

## ESTIMATING THE BIOMASS OF HAND-PILED FUELS FOR SMOKE MANAGEMENT PLANNING

Final Report to the Joint Fire Science Program

Project Number: 07-2-1-57

March 31, 2009



### PRINCIPAL INVESTIGATORS:

*Clinton S. Wright and Robert E. Vihnanek*

USDA Forest Service, Pacific Northwest Research Station  
Fire and Environmental Research Applications (FERA) team

Pacific Wildland Fire Sciences Laboratory  
400 North 34<sup>th</sup> Street, Suite 201, Seattle, WA 98103  
Telephone: (206) 732-7827 Facsimile: (206) 732-7801  
E-mail: [cwright@fs.fed.us](mailto:cwright@fs.fed.us), [bvihnanek@fs.fed.us](mailto:bvihnanek@fs.fed.us)

### COOPERATORS:

*James Russell* – USFS, Pacific Northwest Region, Portland, OR  
*Mark Middy* – NPS, Whiskeytown National Recreation Area, Whiskeytown, CA  
*Jim Bailey* – USFS, Okanogan-Wenatchee National Forest, Naches, WA  
*Steve Davis* – USFS, Los Padres National Forest, San Luis Obispo, CA  
*Robert Sanders* – USFS, Sequoia National Forest, Porterville, CA  
*Cameron Balog* – University of Washington, Seattle, WA  
*Paige Eagle* – University of Washington, Seattle, WA

### PROJECT SUMMARY:

Dimensions, volume, and biomass were measured for 121 hand-constructed piles composed primarily of coniferous (n=61) and shrub/hardwood (n=60) 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 to allow users who require estimates of pile volume for regulatory reporting. Biomass and volume estimation equations are being programmed into a web-based calculator to allow users to estimate either value from pile dimensions.

## INTRODUCTION:

In many dry forests understory growth is present in excess of historical natural levels and may contribute to more extreme wildland fire behavior and elevated fire hazard. Anomalously high amounts of understory biomass may cause potentially more extreme fire behavior than was common historically, leading to fires which 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, Graham et al. 1999, Agee et al. 2000).

Federal land management policy (e.g., National Fire Plan and Healthy Forest Restoration Act of 2003) directs 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 (i.e., thinning, brush cutting, and mastication) are being used to re-shape dry forests and woodlands with the intention of reducing their susceptibility to catastrophic fires. Substantial increases in dead and down surface fuels are one consequence of mechanical treatments. Surface fuel treatment following thinning or brush cutting is necessary to effectively mitigate wildland fire risk.

Heavy equipment was used to pile activity fuels following clearcut and partial-cut harvest operations. Machines are less practical for piling the remaining surface fuels following thinning where the overstory is left in place. Piling by hand followed by burning is being utilized 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 (Figure 1).



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

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 restrictions (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. Hand piling

and burning mitigates some of the concerns about safety and air quality and is a viable alternative for treating a variety of areas. 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).

Use of hand piling widens the prescription window, allowing managers to use fire under weather and fuel moisture conditions that are inappropriate or ineffective for



Figure 2. Hand pile burning during winter conditions with limited staff on Federal lands near Casper, Wyoming.

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 (Figure 2). 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 air quality impacts of smoke. Pile burning can also be more easily monitored and controlled, minimizing escape potential.

Federal land management policies also specify that 60 percent of areas treated for fuel reduction should be 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 60,000 acres were treated with hand piling and burning in the Pacific Northwest (U.S. Forest Service, Region 6 – Washington and Oregon) in 2005 (James Russell, personal communication). The ability to accurately quantify the mass of hand-piled fuels will allow fire and air resource managers to make more sophisticated estimates of potential emissions and smoke impacts. The need for land managers to mitigate risk 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. 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.

