimate biomass, as we expected machine-constructed piles to contain mechanically compacted and larger fuel particles. This was true for hand piles composed of shrub and hardwood debris (142.6 percent mean overestimate), but not for hand piles composed of primarily coniferous material (32.5 percent mean underestimate) when using a packing ratio of 0.10, which is the most appropriate value based on the guidelines included in Hardy (1996). Adjusting the

Table 5—Comparison of measured and estimated biomass using the methods of Hardy (1996) with two different packing ratios (PR) and the methods of this study for 121 hand piles

	Measured	Modeled[a]		
	this study	Hardy (0.10 PR)	Hardy (0.15 PR)	This study
Conifer-dominated:				
Mean biomass (kg)	177.3	106.4	159.6	172.4
Mean difference (percentage)		-32.5	+1.3	+7.7
Underestimate (no. of piles)		56/63	41/63	34/63
Overestimate (no. of piles)		7/63	22/63	29/63
Shrub/hardwood-dominated:				
Mean biomass (kg)	134.1	235.6	353.4	109.1
Mean difference (percentage)		+142.6	+263.9	+4.2
Underestimate (no. of piles)		9/58	1/58	32/58
Overestimate (no. of piles)		49/58	57/58	26/58

[a] The Hardy method calculates pile volume geometrically, multiplies by a packing ratio to estimate the amount of the pile volume that is solid material, and multiplies the solid material volume by the wood density of the material present in the pile. This study corrects geometric volume to true volume and relates true volume to biomass using regression models.

Table 6—Emission factors used to calculate the mass of emission produced from burning hand piles

	Emission factor		
Pollutant[a]	Flaming	Smoldering	Residual
	- - - - - - - - - - - - kg/Mg - - - - - - - - - - - -		
PM[b]	10.95	10.95	10.95
PM_{10}[b]	7.75	7.75	7.75
$PM_{2.5}$[b]	6.75	6.75	6.75
CO[c]	26.33	65.19	65.19
CO_2[c]	857.31	772.47	772.47
CH_4[c]	1.64	5.52	5.52
NMHC[c]	1.78	3.39	3.39

[a] PM = particulate matter; PM_{10} = particulate matter <10 m in aerodynamic diameter; $PM_{2.5}$ = particulate matter <2.5 m in aerodynamic diameter; CO = carbon monoxide; CO_2 = carbon dioxide; CH_4 = methane; NMHC = nonmethane hydrocarbons.
[b] The same emission factor from Hardy (1996) is assumed for flaming, smoldering, and residual combustion as is done in CONSUME 3.0 (Prichard et al., n.d.).
[c] Emission factors from Steven Baker, personal communication as cited in Prichard et al. (n.d.).

packing ratio from 0.10 to 0.15 when using the Hardy methodology improved the accuracy of biomass predictions for conifer-dominated piles (1.3 percent mean overestimate), but made shrub hand pile biomass predictions worse (263.9 percent mean overestimate). Using the relationships observed in this study (table 4) to predict pile biomass based on measured dimensions, we observed 7.7 and 4.2 percent overestimates for conifer and shrub/hardwood hand piles, respectively.

Using the method of Hardy (1996), which was developed for machine piles, for shrub and hardwood hand piles tended to overestimate biomass and would therefore overestimate emissions from burning, whereas the opposite was true for conifer hand piles. As outlined in the previous section, the Hardy method is sensitive to inaccuracies in estimating the true pile volume and packing ratio. We feel that our procedure, which is outlined in the following section, improves the accuracy of estimates of hand-piled biomass and therefore subsequent smoke emissions by eliminating the need to estimate true pile volume and packing ratio.

Procedure for Estimating Emissions

Hardy (1996) provided a very helpful section outlining a six-step process necessary to calculate the biomass of machine-piled fuels and the resulting emissions when machine piles are burned. In this section, we offer companion directions for hand-piled fuels. The steps outlined are encoded into a Web calculator (http://depts.washington.edu/nwfire/handpiles), and require that the user enter only a few easily measured variables (pile shape, pile dimensions, pile type, number of piles, and estimated proportion consumed).

The steps outlined are encoded into a Web calculator (http://depts.washington.edu/nwfire/handpiles), and require that the user enter only a few easily measured variables (pile shape, pile dimensions, pile type, number of piles, and estimated proportion consumed).

Step 1—

Select the pile shape that most closely resembles your pile(s) and measure the necessary dimensions as shown in figure 4. We found hand piles to be predominantly paraboloid and half-ellipsoid in shape. From the shape assignment and dimensions we calculate geometric volume; geometric volume is then adjusted to reflect what we have termed true volume by using equations 1 or 2 in table 4, depending on the calculated geometric volume.

