United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

General Technical
Report
PNW-GTR-872

January 2013

Biomass Production on the Olympic and Kitsap Peninsulas, Washington: Updated Logging Residue Ratios, Slash Pile Volume-to-Weight Ratios, and Supply Curves for Selected Locations

Jason C. Cross, Eric C. Turnblom, and Gregory J. Ettl

Authors

Jason C. Cross is with the Olympic Natural Resources Center, University of Washington, College of the Environment, School of Forest and Environmental Sciences, P.O. Box 1628, Forks, WA 98331-1628; **Eric C. Turnblom** and **Gregory J. Ettl** are with the School of Environmental and Forest Sciences, College of the Environment, University of Washington, Box 352100, Seattle, WA 98195-2100. This work was performed under Cooperative Agreements 09-CA-11261991-010 (PNW), 09-CA-11261991-007 (PNW), and DE-FG02-97ER41020 (WSU).

Biomass Production on the Olympic and Kitsap Peninsulas, Washington: Updated Logging Residue Ratios, Slash Pile Volume-to-Weight Ratios, and Supply Curves for Selected Locations

Jason C. Cross, Eric C. Turnblom, and Gregory J. Ettl

U.S. Department of Agriculture, Forest Service
Pacific Northwest Research Station
Portland, Oregon
General Technical Report PNW-GTR-872
January 2013

Published in cooperation with:

University of Washington
College of the Environment
School of Environmental and Forest Sciences
Olympic Natural Resources Center
Forks, Washington

Washington State University Energy Program
Northwest Clean Energy Application Center
Olympia, Washington

Abstract

Cross, Jason C.; Turnblom, Eric C.; Ettl, Gregory J. 2013. Biomass production on the Olympic and Kitsap Peninsulas, Washington: updated logging residue ratios, slash pile volume-to-weight ratios, and supply curves for selected locations. Gen. Tech. Rep. PNW-GTR-872. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 30 p.

Biomass residue produced by timber harvest operations is estimated for the Olympic and Kitsap Peninsulas, Washington. Scattered residues were sampled in 53 harvest units and piled residues were completely enumerated in 55 harvest units. Production is based on 2008 and 2009 data and is stratified by forest location, ownership type, harvest intensity, and harvest method. An additional sampling was taken to ascertain the mass of wood present in a pile of biomass: 20 piles of biomass were measured for gross volume, processed into hog fuel, and remeasured for volume; five samples were drawn from each pile and examined for volume, green mass, and bone-dry mass. An equation relating mass of wood in a pile to the gross biomass volume is derived. Finally, the availability and average delivered cost per ton of biomass is calculated for five delivery centers on the Olympic Peninsula.

Keywords: Biomass, residue, slash, hog fuel, production, volume, density, supply curve.

Summary

Logging residue (slash) consists primarily of the branches and tree tops of harvested merchantable timber; excluding snags, downed logs, and stumps. Residues may be scattered about the harvest unit, concentrated in piles, or both—depending on the harvest method and equipment used. Accurate estimates of residue production are immediately useful to managers who must marshal resources for smoke abatement, fire-risk reduction, and regeneration efforts, and to landowners who bear the financial burden of such activities. Additionally, changes in national and state energy policies have created opportunities for offsite utilization of residues if sufficient quantities can be delivered at competitive prices. This analysis of direct field measurements seeks to update the estimators of wood in piled logging residue (Little 1982) and biomass supply studies based on those estimators (Hardy 1996; Howard 1978, 1981; Kerstetter and Lyons 2001). Specifically, the purpose of this project was to quantify (1) the production of logging residue in Clallam, Jefferson, Kitsap, Mason, and Grays Harbor Counties for 2008 and 2009; (2) the volume of solid wood contained in a slash pile; and (3) the total supply and average price of biomass deliverable to the cities of Forks, Port Angeles, Port Townsend, Shelton, and Aberdeen, Washington.

Production

The study reviewed the state of Washington's 1,400+ Forest Practice Applications (FPAs) on the Olympic and Kitsap Peninsulas for calendar years 2008 and 2009. The set was narrowed to 975 FPAs—encompassing 66,729 ac by excluding units of less than 15 ac as well as single-tree, right-of-way, and salvage operations. As federal and tribal timber harvests do not require FPAs, they too were excluded. Applications were stratified by four factors thought to be associated with distinct production rates: forest location (east/west side of the Olympic Peninsula), harvest intensity (clearcut/thinning), ownership type (public/nonpublic), and harvest method (ground/cable/mixed). Eighty-nine percent of timber harvest was located on the west side of the Olympic Peninsula, and clearcuts accounted for 88 percent of harvest intensity. To capture mean residue production (ft^3/ac) within 15 percent four times out of five, the desired sample size of 86 harvest units was allocated among strata according to proportion of harvest activity. In total, 511 transects were installed to sample scattered residues on 53 harvest units; all 3,075 slash piles were measured on 55 harvest units. An Type II analysis of variance (ANOVA) on transect data found ownership to be a factor associated with different production rates—1,588 ft^3/ac on public lands versus 1,155 ft^3/ac on nonpublic land. A similar test on piled residue data resulted in two distinct production groupings: "high"

production yielded an average 325 ft^3/ac; "low" production yielded 65 ft^3/ac. Both groups consisted of strata with each level of forest location, harvest intensity, and ownership type. Harvest method was not identified as a factor associated with different production levels. Annualized harvest rates and volumes (FPAs) with residue production attributes and ratios are summarized below:

- FPA acreage: 33,364 ac
- Harvested timber volume: 885 million board feet
- Transected residues: 1,292 ft^3/ac
- Pile residues: 307 ft^3/ac
- Total residues: 1,599 ft^3/ac
- Bone dry tons (BDT) of residue per acre: 19
- Ratio of BDT to harvested thousand board feet: 3:4

Volume-to-Weight Ratios

The gross volume of a slash pile is a combination of wood and air. Residue production estimates should reflect only the wood component. The existing ratio estimator for volume-to-weight dates from 30 years ago and does not represent current harvest methods or forest conditions. An experiment was conducted to update the volume-to-weight ratio estimator: each of 20 selected slash piles was measured for gross volume before and after processing; five samples were drawn from each processed hog-fuel pile for further laboratory analyses to determine moisture content, compaction, and specific gravity. Results indicated that the volume of processed hog fuel is a function of the square root of the original slash pile volume; and the solid wood volume of a hog-fuel pile is approximately 38 percent of its volume. The green density of the wood component was quantified at 18.72 lb/ft^3; bone dry density was 9.05 lb/ft^3. Given the cubic-foot volume (V_s) of a slash pile, the bone-dry mass of the wood component in pounds is given by:

$$\text{Bone dry mass} = (92.18V_s^{1/2} - 4{,}468) \times 9.05 \text{ lb/ft}^3$$

Supply Curves

Supply curves describe the behavior of average unit cost as the cumulative supply delivered to a specific location increases. The cities of Forks, Port Angeles, Port Townsend, Shelton, and Aberdeen were selected as delivery locations on the basis that all have existing industrial milling capacity and are therefore more likely to utilize logging residues. The components of a logging residue supply curve are site production, recovery costs, and transportation costs.