Past pile characterization research (McNab 1980, 1981; McNab and Saucier 1980; Little 1982; Johnson 1984; Hardy 1996) dealt only with large, crane-constructed and tractor-built piles. 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, smaller non-merchantable material is commonly thinned and piled on site without the aid of machinery and contains needles, twigs, and small diameter branches. 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). We hypothesize that using the computations recommended by Hardy (1996) for machine-piled fuels likely overestimates biomass and emissions as we expect machine-constructed piles to contain more tightly packed and larger fuel particles – factors that reduce combustion efficiency, increase burn-out times, and potentially increase expected emissions.

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

<b>Characteristic</b>	<b>Potential differences – In comparison with machine piles, hand piles:</b>
Woody material	Lack large logs; have a greater proportion of biomass in small size classes
Dimensions	Are smaller
Bulk density	Have a lower bulk density
Packing ratio	Have a more optimal packing ratio for more efficient combustion
Soil content	Are cleaner with less soil contamination for more efficient combustion

**OBJECTIVES:**

Land managers and air quality regulators need a tool to accurately and efficiently estimate the biomass of hand-piled fuels as pile burning becomes a more widespread and common method for treating high fire hazard areas with heavy surface fuels. Our objective was to quantify the relationships between pile composition, pile size (dimensions and volume), and pile biomass by measuring and weighing hand-constructed piles. We sampled different vegetation types (i.e., conifer, shrub, and hardwood), shapes, and pile sizes to develop equations for estimating the volume and biomass of hand piles. We also wanted to 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 (Prichard no date) to evaluate the different outcomes that are predicted by the two data sets.

### PROJECT LOCATIONS:

Measurements of dimensions, volume, and biomass of hand piles were made at four locations in the western United States (Appendix A): Naches (WA), Whiskeytown (CA), San Luis Obispo (CA), and Porterville (CA). Approximately equal numbers of conifer and shrub/hardwood piles were measured. Sample sites were typical of hand-piling operations in the West.

### METHODS:

The field portion of this study was concentrated in forest and woodland types in the western United States. Stands with hand piles were selected in Washington and California with the assistance of local and regional fire and fuels managers (Figure 3). 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.

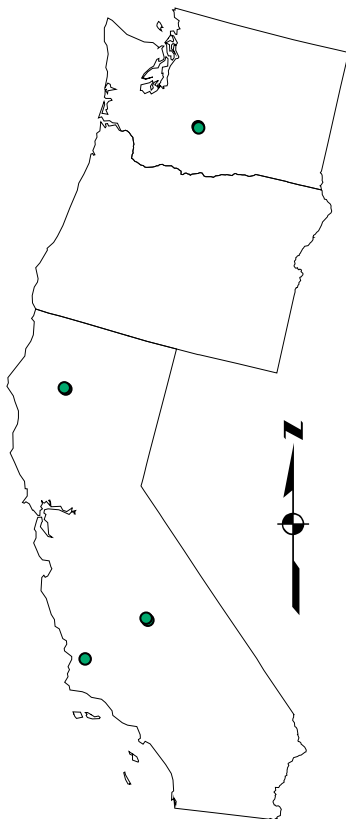


Figure 3. Approximate hand pile sample locations.

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 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 multiple piles of varying size in a total of seven stands at four locations (Appendix A). Within stands piles were randomly selected to be measured, deconstructed and weighed in an attempt to remove bias from the pile-selection process. We had originally proposed to measure 90 piles (30 conifer, 30 shrub, 30 hardwood), but ended up measuring 121 piles (61 conifer, 60 shrub/hardwood).