Step 2—

Determine the pile composition (conifer-dominated or shrub/hardwood-dominated). Conifer-dominated hand piles tend to be heavier for a given pile volume than shrub/hardwood-dominated hand piles in our data set; the relationship between volume and mass is modeled with separate equations. From the composition assignment we calculate pile biomass by using equations 3 or 4 in table 4 as appropriate.

Step 3—

Count and enter the number of piles that meet the shape, size, and composition criteria above.

Step 4—

Estimate the proportion of the fuel in pile(s) that will be consumed during burning operations. Hardy (1996) noted that between 75 and 95 percent of piled fuels are consumed during typical pile burning conditions. CONSUME 3.0 (Prichard et al., n.d.) assumes 90 percent of piled biomass is consumed. We supply a default value of 90 percent, although users may override this at their discretion, and should consider doing so if burning operations are being conducted under wet or snowy conditions when less consumption is expected. Regardless of weather or fuel conditions, like CONSUME 3.0, we assume that 70 percent of the consumption occurs during the flaming phase of combustion, 15 percent occurs during the smoldering phase of combustion, and 15 percent occurs during the glowing phase of combustion.

Step 5—

Calculate the mass of emissions produced from flaming, smoldering and glowing combustion. We calculate emissions by multiplying the estimated proportional consumption by emission factors (table 6) for seven important pollutant species, including all particulate matter (PM), PM smaller than 10 µm in aerodynamic diameter (PM_{10}), PM smaller than 2.5 µm in aerodynamic diameter ($PM_{2.5}$), carbon monoxide, carbon dioxide, methane, and nonmethane hydrocarbons. In comparison with machine piles, we observed hand piles to be very clean, resulting in maximal combustion efficiency and fewer emissions when compared with comparably-sized machine piles that are contaminated with mineral soil during their construction (Hardy 1996).

Conclusion

Regulations in Oregon and several other Western States require prescribed fire practitioners to estimate emissions from prescribed burning activities, including pile burning (see Hardy et al. 2001 for a thorough discussion of fire and smoke management and regulation). Emissions predictions require estimates of preburn pile biomass. Therefore, it is important that fuel managers and air quality regulators have the tools necessary to accurately estimate the volume and biomass of hand-piled fuels to better estimate emissions from pile burning activities to address both mitigation and regulatory compliance. This study collected data and developed tools to improve the characterization of hand piles using direct methods in an attempt to reduce the compounding inaccuracies that can result from estimates based on pile volume, packing ratio, and wood density.

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English Equivalents

When you know:	Multiply by:	To find:
Micrometers (µm)	0.039	Mil
Centimeters (cm)	.394	Inches
Meters (m)	3.281	Feet
Cubic meters (m^3)	35.315	Cubic feet
Hectares (ha)	2.471	Acres
Grams per cubic centimeter (g/cm^3)	62.428	Pounds per cubic foot
Kilograms per cubic meter (kg/m^3)	.062	Pounds per cubic foot
Kilograms (kg)	2.205	Pounds
Megagrams (Mg)	1.102	Tons
Kilograms per megagram (kg/Mg)	2.000	Pounds per ton