Data from the Washington State Forestland Database were used to identify timber-producing parcels and stratify them directly for location and ownership type. Parcels were aggregated in 10-minute intervals based on delivery time to a given delivery center. Harvest type and method were imposed on the aggregated interval acreage in the proportions indicated by the production study. Base rates of $35 per BDT for in-woods recovery and $65 per hour for transportation costs were assumed; both rates are subject to a fuel surcharge assessed at a rate of 1 percent for every 10 cent increase in diesel prices.

The supply curves assembled with the production and cost values indicate Forks to be the most competitive delivery site for quantities up to 50,000 BDTs (MBDTs). Overall, Aberdeen had access to the greatest annual quantity of hog fuel (600 MBDT/year), while hog fuel available for delivery to Shelton had the lowest average unit price ($53.26/BDT). Port Angeles and Port Townsend have access to decidedly smaller quantities at the highest average prices. Delivery centers are ranked from the highest to lowest annual quantity of hog fuel deliverable at an average unit price of $50/BDT: Aberdeen (410 MBDT/Y), Shelton (320 MBDT/Y), Forks (280 MBDT/Y), Port Angeles (110 MBDT/Y), and Port Townsend (100 MBDT/Y).

Contents

Introduction

The marketability of slash produced from timber harvest is contingent upon (1) the quantity produced and (2) the average unit cost on delivery.

Timber harvest activities produce residues (slash) that consist primarily of the branches and tree tops of harvested merchantable timber. This material excludes snags and downed logs that are required to remain onsite to perform various ecologic functions. In the past, this material would likely have been burned in some manner to prepare the site for replanting; however, increasing interest in biomass as a source of renewable energy has created a market for slash to be removed offsite and used as hog fuel. The marketability of slash produced from timber harvest is contingent upon (1) the quantity produced and (2) the average unit cost on delivery. With respect to quantity, slash may be left scattered about the area after harvest or concentrated in piles—methods exist to survey and quantify both types. Similarly, previous studies have constructed supply curves that explain the relationship between cumulative delivered quantity and average cost per unit. If markets are to be created and sustained for the offsite utilization of slash, and those markets are to be met with wise policies governing such removals, then the quantities and delivered cost must be known with sufficient confidence. The purpose of this investigation is to capture the quantities and costs for the Olympic and Kitsap Peninsulas of Washington.

Logging Residue Production

When timber is harvested, woody biomass of the stand may be divided among three broad categories: (1) merchantable products removed from the stand; (2) retained trees, snags, stumps, and down logs; and (3) logging residues (slash) that may remain, be removed, or some combination thereof. The amount of trees, snags, and logs remaining after harvest differs with ownership, harvest intensity, and harvest method. Policies differ as to the quantity of trees, snags, and downed logs to be retained on federal, state, and private timberlands. Thinning, shelterwood, and clearcut harvest types retain decreasing levels of standing timber while increasing the expected production of slash. Ground-based harvest methods may result in a notably different distribution of biomass than cable-based methods. Whatever the quantity and distribution of remaining biomass, it contributes to ecologic functions, including shade and large woody debris recruitment potential to nearby streams (NCASI 2000), nutrient cycling and site productivity (Titus et al. 2006), and habitat for animals (Jacobs et al. 2007). Tree stumps also stabilize soil for years after harvest. Of particular interest to this investigation is the production of logging slash—consisting primarily of the branches and tree tops from merchantable timber products—that often remains but may be removed.

The fate of slash that remains after timber harvest—either scattered about the forest floor or concentrated in piles—is to decompose and serve as nutrient capital for soil, enter recalcitrant soil pools, or act as fuel for (wild or prescribed) fires. As long as slash remains, it is an impediment to reforestation efforts, although piling slash has the advantage of exposing the forest floor, thereby promoting the establishment of the subsequent cohort of trees. In addition to providing nitrogen (N) and other nutrients through decomposition, slash is a source of carbon (C) emissions to the atmosphere, and removal may decrease soil C (Palosuo et al. 2000); however, emissions from decay are lower, and more slowly released than if burned (Lee et al. 2010). Some N is volatized by prescribed burning or wildfire and the loss can be calculated (Little and Ohmann 1988); however, Mroz et al. (1980) noted that not all studies confirm a reduction in N, concluding that generalizations about the effect of fire on soil N over wide areas and different forest floor materials are difficult. Little and Ohmann (1988) concluded that N loss is proportional to consumption of the forest floor; however, some sites showed a gain (the largest +171.3 lb/ac), while others showed losses (the largest -594.2 lb/ac) in soil N following burning.

Nitrogen is the major growth-limiting nutrient among forests of the Pacific Northwest (Peterson and Gessel 1983). Changes in nutrient budgets owing to timber harvest operations and various slash treatment strategies have been well studied (Feller 1988, Feller and Kimmins 1984, Jurgensen et al. 1997, Kraemer and Hermann 1979, Little and Ohmann 1988, Mroz et al. 1980). Nitrogen enters the forest floor and soil through decomposition and mineralization of parent material (Edmonds 1980) and is rapidly taken up by plants. Little and Ohmann (1988) noted that decaying organic matter on the forest floor excludes sound woody material 0.1 in and larger (properly considered woody fuel). Thus, during early stages of postharvest stand development, where the forest floor is the primary source of N (Grier et al. 1974), slash seems not to be a significant source.

Increasing demand for renewable energy has created markets for slash to be used offsite as a boiler fuel. When slash displaces a fossil fuel in a boiler, greenhouse gas (GHG) emissions of slash are less than half that of onsite combustion or decomposition (Lee et al. 2010), even after accounting for the emissions produced by processing and transportation. The effects of slash removal on soil nutrient budgets are likely to differ among sites: If slash removal is similar to the effects of prescribed fire, we would expect a substantial reduction in available C, a general reduction in total N, although responses range widely (Little and Ohman 1988), and an increase in the available N (Antos et al. 2003), perhaps owing to a lowering of the C/N ratio. Although initial studies in western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) forests found no relationship between site productivity and soil C and N or C/N ratios (Edmonds and Chappell 1994), the impacts of mechanical slash removal will require further research. Slash removal also reduces the risk of unintended fires by reducing fuel loads; lowers the risk of producing smoke from any type of fire; and aids in reforestation efforts by exposing a larger proportion of the forest floor to sunlight, allowing reforestation on areas that might otherwise be occupied by slash piles. The increased interest in offsite slash utilization alone warrants investigation into its production, but also the need to develop management guidelines for utilization to protect against deleterious effects of removal. This paper reports on a study that updates the estimates of logging residue production on the Olympic and Kitsap Peninsulas in Washington state for calendar years 2008 and 2009. This study examines slash postharvest and does not consider differences in C storage in relation to stand age (Harmon et al. 1990) or differences of intrastand storage pools (Janisch and Harmon 2002, Pregitzer et al. 2004) or silvicultural practices in the more general sense (Foley et al. 2009, Harmon and Marks 2002).