Within stands, piles were randomly selected using a random walk procedure. The closest pile that was 10 m at a random azimuth from a pre-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, dimensions required to compute the volume of one of seven specific

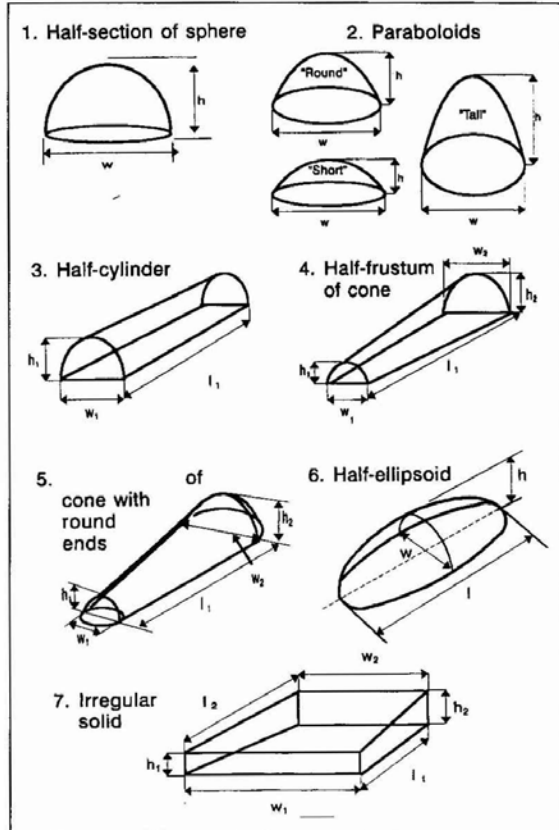


Figure 4. Geometric pile shapes and required dimensions. Figure 1 from Hardy (1996).

geometric shapes were measured (Figure 4) and the appropriate volume formula was employed (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 and measurements of the vertical offset (nearest 3 cm) from the level line were taken at 15 cm intervals in the horizontal from the pile center (Figure 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).<sup>1</sup> For the purposes of this study we consider the TIN-derived shapes and volumes (Figure 6) to be the best representation of the true volume of the pile.

Following dimension and surface measurements, piles were deconstructed and sorted into species and size class groups (<2.5, 2.5-7.6, and >7.6 cm diameter). Species and size class groups of separated piles were weighed in the field with a precision hanging scale (nearest 10 g). Moisture content subsamples were collected for each category for each pile to convert field-measured weight to oven-dry weight.

Table 2. Volume formulas for geometric shapes. See figure 4 (above) for illustration of dimensions.

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

<sup>1</sup> 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.

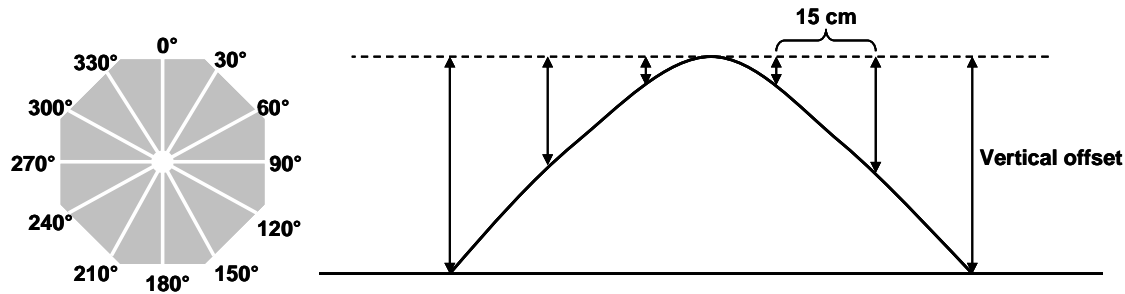


Figure 5. Overhead plan view (left) and cross-section view (right) of pile surface measurement methodology.

Volume, biomass, and composition data were synthesized and used to calculate physical properties, including packing ratio (the ratio of solid material volume to total pile volume) and bulk density (the ratio of pile biomass to total pile volume). Ordinary least squares regression was used to develop equations: (1) to estimate true volume