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Appendix

Table 7—Conifer hand pile data

Pile ID[a]	Shape[b]	Geometric volume	True volume	Biomass	Bulk density	Packing ratio	<2.5 cm diameter	2.5–7.6 cm diameter	>7.6 cm diameter
		m^3	m^3	*kg*	kg/m^3	m^3/m^3	- - - - *Proportion of biomass* - - - -		
BC01	E	3.13	2.68	84.72	31.57	0.06	0.35	0.57	0.07
BC03	P	2.36	2.26	61.19	27.08	0.05	0.71	0.24	0.05
BC04	P	1.53	1.48	44.47	30.10	0.07	0.65	0.29	0.06
BC05	P	3.29	3.41	384.60	112.91	0.30	0.09	0.06	0.85
BC06	P	4.07	3.78	188.60	49.91	0.13	0.30	0.06	0.64
BC07	E	2.95	3.63	243.72	67.23	0.17	0.10	0.09	0.82
BC08	P	3.29	3.74	177.95	47.53	0.12	0.20	0.22	0.59
BC09	P	4.22	4.43	245.63	55.47	0.13	0.20	0.12	0.68
BC10	P	5.32	5.76	410.48	71.28	0.18	0.25	0.06	0.69
BC11	E	3.99	3.45	266.79	77.28	0.20	0.22	0.07	0.71
BC12	E	4.25	3.71	225.63	60.75	0.16	0.28	0.10	0.62
BC13	E	3.74	3.13	249.41	79.73	0.21	0.20	0.09	0.71
BC14	E	5.19	6.11	292.45	47.88	0.12	0.18	0.08	0.74
CS01	P	6.28	7.81	379.82	48.61	0.12	0.21	0.15	0.64
CS02	P	5.98	6.46	379.24	58.71	0.15	0.16	0.12	0.72
CS03	P	2.95	3.19	217.42	68.07	0.16	0.25	0.28	0.47
DT01	P	1.59	1.50	107.92	71.81	0.16	0.18	0.15	0.67
DT02	P	1.46	2.01	160.30	79.81	0.20	0.21	0.19	0.60
DT03	P	1.31	1.07	76.83	72.10	0.18	0.33	0.22	0.45
DT04	P	0.99	1.08	73.14	67.44	0.17	0.31	0.24	0.45
DT05	E	1.06	1.12	106.70	95.08	0.23	0.13	0.28	0.59
DT06	E	3.33	2.45	136.50	55.70	0.15	0.33	0.23	0.44
DT07	P	1.30	1.41	122.95	87.05	0.23	0.20	0.11	0.69
DT08	P	1.05	0.95	108.33	113.93	0.30	0.21	0.13	0.66
DT09	E	3.11	2.41	195.32	81.10	0.21	0.24	0.29	0.48
DT10	E	3.06	2.59	213.80	82.63	0.22	0.16	0.17	0.67
DT11	E	1.03	1.02	109.30	107.67	0.28	0.15	0.23	0.62
DT12	P	1.15	0.92	78.25	84.90	0.22	0.32	0.23	0.45
DT13	P	1.38	1.14	60.70	53.43	0.14	0.40	0.31	0.29
DT14	P	1.23	1.76	154.42	87.72	0.24	0.16	0.33	0.51
DT15	P	1.12	1.52	231.77	152.45	0.40	0.13	0.11	0.76
DT16	E	2.21	1.92	151.57	79.03	0.21	0.26	0.26	0.48
DT17	E	2.65	2.05	224.29	109.24	0.27	0.14	0.10	0.76
DT18	P	1.28	0.99	104.72	105.54	0.28	0.13	0.10	0.77
DT19	P	1.01	1.91	90.04	47.06	0.12	0.29	0.39	0.32
DT20	P	0.75	0.91	107.95	118.06	0.29	0.17	0.51	0.33
DT21	E	2.06	1.96	179.11	91.48	0.24	0.14	0.21	0.65
DT22	E	1.46	1.21	178.24	146.86	0.39	0.18	0.18	0.65
RS01	E	5.75	4.32	316.03	73.16	0.17	0.26	0.47	0.28
RS02	P	1.12	1.28	76.17	59.62	0.15	0.43	0.52	0.05
RS03	P	1.30	1.27	66.72	52.56	0.12	0.41	0.60	0.00

Table 7—Conifer hand pile data (continued)

Pile ID[a]	Shape[b]	Geometric volume	True volume	Biomass	Bulk density	Packing ratio	<2.5 cm diameter	2.5–7.6 cm diameter	>7.6 cm diameter
		m^3	*m^3*	*kg*	*kg/m^3*	*m^3/m^3*	- - - - *Proportion of biomass* - - - -		
RS04	P	3.04	2.29	219.36	95.59	0.23	0.25	0.34	0.41
RS05	C	3.74	2.41	164.74	68.39	0.15	0.32	0.57	0.11
RS06	C	2.32	1.37	75.60	55.12	0.13	0.40	0.60	0.00
RS07	P	2.39	2.75	142.45	51.79	0.12	0.27	0.37	0.35
RS08	P	0.77	1.31	76.00	58.18	0.13	0.35	0.50	0.15
RS09	P	1.40	1.84	129.73	70.68	0.16	0.28	0.43	0.29
RS10	F	5.12	2.85	246.53	86.39	0.20	0.24	0.37	0.39
RS11	P	2.01	1.71	116.13	67.96	0.15	0.19	0.47	0.34
RS12	C	5.40	2.46	218.65	88.97	0.19	0.22	0.45	0.33
RS13	C	4.64	2.43	74.91	30.83	0.07	0.36	0.42	0.22
RS14	P	2.70	2.93	257.46	87.82	0.20	0.20	0.30	0.49
RS15	P	0.95	1.38	88.32	64.16	0.14	0.24	0.09	0.68
RS16	P	2.11	2.13	132.27	62.03	0.15	0.44	0.40	0.16
RS17	E	1.55	1.94	138.79	71.54	0.16	0.22	0.24	0.54
RS18	E	2.40	2.34	202.21	86.29	0.20	0.22	0.49	0.30
RS19	P	1.15	1.32	101.67	76.82	0.18	0.21	0.29	0.50
RS20	E	1.80	2.15	152.82	71.20	0.16	0.23	0.33	0.44
RS21	I	4.80	3.85	313.34	81.44	0.20	0.22	0.40	0.38
RS22	E	2.19	1.95	173.92	89.35	0.22	0.25	0.45	0.30
RS23	P	1.91	2.15	225.78	104.80	0.23	0.12	0.56	0.32
RS24	E	4.14	3.90	468.96	120.20	0.26	0.15	0.35	0.51
RS25	E	1.49	1.23	169.80	138.45	0.30	0.11	0.13	0.76