Materials and Methods

The study reviewed all Forest Practice Applications (FPAs)[1] received by the Washington State Department of Natural Resources (DNR) from January 1, 2008, through December 31, 2009. The study area included the five counties of the Olympic and Kitsap Peninsulas of Washington shown in figure 1: Clallam, Jefferson, Kitsap, Mason, and Grays Harbor. The FPAs were stratified by factors suggested by Kerstetter and Lyons (2001) thought to influence production of logging residues: forest location, harvest intensity, ownership type, and harvest method. Forest location was composed of east (denoted L_e) and west (L_w) levels, divided by the boundary between ranges 6 and 7 west (roughly at the Elwha River in Clallam County and the longitudinal boundary between Mason and Grays Harbor Counties). Levels of harvest intensity were clearcut (I_c) or thinning (I_t). Ownership consisted of public (O_p) or nonpublic (O_n) levels, where nonpublic lands may include private industrial, nonindustrial, timber investment management organizations, real-estate investment trusts, and land conservation organizations. Harvest method had levels of ground (M_g), cable (M_k), or mixed (M_x). Levels of each stratum correspond to explicit declarations in each FPA, making stratification a straightforward process. Excluded from the study were operations producing insignificant or noncommercial quantities of biomass such as cedar salvage, individual tree salvage, right-of-way-only harvests, and units smaller than 15 ac; also excluded were FPAs that were denied,

[1] Forest practices are related to growing, harvesting, or processing timber, including, but not limited to, road and trail construction and maintenance, thinning, salvage, harvesting, reforestation, brush control, suppression of diseases and insects, and using fertilizers. These practices are regulated by the Washington Forest Practices Act and its corresponding rules, promulgated by the Department of Natural Resources.

Figure 1—Study area with selected supply curve delivery locations. The Olympic and Kitsap Peninsulas of Washington are composed of Clallam, Jefferson, Grays Harbor, Mason, and Kitsap Counties. The cities of Aberdeen, Forks, Port Angeles, Port Townsend, and Shelton were selected as supply curve delivery locations.

withdrawn, and subsequently renewed. Federal and tribal lands do not require an FPA and were not included. Exclusions and omissions narrowed the set of FPAs in the study to 974 covering 66,729 ac.

A sample size of 86 harvest units was found to be sufficient to capture mean cubic-foot volume of residue produced per harvested acre within 15 percent of the true mean 4 times out of 5. This is a slight deviation in targeted precision and accuracy from Howard (1981), who sought to capture residue production per acre within 20 percent of the true mean 9 times out of 10. A coefficient of variation of 85 percent was employed to compute sample size as residue volume per acre was the major contributor to total variance. Proportional allocation was used to assign sample sizes to the defined strata with an imposed minimum of two sample units regardless, in order to offer minimal assurance against extreme values and to allow for variance calculation. The proportion of harvested acres and associated sample size by stratum is detailed in table 1.

Table 1—Harvest acreage proportion and sample size by stratum for calendar years 2008 and 2009

Forest location	Ownership	Clearcut			Thinning		
		Ground	Cable	Mixed	Ground	Cable	Mixed
East	Public	0.012 (2)	0.001 (2)	0.017 (2)	0.002 (2)	0.000 (2)	0.002 (2)
	Nonpublic	0.027 (2)	0.002 (2)	0.036 (3)	0.004 (2)	0.000 (2)	0.005 (2)
West	Public	0.102 (6)	0.008 (2)	0.138 (8)	0.014 (2)	0.001 (2)	0.019 (2)
	Nonpublic	0.221 (13)	0.017 (2)	0.296 (17)	0.031 (2)	0.002 (2)	0.042 (3)

Note: Each cell details the proportion of 66,729 ac included in the study by factors thought to be associated with different levels of residue production: forest location, harvest type, ownership type, and harvest method. Each proportion is accompanied by the harvest unit sample size in parentheses required to capture mean residue production within 15 percent at 80 percent confidence, assuming a coefficient of variation of 85 percent. A minimum of two sample units is assigned even if the proportion warrants fewer.

For each harvest unit sampled, transects were installed to sample the biomass scattered about the forest floor following timber harvest operations. Harvest units in excess of 30 ac had 10 initiation points; harvest units less than 30 ac were sampled at a rate of one initiation point per 3 ac. With transect subsampling intensity thus defined, the dimensions of a square grid were derived. The first transect initiation point was located by randomly placing an intersection nearest a convenient harvest unit access point. Subsequent initiation points were located at the systematic grid intersections on a map or aerial photograph. From each initiation point radiated three 100-ft large-fuel transects; the direction of the first was assigned randomly, with the second and third at azimuths ± 120° to the first. Large fuels were defined as pieces with diameters greater than 3 in and lengths greater than 1 ft. The diameter of each large piece at its intersection with the transect was recorded. Three shorter transects were nested within each large-fuel transect to capture progressively smaller material: a 4-foot transect—from 14 to 18 ft along the large fuel transect to capture pieces between 0.10 and 0.25 in diameter; a 6-ft transect (14 to 20 ft) for pieces between 0.26 and 1.00 in diameter; and a 10-ft transect (14 to 24 ft) for pieces between 1.10 and 2.90 in diameter. Pieces were tallied for each fine-fuel transect and included only intact dead sticks and twigs that were detached woody pieces visible on the surface of the forest floor. Material smaller than 0.1 inch in diameter, bark chunks, cones, and splinters were not tallied as they are considered litter/duff (Little and Ohmann 1988). Logs rotted to the point that they could not support their own weight, or those that had lost their original form, were also excluded. Transects falling near unit boundaries or riparian management zone (RMZ)[2] or road edges within units were handled according to the reflection

Material smaller than 0.1 inch in diameter, bark chunks, cones, and splinters were not tallied as they are considered litter/duff.

[2] RMZs are terrestrial areas adjacent to water courses where forest and aquatic dynamics overlap and interact. They are generally measured horizontally from the outer edge of the bankfull width or channel migration zone and extend to limits prescribed by the appropriate law or policy.

method as described in Gregoire and Valentine (2008). Rooted materials including live trees, stumps, snags, or branches were not tallied, nor were rooted materials resting on the ground surface. It was also imperative to separate slash piles found along transects to avoid double counting of material. Any portion of a transect that intercepted a pile was treated as bare ground. Prior to analysis, diameters and piece counts were converted to cubic feet per acre values with methods described by Gregoire and Valentine (2008). Fine-fuel tallies were converted using the midpoint of the transect's diameter range. The mean cubic feet per acre residue volume for each transect type was calculated and the total volume was associated with the initiation point for analysis.