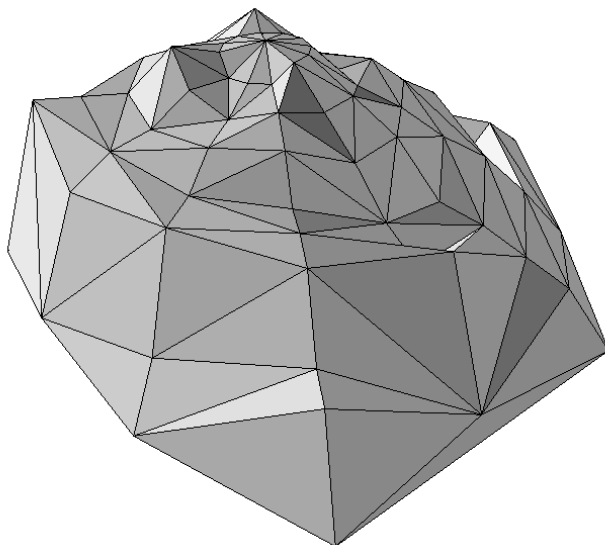


Figure 6. Example TIN lattice for a typical pile at the Naches, WA field site. This pile was 0.73 m high and 1.86 m wide; the “true” volume of this pile was 1.68 m<sup>3</sup>

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, shrub/hardwood, etc.). T-tests were used to test for differences in regression slopes between pile types (Zar 1984). These regression equations are being encoded in a web-based calculator that will allow users to accurately estimate volume and biomass of hand-constructed piles for use in determining potential emissions impacts from burning of these piled fuels.

## RESULTS AND DISCUSSION:

Data analysis and model development are complete; software programming is ongoing with completion anticipated by June 2009. The results of this study will be incorporated into future versions of the CONSUME software or its successor application.

Summary data for sampled hand-constructed piles appear in Table 3. In general hand piles are of a modest size (overall mean volume=3.01 m<sup>3</sup>; overall mean biomass=156.63 kg); the largest pile we measured was 14.47 m<sup>3</sup>, and the heaviest pile weighed 672.14 kg. Piles composed primarily of coniferous material tended to have higher bulk density, in

large part owing to the greater percentage of large (>7.6 cm diameter) woody particles in the pile. While there were differences in overall size, of the shrub and hardwood piles we measured there was little difference in the bulk density and the size distribution of the fuel particles. On average pile volume determined using pile dimensions and geometric formulas (geometric volume) overestimated true pile volume.

Table 3. Summary hand pile data. Shrub and hardwood categories were combined for all analyses.

	<b>Conifer (n=61)</b>	<b>Shrub (n=52)</b>	<b>Hardwood (n=8)</b>
	----- mean ± standard error -----		
Geometric volume (m <sup>3</sup> )	2.60 ± 0.20	4.05 ± 0.54	2.63 ± 0.38
True volume (m <sup>3</sup> )	2.45 ± 0.19	3.75 ± 0.36	2.50 ± 0.23
Biomass (kg)	180.77 ± 12.25	141.11 ± 18.61	73.49 ± 11.07
Bulk density (kg · m <sup>-3</sup> )	78.34 ± 3.30	34.81 ± 2.64	30.14 ± 4.15
Mass <2.5 cm (% of total)	24.0 ± 1.3	56.6 ± 4.1	58.2 ± 6.8
Mass 2.5-7.6 cm (% of total)	27.7 ± 2.0	36.6 ± 3.1	28.0 ± 3.8
Mass >7.6 cm (% of total)	48.3 ± 2.8	9.6 ± 2.0	13.8 ± 7.0

Most piles were classified as either paraboloids (n=64) or ellipsoids (n=44). Only a few half-cylinders (n=4), half-frustrums of a cone (n=6), and irregular solids (n=3) were observed among the 121 piles sampled in the field. 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. 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 larger the pile the more the geometric method of calculating volume appears to overestimate true volume (Figure 7). This could have important implications for prescribed burning of piles in states such as Utah, where piled debris up to 850 m<sup>3</sup> (30,000 ft<sup>3</sup>) 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.