[a] Pile ID abbreviations refer to stands at different sites: BC and CS = Bear Creek (Porterville, California), DT = Devil's Table (Naches, Washington), RS = Rattlesnake (Naches, Washington).
[b] Shapes are E = half-ellipsoid, P = paraboloid, C = half-cylinder, F = half-frustum of a cone, I = irregular solid.

Table 8—Shrub/hardwood hand pile data

Pile ID[a]	Shape[b]	Geometric volume	True volume	Biomass	Bulk density	Packing ratio	<2.5 cm diameter	2.5–7.6 cm diameter	>7.6 cm diameter
		m^3	*m^3*	*kg*	*kg/m^3*	*m^3/m^3*	- - - - *Proportion of biomass* - - - -		
BC02	E	3.22	3.01	94.32	31.29	0.05	0.65	0.35	0.00
CH01	E	10.35	11.07	318.56	28.77	0.04	0.97	0.03	0.00
CPM01	P	3.65	5.24	213.49	40.74	0.07	0.22	0.70	0.07
CPM02	F	4.97	3.16	83.99	26.58	0.04	0.43	0.51	0.06
CPM03	P	6.74	7.62	270.65	35.53	0.06	0.21	0.79	0.00
CPM04	P	2.67	3.17	92.48	29.18	0.05	0.27	0.58	0.15
CPM05	E	6.91	4.07	158.29	38.91	0.06	0.28	0.68	0.04
CPM06	P	1.63	2.66	77.91	29.27	0.04	0.21	0.79	0.00
CPM07	E	23.56	14.47	553.87	38.28	0.06	0.19	0.69	0.12
CPO02	I	4.17	3.25	66.39	20.43	0.03	0.41	0.59	0.00

Table 8—Shrub/hardwood hand pile data (continued)