Slash pile volumes were completely enumerated across sampled units. The methods used to evaluate pile volumes were first introduced by Howard (1981) and Little (1982); we employed the expanded set of pile geometries described by Hardy (1996) to increase precision of estimates. Pile origins were recorded as ground or cable. The percentage of gross pile volume consisting of pieces > 1 ft^3 was estimated and recorded. The volume of soil was also estimated as a percentage of gross pile volume. Lengths and widths were measured at ground level with tapes, while heights were measured with a Laser Technology "TruPulse 200"[3] laser rangefinder/heightfinder with a precision of 0.10 ft. Residue piles consist of a mixture of wood and air but only the wood component was to be analyzed. Gross slash pile volumes were scaled by a factor of 0.3324—an updated version of Little's (1982) ratio that is derived in the "Volume-to-Weight Ratios" section—relating hog fuel pile volume to gross slash pile volume. Hog fuel pile volumes were scaled by 0.377 to account for the air portion of the hog fuel pile—a factor also derived in the "Volume-to-Weight Ratios" section—resulting in cubic feet of solid biomass. Solid biomass volumes were summed within sample units and divided by unit acres resulting in cubic feet per acre values for analysis.

Overall sample size reflected the anticipated degree of dispersion within strata that relied, in part, on the results from similar efforts by Howard (1981) and Hardy (1996). As described, the methods to acquire our data define a stratified random sampling process (Cochoran 1977). However, we analyze our data using a model derived from an experimental design context to serve a secondary objective of simultaneously testing our strata definitions. Although there are reasons to believe that our strata definition factors will be associated with different slash production values (Kerstetter and Lyons 2001), we seek to test these assumptions. The reader should not infer that significant stratum definition factors are in any way causative in nature; on the contrary, significant strata differences are merely useful

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

associations with slash production values. Using the analysis to finalize strata definitions simultaneously with producing estimates for them may slightly degrade estimator optimality, but probably not significantly. Since sample sizes differ by stratum, the model describing residue production by harvested acre will be unbalanced. Further, the strata being analyzed for differences in production rates contain fixed effects (the factors comprising the defined strata) as well as random, nested effects owing to subsampling; therefore, the model is also a mixed-effects model (Oelhert 2000). Hasse diagrams (Lohr 1995, Oehlert 2000) are useful for visualizing and quantifying experimental models; a diagram representing the sampling model is presented in figure 2.

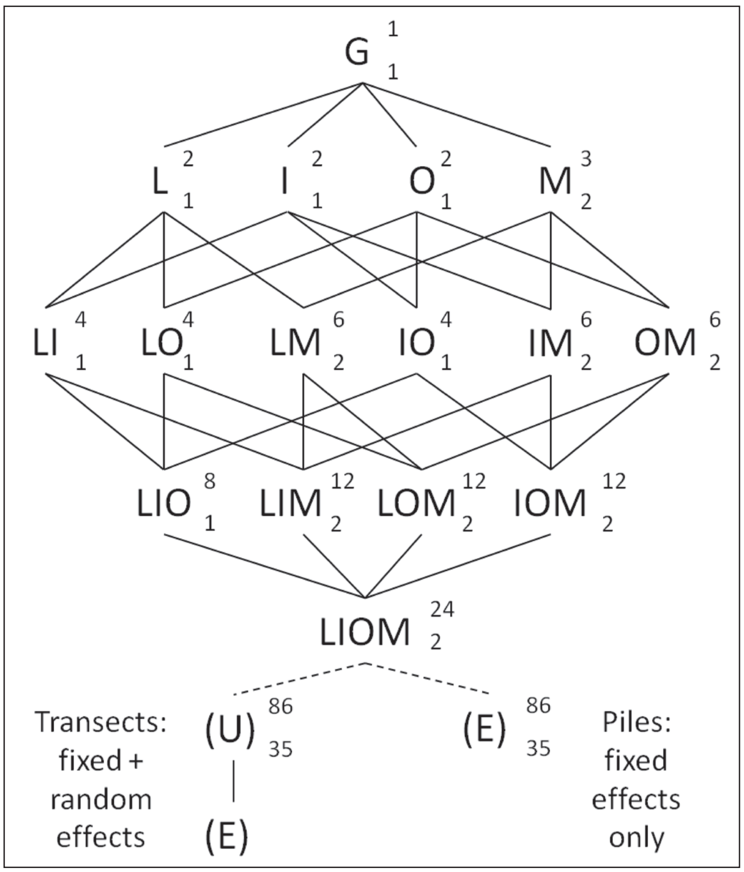

Figure 2—Hasse diagram of residue production model. The diagram starts with the grand mean, G, at the top. Each node at the second level corresponds to a factor thought to be associated with residue production: forest location (L^2_1), harvest intensity (I^2_1), ownership type (O^2_1), and harvest method (M^3_2). Superscripts indicate the number of levels for factors or interactions; subscripts denote associated degrees of freedom. Nodes at the third, fourth, and fifth levels represent 2-, 3-, and 4-way interactions. Nodes in parentheses indicate random effects: (U) represents randomly sampled transect harvest units with nested initiation points (E). Piles were completely enumerated (E) across harvest units on the right-hand side (no nesting).

Results

By the end of the data collection period, 6 of 24 strata representing 12.8 percent of FPA acres in the study had had only one unit harvested. Having no replicated observations in any stratum causes difficulties in stratum variance calculation, and causes statistical aliasing of main and interaction effects in the analysis of an experimental model. Therefore, the single observations from these six strata were dropped from the analysis, to guard also against the possibility that these single replicates might be unusual instances, that is, not truly representative of their respective strata. An additional nine strata representing 1.8 percent of the total acres could not be sampled for a lack of available harvest units. Ultimately, the analysis included nine strata accounting for 85.4 percent of the study acres.

In total, 511 transects were installed spread across 53 harvest units and 3,075 piles were measured across 55 sample units.

Transects—

In total, 511 transects were installed spread across 53 harvest units. Each transect record contains a list of large-fuel diameters and tallies for each fine-fuel survey. A single diameter value recorded on transect A, point 8 in FPA 2610223 was determined to be biologically infeasible and was removed from analysis. Scatter plots of residual versus predicted values for the linear model indicated by figure 2 describing residue production revealed heteroskedasticity among the data set (i.e., variance increased with predicted mean value). A boxplot of volume per acre by strata indicated a strong positive skew in the distribution. Constancy of variance and normally distributed data were requirements for the selected statistical analysis. A $\log_e$ transformation (Ln) of volumes sufficiently restored homoskedasticity and normalized distributions of transect and pile data sets. Figure 3 illustrates the before- and after-transformation variances and distributions of transect data.