Conifer and shrub/hardwood piles had different physical characteristics. Conifer piles tended to have greater biomass for comparable size as measured by bulk density (Table 3). Based on these differences in composition separate equations for estimating pile biomass from true volume were developed for describing the relationships between true pile volume and biomass (Figure 8). The slope coefficients of the conifer and shrub/hardwood piles were significantly different ( $t = 8.377$ ;  $p < 0.001$ ) indicating that the relationships between pile volume and pile biomass differed.



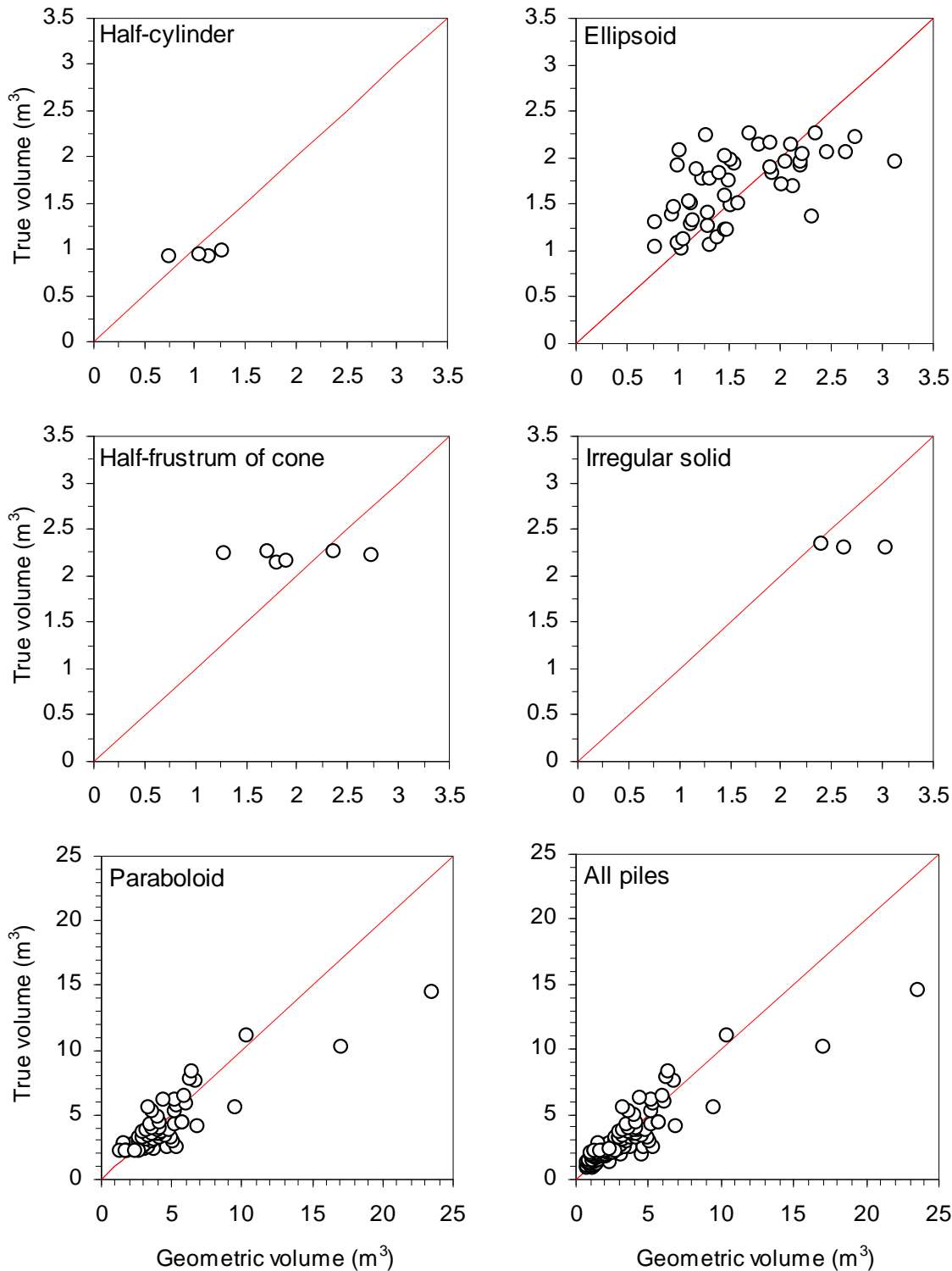


Figure 7. Relationship between geometric volume and true volume for different pile shapes. Data points below the red 1:1 line indicate instances in which the geometric volume overpredicts the true volume. Note that most piles were classified as either paraboloids or ellipsoids. A general equation for correcting geometric volume to true volume using polynomial regression through the origin for all piles is proposed:  $y = 1.0185(x) - 0.0186(x^2)$ , where  $y$  is true volume in  $m^3$  and  $x$  is geometric volume in  $m^3$  ( $R^2 = 0.81$ ).

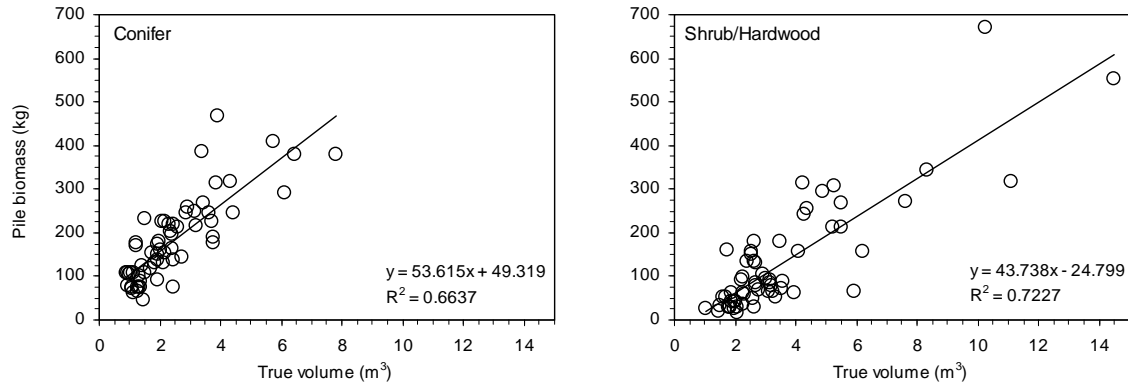


Figure 8. Plot showing the relationship between true pile volume and pile biomass for conifer (left) and shrub/hardwood piles (right).

We hypothesized that using relationships derived from machine piled fuels for hand piles would tend to overestimate biomass because of differences in particle composition and packing. Biomass estimates for 60 conifer hand-piles using the methods of Hardy (1996) and a packing ratio of 0.10 (the