Pile ID[a]	Shape[b]	Geometric volume	True volume	Biomass	Bulk density	Packing ratio	<2.5 cm diameter	2.5–7.6 cm diameter	>7.6 cm diameter
		m^3	*m^3*	*kg*	*kg/m^3*	*m^3/m^3*	- - - - *Proportion of biomass*		- - - -
FM01	P	6.39	8.34	344.85	41.36	0.07	0.48	0.44	0.08
FM02	E	9.53	5.52	211.19	38.23	0.06	0.55	0.42	0.03
FM03	E	2.89	2.53	155.41	61.46	0.10	0.29	0.45	0.27
FM04	P	1.46	1.58	50.94	32.19	0.06	0.58	0.42	0.00
FM05	E	17.03	10.23	672.14	65.69	0.10	0.21	0.59	0.20
FM06	P	4.48	6.19	158.24	25.58	0.04	0.49	0.40	0.11
FM07	P	5.21	5.29	308.35	58.30	0.09	0.36	0.60	0.04
FM08	F	3.63	3.94	62.14	15.76	0.02	0.67	0.33	0.00
FM09	P	1.92	1.90	60.96	32.05	0.05	0.57	0.43	0.00
FM10	E	2.62	2.30	60.42	26.24	0.04	0.38	0.35	0.28
FM11	F	2.74	2.21	91.96	41.57	0.06	0.38	0.62	0.00
FM12	P	1.60	2.78	70.32	25.29	0.04	0.48	0.43	0.08
FM13	E	2.22	2.04	43.19	21.17	0.03	0.62	0.38	0.00
FM14	P	2.99	3.19	77.06	24.14	0.04	0.59	0.41	0.00
FM15	I	1.50	1.74	158.77	91.11	0.14	0.24	0.65	0.10
MM08	P	1.92	1.83	28.78	15.76	0.03	0.78	0.22	0.00
MM09	E	3.12	1.95	41.13	21.04	0.04	0.75	0.16	0.09
MM10	F	4.59	1.82	30.09	16.54	0.03	0.88	0.12	0.00
MM11	E	4.53	3.33	51.28	15.40	0.02	0.87	0.13	0.00
MM12	P	1.71	2.25	35.59	15.80	0.02	0.97	0.03	0.00
MM13	P	0.79	1.03	27.04	26.25	0.04	1.00	0.00	0.00
MM14	P	1.13	1.50	33.72	22.52	0.03	0.76	0.25	0.00
MM15	E	2.13	1.69	53.81	31.79	0.05	1.00	0.00	0.00
MM16	E	1.19	1.87	42.46	22.75	0.03	0.99	0.01	0.00
MM17	E	3.19	3.09	66.88	21.64	0.03	0.96	0.04	0.00
MM18	P	2.06	2.63	27.98	10.64	0.02	1.00	0.00	0.00
MM19	P	1.02	2.07	15.70	7.59	0.01	0.98	0.02	0.00
MM20	P	6.10	5.92	65.44	11.06	0.02	0.64	0.36	0.00
MM21	P	0.97	1.46	19.78	13.56	0.02	0.93	0.07	0.00
MM22	P	1.52	1.98	27.55	13.92	0.02	1.00	0.00	0.00
MM23	E	3.59	3.57	88.48	24.78	0.03	0.74	0.26	0.00
MM24	E	2.46	2.05	30.59	14.95	0.02	0.93	0.07	0.00
MM25	E	4.16	3.54	71.82	20.27	0.03	0.93	0.07	0.00
MM26	P	2.01	2.58	47.81	18.54	0.03	0.86	0.14	0.00
MM27	P	1.32	1.77	27.87	15.74	0.02	0.99	0.02	0.00
RP01	F	2.45	2.67	131.06	49.11	0.07	0.33	0.25	0.43
RP02	E	2.99	2.65	135.45	51.04	0.07	0.32	0.14	0.54
RP03	P	1.28	2.24	96.96	43.19	0.06	0.44	0.31	0.25
RP04	P	3.31	5.51	269.58	48.89	0.07	0.31	0.47	0.22
RP05	E	5.73	4.38	253.76	57.89	0.08	0.36	0.29	0.35
RP06	P	2.15	2.65	180.69	68.12	0.10	0.29	0.34	0.37
RP07	P	3.50	4.26	243.33	57.15	0.08	0.21	0.27	0.52
RP08	E	3.86	3.50	179.78	51.40	0.08	0.24	0.43	0.33
RP09	E	4.09	4.89	295.21	60.42	0.09	0.37	0.23	0.40

Table 8—Shrub/hardwood hand pile data (continued)

Pile ID[a]	Shape[b]	Geometric volume	True volume	Biomass	Bulk density	Packing ratio	<2.5 cm diameter	2.5–7.6 cm diameter	>7.6 cm diameter
		m^3	*m^3*	*kg*	*kg/m^3*	*m^3/m^3*	- - - - *Proportion of biomass* - - - -		
RP10	P	2.44	2.38	135.28	56.91	0.08	0.19	0.55	0.26
RP11	P	1.95	2.52	149.54	59.26	0.09	0.39	0.48	0.13
RP12	P	5.18	4.24	315.16	74.25	0.11	0.28	0.30	0.42
RP13	E	3.57	2.94	104.07	35.46	0.05	0.64	0.34	0.02

[a] Pile ID abbreviations refer to stands at different sites: BC = Bear Creek (Porterville, California), CH = Chamise (Porterville, California), CPM and CPO = Carr Powerhouse (Whiskeytown, California), FM = Figueroa Mountain (San Luis Obispo, California), MM = Muletown Manzanita (Whiskeytown, California), RP = Ray’s Place (Porterville, California).

[b] Shapes are E = half-ellipsoid, P = paraboloid, F = half-frustum of a cone, and I = irregular solid.

Pacific Northwest Research Station

Web site	http://www.fs.fed.us/pnw
Telephone	(503) 808-2592
Publication requests	(503) 808-2138
FAX	(503) 808-2130
E-mail	pnw_pnwpubs@fs.fed.us
Mailing address	Publications Distribution Pacific Northwest Research Station P.O. Box 3890 Portland, OR 97208-3890

U.S. Department of Agriculture
Pacific Northwest Research Station
333 SW First Avenue
P.O. Box 3890
Portland, OR 97208-3890