A type II ANOVA found ownership to significantly affect Ln-transformed residue volume production; an F-statistic of 2.078 on 1 and 50 degrees of freedom yielded a p-value of 0.1557 that was less than our desired type I error limit (0.2). Location, harvest type, and harvest method were not found to be significant factors. The updated linear model describing Ln-transformed transect data suggested in figure 2 indicates that public lands have a production rate of 1,588 ft^3 of biomass per harvested acre; nonpublic lands produce 1,155 ft^3 of biomass per harvested acre. Both values have a variance of 4.23 in LN-space. Table 2 summarizes transect residue production.

Piles—

In total, 3,075 piles were measured across 55 sample units. Similar to transect data, pile data demonstrated heteroskedasticity and a positively skewed distribution by stratum transect and pile data sets (i.e., variance increased with predicted mean

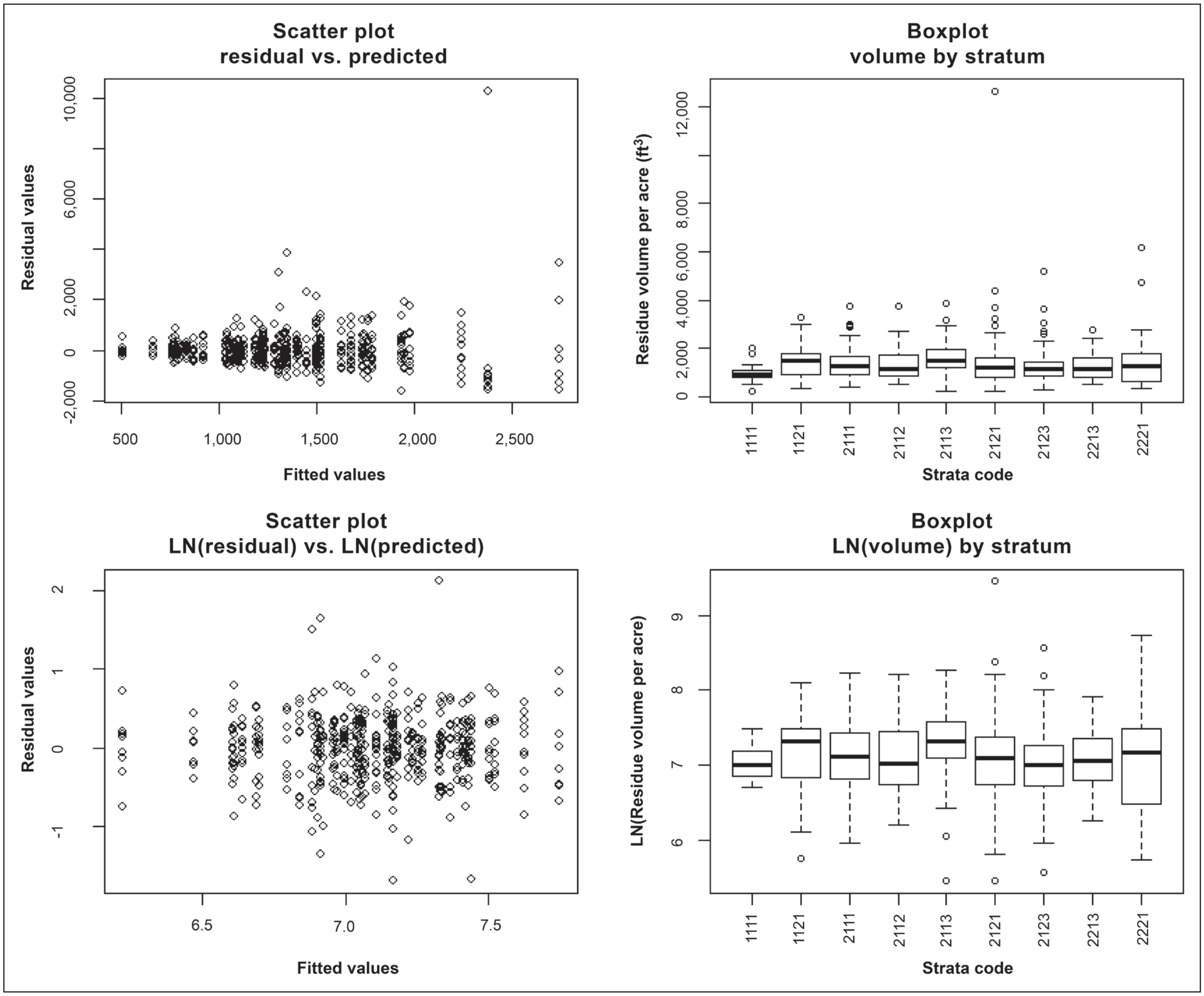

Figure 3—Skedacity and distribution of transect data. Top left: Natural-scale scatter plot of residual versus predicted values based on the production model described in figure 2; note the heteroskedasticity (nonconstant variance). Bottom left: LN-transformation of transect data yielding homoskedasticity (constant variance). Top right: Natural-scale boxplot of cubic-foot volumes of residue per acre by coded stratum; note the positive skew across strata. Bottom right: LN-transformation of transect data yielding normally distributed responses across strata.

value). A natural-log transformation (Ln) of volumes sufficiently restored homoskedasticity and a normalized distribution. Figure 4 illustrates the before- and -after-transformation variances and distributions of pile data.

A type II ANOVA found forest location, harvest type, ownership, and the interaction between intensity and ownership to be associated with different production rates. Results from the type II ANOVA on the updated linear model are detailed in table 3. A reduced set of eight strata (as harvest method is removed), with means ranging from 1.637 to 6.360 in LN-space and a variance of 1.067 in LN-space. A post-hoc pairwise comparison of strata means using the Tukey-Kramer method

Table 2—Transected residue production metrics and confidence interval by ownership

Ownership	Acres[a]	Harvest units[b]	Mean production[c]	80% confidence interval
Public	21,065	18	1,588	1,403 , 1,797
Nonpublic	45,530	35	1,155	1,057 , 1,263
Total[d]	66,595	53	1,292	1,283 , 1,301

[a] Acres reflect proportion of qualifying forest practice applications activity during the study period.

[b] Harvest units indicate sample size of stratum.

[c] Mean production and 80 percent interval values were calculated in LN-space but are reported in natural scale units (cubic foot/acre). Both public and nonpublic strata have a variance of 4.23 in LN-space.

[d] Total mean production is weighted by acres; total variance was 0.0358 in LN-space.