most appropriate value based on the guidelines included in Hardy [1996] and CONSUME 3.0), actually underestimated measured hand-pile biomass by an average of 32.6% compared to a 10.8% overestimate using the relationships observed in this study (Table 4). Adjusting the packing ratio from 0.10 to 0.15 when using the methodology employed in CONSUME 3.0 improved the accuracy of biomass predictions (overestimated biomass by an average of 1.0%). Machine piles are composed of large and often irregularly shaped fuel particles (unmerchantable boles, tree tops, stumps, etc.) that can leave a relatively large amount of air in the overall pile volume if they are not neatly stacked or manually compacted. In contrast, for material that gets piled by hand we suspect that the mixture of particle sizes allow for tighter packing and greater fuel mass for a given volume.

Table 4. Comparison of measured and estimated biomass using the methods of Hardy (1996)/CONSUME 3.0 with two different packing ratios (PR) and the methods of this study for 60 conifer hand piles. The Hardy/CONSUME 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.

	Measured	----- Modeled -----		
	This study	Hardy (0.10 PR)	Hardy (0.15 PR)	This study
Mean biomass (kg)	182.5	117.5	176.9	179.5
Median biomass (kg)	164.7	98.1	147.2	161.7
Underestimate (no. of piles)		53/60	35/60	31/60
Overestimate (no. of piles)		7/60	25/60	29/60

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. This is in contrast to McNab and Saucier (1980) who observed that their simple geometric method for windrowed fuels tended to underestimate the cross-sectional area and volume by approximately 19%.

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 (McNab 1980, Little 1982), 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) suggests a general wood density of 0.56 g/cm<sup>3</sup> (35 lbs/ft<sup>3</sup>) when “species composition is not important.” However, wood density varies considerably by species (Forest Products Laboratory 1999), for example ponderosa pine (0.38 g/cm<sup>3</sup>) is approximately one third less dense than tanoak (0.58 g/cm<sup>3</sup>). 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 estimates of emissions from burning.

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. Direct weighing of large machine-constructed piles is logistically difficult (Little 1982), hence the volume-based methods of Hardy (1996) and McNab (1980, 1981). By virtue of their smaller size we were able to weigh hand piles directly. At least for hand piles, the ability to model pile biomass directly from pile volume removes at least two potential sources of error identified above: estimating packing ratio and selecting wood density.

Regulatory requirements in Oregon and several other Western states require prescribed fire practitioners to estimate emissions from prescribed burning activities. Emissions predictions require estimates of preburn pile biomass (see Hardy et al. 2001 for a thorough discussion of fire and smoke management and regulation), 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.

**DELIVERABLES:**

The Hand Pile Biomass study was proposed as a 1.5-year project. We have completed field data collection and analysis, but will be unable to deliver an update to the CONSUME 3.0 software application. CONSUME 3.0 is being redeveloped and the next generation will not be available for use within the timeframe of this proposal; results of this research will be incorporated into any future version of CONSUME or its successor. In lieu of a CONSUME 3.0 update, we are developing and will deliver a stand-alone calculation tool that will be accessible through the Fire and Environmental Research Applications team web page (<http://www.fs.fed.us/pnw/fera/research>). One manuscript for a Forest Service Research Paper has been drafted; one manuscript for a *Fire Management Today* journal article is in preparation. An annual written progress report was submitted in 2008 (Table 5).

Table 5. Proposed and delivered products for Hand Pile Biomass study.

<b>Proposed</b>	<b>Delivered</b>	<b>Status</b>
U.S. Forest Service research paper	<i>Estimating volume, biomass, and potential emissions of hand-piled fuels</i>	In progress; July 2009
<i>Fire Management Today</i> article	<i>Characterizing hand-piled fuels</i>	In progress; July 2009
Software update	Update of CONSUME 3.0	Postponed indefinitely
Web-based calculator	Hand-pile volume, biomass, and emissions web-based calculator. This replaces the proposed update to CONSUME.	In progress; July 2009
JFSP final report	WRIGHT, C.S. AND R.E. VIHNANEK. 2009. Estimating the biomass of hand-piled fuels for smoke management planning.	Done
JFSP progress report	A JFSP progress reports was submitted in 2008.	Done

**ACKNOWLEDGEMENTS:**

Without the generous assistance provided by our cooperators this research would not have been possible. Many people participated in the field data collection for this project: Jeff Kelly, Shawn Smith, Ernesto Alvarado, Joe Restaino, Kyle Jacobson, Amy Jirka, and Mike Tjoelker. This research was funded by the Joint Fire Science Program.