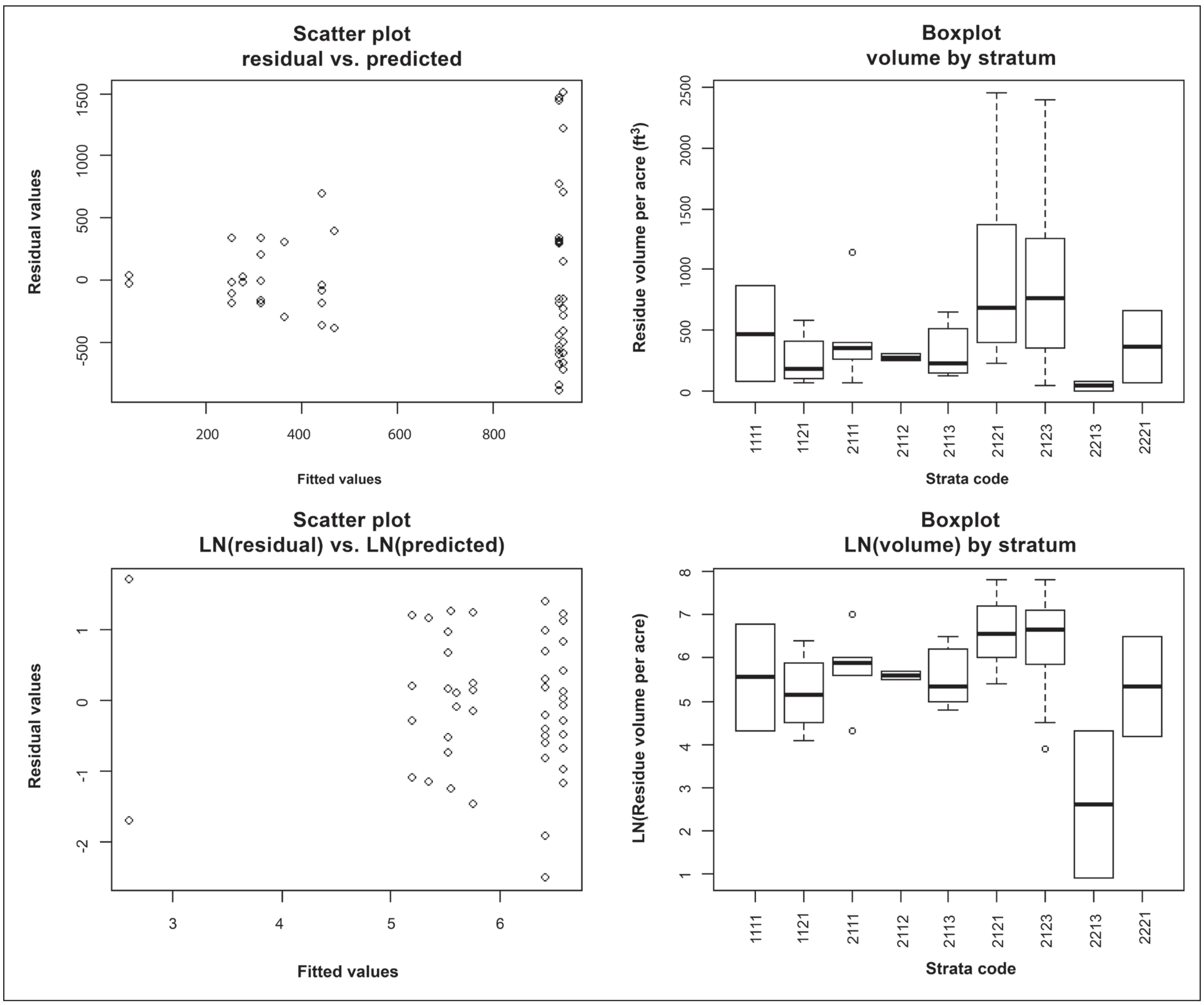

Figure 4—Skedacity and distribution of pile data. Top left: Natural-scale scatter plot of residual versus predicted values based on the production model described in figure 2; note the heteroskedasticity (non-constant variance). Bottom left: LN-transformation of transect data yielding homoskedasticity (constant variance). Top right: Natural scale boxplot of cubic-foot volumes of residue per acre by coded stratum; note the positive skew across strata. Bottom right: LN-transformation of transect data yielding normally distributed responses across strata.

Table 3—Results of a four-way analysis of variance on piled residues

Factor[a]	Sum of squares[b]	Degrees of freedom	Mean squares[c]	Calculated F-statistic[d]	P-value[e]
Forest location	4.114	1	4.114	3.9661	0.0524
Harvest intensity	15.576	1	15.576	15.0162	0.0003
Ownership	8.695	1	8.695	8.3825	0.0058
Intensity: ownership	3.837	1	3.837	3.6991	0.0606
Residuals	47.715	46	1.037		

[a] Interactions between factors are indicated with a colon.

[b] Sum of squares (SS) calculation was performed by the open-source statistical package R (http://cran.r-project.org) perform. Type II SS were used to account for unbalanced sampling among strata.

[c] Mean square (MS) value for a factor is the quotient of SS and the degrees of freedom (DF), SS ÷ DF.

[d] The calculated F-statistic is the quotient $MS_{factor} \div MS_{residuals}$, which are compared to critical $F_{.20\,(1,46)}$ value to determine P-values.

[e] In this investigation, a P-value < 0.20 indicates significance.

Table 4—Piled residue production metrics and confidence interval by strata group

Strata group	Group acres	Harvest units	Mean ft^3/ac production	80% confidence interval (ft^3/ac)
High	61,524	51	325	313 , 337
Low	4,538	4	65	58 , 75
Total	66,062	55	307	306 , 307

Note: Strata groupings were identified using Tukey's HSD test; group names reflect relative residue production rates. The high production group includes strata $L_wI_cO_n$, $L_wI_cO_p$, $L_eI_cO_n$, and $L_wI_tO_n$. The low production group includes $L_eI_cO_n$, and $L_eI_tO_n$. Production estimates (and associated confidence intervals) were not available for strata $L_wI_tO_p$ and $L_eI_tO_p$, as no data existed. Acres indicate stratum's proportion of total activity during the study period; harvest units denote sample size across strata. Mean production and 80 percent interval values were calculated in LN-space but reported in natural scale units (ft^3/ac). Both high and low strata groups have a variance of 1.037 in LN-space. Total mean value is weighted by acres; total variance was 0.0025 in LN-space.

(Oehlert 2000) found that two distinct groups existed, where means between the groups could be distinguished from each other and means within a group could not be distinguished from one another. The first group consisted of strata $L_wI_cO_p$, $L_wI_cO_n$, $L_eI_cO_n$, and $L_wI_tO_n$ and was labeled "high" for its average production rate of 325 ft^3 of residue per harvested acre. The second group included strata $L_eI_cO_n$ and $L_wI_tO_p$ and was labeled "low" with an average production rate of 65 ft^3 per harvested acre. No data existed in strata $L_eI_tO_p$ and $L_eI_tO_n$, and thus precluded production estimates, variance calculations, and the construction of confidence intervals. Production by group is summarized in table 4.