## LITERATURE CITED:

- AGEE, J.K. 1996. The influence of forest structure on fire behavior. Proceedings of the 17th Annual Forest Vegetation Management Conference, Redding, CA. pp. 52-68.
- AGEE, J.K., B. BAHRO, M.A. FINNEY, P.N. OMI, D.B. SAPSIS, C.N. SKINNER, J.W. VAN WAGTENDONK AND C.P. WEATHERSPOON. 2000. The use of shaded fuel breaks in landscape fire management. *Forest Ecology and Management* 127: 55-66.
- ESRI. 2008. ArcGIS version 9.1. ESRI, Inc., Redlands, CA.
- FOREST PRODUCTS LABORATORY. 1999. Woody handbook – wood as an engineering material. General Technical Report FPL-GTR-113. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463 p.
- GRAHAM, R.T., A.E. HARVEY, T.B. JAIN AND J.R. TONN. 1999. The effects of thinning and similar stand treatments on fire behavior in western forests. General Technical Report PNW-GTR-463. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 27 p.
- HARDY, C.C. 1996. Guidelines for estimating volume, biomass and smoke production for piled slash. General Technical Report PNW-GTR-364. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 17 p.
- HARDY, C.C., R.D. OTTMAR, J.L. PETERSON, J.E. CORE AND P. SEAMON (editors/compiler). 2001. Smoke management guide for prescribed and wildland fire. 2001 Edition. PMS-420-2. National Wildfire Coordination Group, National Interagency Fire Center. 226 p.
- JOHANSEN, R.W. 1981. Windrows vs. small piles for forest debris removal. *Fire Management Notes* 42(2): 7-9.
- JOHNSON, V.J. 1984. How shape affects the burning of piled debris. *Fire Management Notes* 45(3): 12-15.
- LITTLE, S.N. 1982. Estimating the volume of wood in large piles of logging residue. Administrative Report PNW-1. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 7 p.
- MCNAB, W.H. 1980. A technique for inventorying volumes and weights of windrowed forest residues. Research Paper SE-215. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 8 p.
- MCNAB, W.H. 1981. Inventorying windrowed logging residues. General Technical Report SO-34. U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. pp. 234-237.

- MCNAB, W.H. AND SAUCIER, J.R. 1980. Estimating quantities of windrowed forest residues: a management tool for increased biomass utilization. Georgia Forest Research paper No. 11. Georgia Forestry Commission, Research Division. 4 p.
- PRICHARD, S.J., R.D. OTTMAR AND G.K. ANDERSON. no date. Consume 3.0 User's Guide. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Available online at: <http://www.fs.fed.us/pnw/fera/research/smoke/consume>. 234 p.
- WARD, D.E., C.C. HARDY, D.V. SANDBERG AND T.E. REINHARDT. 1989. Mitigation of prescribed fire atmospheric pollution through increased utilization of hardwoods, pile residues, and long-needled conifers: Part III – emissions characterization. Final Report IAG DA-A1179-85BP 18509. U.S. Department of Energy.
- ZAR, J.H. 1984. Biostatistical analysis. Second edition. Prentice Hall, Englewood Cliffs, NJ. 718 p.

## APPENDIX A

### STUDY LOCATIONS:

Locations where hand-pile biomass and volume were measured in the western United States. A total of 121 piles of various mixtures of coniferous, hardwood, and shrub species were measured and weighed.

#### Okanogan-Wenatchee National Forest – Naches, WA

Forty-seven hand piles composed of ponderosa pine, Douglas-fir, western larch and grand fir were measured and weighed in two treatment units. Piles were constructed 0.75 to 2 years before sampling.

- Rattlesnake Treatment Unit
- Devil's Table Treatment Unit

#### Whiskeytown National Recreation Area – Whiskeytown, CA

Twenty-eight hand piles composed of manzanita, knobcone pine, oak, and various shrub species were measured and weighed in two locations. Piles were constructed less than one year before sampling.

- Carr Powerhouse Road
- Muletown Road

#### Sequoia National Forest – Porterville, CA

Thirty-one hand piles composed of Port Orford Cedar, manzanita, mountain mahogany, oak, ponderosa pine, knobcone pine, and chamise were measured and weighed in two locations.

- Bear Creek
- Ray's Place

#### Los Padres National Forest – San Luis Obispo, CA

Fifteen hand piles composed of Coulter pine, manzanita, and oak were measured at one location. Five additional piles were measured, but not weighed at a second location (Monterrey Ridge); these piles were not included in any analyses.

- Figueroa Mountain
- Monterrey Ridge