As timber harvest operations affect the production of residues, the economic conditions that affect timber production likely also affect residue production.

Discussion and Applications to Management

As timber harvest operations affect the production of residues, the economic conditions that affect timber production likely also affect residue production. Sampling was constrained by low timber prices, which resulted in an insufficient supply of units in strata with marginally higher cost harvest types and methods: thinning operations accounted for only 12.2 percent of the acres in the study, and cable-only methods accounted for 3.1 percent of the study acres. More than 100 FPAs representing these strata were included in the study, but less than 10 percent of the strata had been harvested. The labor required to install transects and census slash piles was higher than expected (2 man-days versus 1 expected); however, this did not affect the sampling matrix and all available units were sampled.

Initial exploration of transect and pile data revealed uneven variances and nonnormal distribution of production rates within strata. An LN transformation of transect and pile results sufficiently restored homoskedasticity and normality. A four-way Type II ANOVA found that forest ownership is a significant factor in scattered residue production—publicly owned lands yield 1,588 ft^3/ac, which is 433 ft^3/ac greater more than nonpublic lands (1,155 ft^3/ac). A similar test on piled volumes found forest location, harvest type, ownership, and the interaction between intensity and ownership to be factors significantly affecting production. However, a comparison of the six strata means found that distinct production rates existed for only two groups: a "high"-yield group produced a mean of 325 ft^3/ac; the "low" group yielded 65 ft^3/ac. Although no data existed for rigorous analysis of piled residue on east-side thinnings (L_eI_t), the reader may require production estimates. The linear model describing piled residue production indicated "low" production rates for both strata according to table 4.

The sampling design kept transects and pile measurements disjoint. Therefore, the total residue produced on a harvest unit was simply the sum of transect and pile production rates. The transect factor combines with the pile groupings to yield four combined production rates ranging from 1,478 ft^3/ac to 1,913 ft^3/ac. The total acre-weighted mean production rate was 1,599 ft^3/ac with an 80 percent confidence interval of (1,563, 1,636) ft^3/ac. The combined results are summarized in table 5.

Applying the weighted mean production of 1,599 ft^3/ac to an annual harvest of 33,364 acres yields a total annual residue production of 53,349,036 ft^3 on the Olympic and Kitsap Peninsulas of Washington. If the bone-dry density of the wood is 24.18 lb/ft^3, then total annual production can be expressed as 1,289,979,690, or 644,989 bone-dry tons (BDTs). The reported harvest volume from the FPA survey was 1.67 billion board-feet, or 883 million board feet annually; therefore, approximately 3 BDTs of residue were produced for every 4 MBF of harvested timber.

Table 5—Combined transected and piled residue production metrics and confidence intervals by strata group

Distribution			Production[d]			
Strata group[a]	Acres[b]	Harvest units[c]	Transect	Piled	Total	80% confidence interval
$High_p$	16,549	15	1,588	325	1,913	1,887 , 1,939
$High_n$	44,975	36	1,153	325	1,478	1,465 , 1,491
Low_p	4,538	4	1,588	65	1,653	1,610 , 1,697
Total[e]	66,062	55	1,292	307	1,599	1,563 , 1,636

[a] Groups are the combination of transect (public/nonpublic) and pile (high/low) strata. Subscripts p and n indicate public and nonpublic ownership, respectively. Group $HIGH_p$ includes stratum $L_wI_cO_p$; $HIGH_n$ includes strata $L_wI_cO_n$, $L_eI_cO_n$, and $L_wI_tO_n$; LOW_p includes strata $L_eI_cO_p$ and $L_wI_tO_p$.

[b] Acres indicate group's proportion of total qualifying forest practice applications activity during the study period.

[c] Harvest units indicate group sample size.

[d] Mean production and 80 percent confidence interval values were calculated in LN-space but reported in natural scale units (ft^3/ac). As transect and pile sampling was disjoint (i.e., independent), variances were additive with covariance = 0; strata group variances are 4.270 in LN-space.

[e] Total mean values are weighted by acres; total variance is 0.445 in LN-space.

Volume-to-Weight Ratios

Quantifying piled logging slash has long been important for smoke and fire management. However, the potential for offsite utilization of slash as a feedstock in energy production is driving interest in updated and improved production rate estimates. Howard (1978, 1981) and Hardy (1996) described and implemented methods for sampling scattered and piled residues. Few published studies have attempted to quantify the volume and mass of piled logging residues: Howard (1981), Hardy (1996), and Wright and Vihnanek (2009) all rely on the volume-to-weight ratio developed by Little (1982)—a study based on measurements of nine slash piles from national forest harvest units in the Pacific Northwest harvested between 1979 and 1980. Significant changes in timber type and harvest methods have likely affected the composition of slash piles and warrant updated volume-to-weight ratios—the objective of this brief investigation.

Methods

Twenty slash piles consisting primarily of branches and tops of harvested merchantable timber and excluding snags, downed logs, and stumps were made available for analysis across three harvest units located near Forks, Washington. These piles are not associated with harvest units or pile measurements mentioned previous to this section. Field procedures were conditioned on the manner in which logging residue was harvested and removed from the harvest site by our cooperator. The equipment and machinery used to gather, process, and transport residues precluded replicating directly Little's (1982) methods; however, the objective remained to solve for mass using the general equation:

$$\text{Mass} = \text{volume x density} \quad (1)$$

Volume—

Volume measurements were taken in two stages: (1) The first set of measurements were taken at the harvest site where slash piles were assigned one of the geometric shapes described by Hardy (1996) and the associated measurements to calculate gross residue volume (V_s) were recorded. (2) A residue pile was subsequently processed into hog fuel and taken to an intermediate location where a second set of volume measurements were taken. Processed residue piles produced numerous truck loads of hog fuel. At the second location, a front-end loader was used to reconstitute a complete pile from the truck loads of hog fuel arriving from the harvest site. Piles were constructed with a circular footprint such that the radius of the pile could be derived from a direct measurement of its circumference. Pile heights were recorded from a distance of 100 ft from the pile center using a clinometer with precision to 0.5 percent. The shape of the curve illustrated in figure 5 is given by the equation:

$$y = \{[\cos((\pi \text{ x } x) \div r) + 1] \div 2\} \text{ x } h \quad (2)$$

Where r is the derived radius of the pile and h is its height and x ranges from $-r$ to r; equation (2) scales a cosine curve to an amplitude of h and a half-period of r. The volume (V_h) of the solid (pile) formed by rotating equation (2) about the y-axis is given by:

$$V_h = [(\pi^2 - 4) \text{ x } h \text{ x } r^2] \div 2\pi \quad (3)$$

The hog fuel pile contains the same quantity of solid wood as the original slash pile, only with less air. If we let f() represent the relationship of piled hog fuel volume (V_h) to the volume of the original slash pile (V_s), then volume in equation (1) can be written as:

$$\text{Volume} = \text{f}(V_s) \quad (4)$$

And by substitution, (1) becomes:

$$\text{Mass} = \text{f}(V_s) \text{ x density}$$

Jason Cross

Figure 5—Processed hog fuel pile with profile curve estimate. The function describing the curve (in green) is given by the equation: $y = \{[\cos((\pi \times x) \div r) + 1] \div 2\} \times h$. Where r is the half-period of the curve (y-axis to endpoint) and was derived from a direct measurement of circumference; h was the height measured from 100 distance from the center using a clinometer.

Density—

We are interested in quantifying the solid wood component of a hog fuel pile. However, other pile components must be properly accounted for in order to isolate the bone-dry mass of wood: air and water (in the form of wood moisture content). A modified version of Glass and Zelinka's (2010) formula provides an alternate version of equation (1), expanding density to more completely account for these pile elements:

$$\text{Density} = [1 - a] \text{ x } [1 + x] \text{ x } [G_b \text{ x } P_b] \quad (5)$$

where:

a = air proportion in pile,

x = moisture content of pile,

G_b = specific gravity of wood in pile, and

P_b = specific gravity of water (62.43 lbs/ft^3).

To estimate the distribution of parameters of a, x, and G_b for each pile, five samples of hog fuel were drawn from each hog fuel pile and removed for further analysis. For each sample, four measurements were taken in the following order:

green mass of sample (M_g); green volume of the sample with air (V_{g+a});[4] green volume of sample without air (V_g);[5] and bone-dry mass of sample (M_d).[6] The values of variables a, x, and G_b were calculated and recorded.[7]

Results

Volume—

The set of 20 gross pile volumes ranged from 5,243 ft^3 to 99,452 ft^3; hog fuel pile volumes ranged from 2,549 ft^3 to 21,674 ft^3. A model relating hog fuel pile volumes to slash pile volumes as a straight line through the origin—matching Little's (1982) methods—was applied to the data and yielded a slope of 0.3324. However, a plot of residual versus fitted values indicated that the relationship was not linear: Figure 6 details the negative-trend among residual values. A subsequent model relating hog fuel pile volume as a function of the square root of slash pile volume yielded a coefficient of 92.18 and intercept of -4,468 with an adjusted R^2 of 0.9317. Figure 7 overlays the fitted curve on the volume data. Substituting the regression coefficient for volume in equation (4) yields the following:

$$V_h = 92.18 V_s^{1/2} - 4{,}468 \tag{4a}$$

Density—

For each set of pile samples, the mean and variance were calculated for a, x, and G_b. Air space (a) had a range of (0.5811, 0.6649), with a mean and stratified variance estimate of (0.6230, 5.32E-04). Moisture content ranged over (0.727, 1.4231), with a mean and stratified variance estimate of (1.0528, 7.67E-03). Specific gravity had a range of [0.36, 0.421] with a mean and stratified variance estimate of (0.3874, 2.25E-04). Equation (5) can be updated with P_b and the mean values for a, x, and G_b:

$$\text{Density} = [1 - 0.6230] \text{ x } [1 + 1.0528] \text{ x } [62.43 \text{ lbs/ft}^3 \text{ x } 0.3874] \tag{5a}$$

This can be simplified to:

$$\text{Density} = 18.72 \text{ (lbs/ft}^3\text{)} \tag{5b}$$

When moisture content is 105.28 percent; however, when bone-dry calculations are desired (i.e., when $x = 0$), equation (5a) becomes:

$$\text{Bone-dry density} = [1 - 0.6230] \text{ x } [62.43 \text{ lbs/ft}^3 \text{ x } 0.3874] \tag{5c}$$

---

[4] Sample placed in a 4L graduated cylinder, permeable plunger used to compress samples with uniform pressure.

[5] Same graduated cylinder filled to top of permeable plunger with water; quantity of water subtracted from V_{g+a}.

[6] 104 °C for 48 hours.

[7] $a = [(V_{g+a} - V_g) \div V_{g+a}]$; $x = [(M_g - M_d) \div M_d]$; $G_b = [(M_d \div V_g) \div 62.43]$.

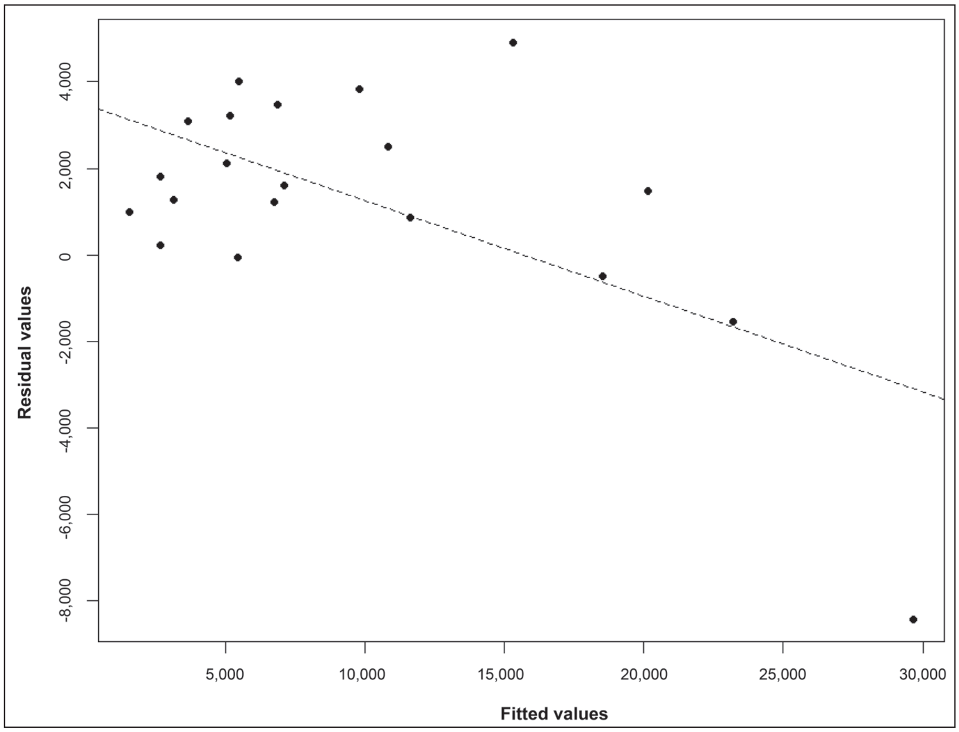

Figure 6—Plot of residual versus fitted values for the linear model $V_h \sim V_s + 0$. The equation of the dotted trendline is y = -0.2211X + 3,458.

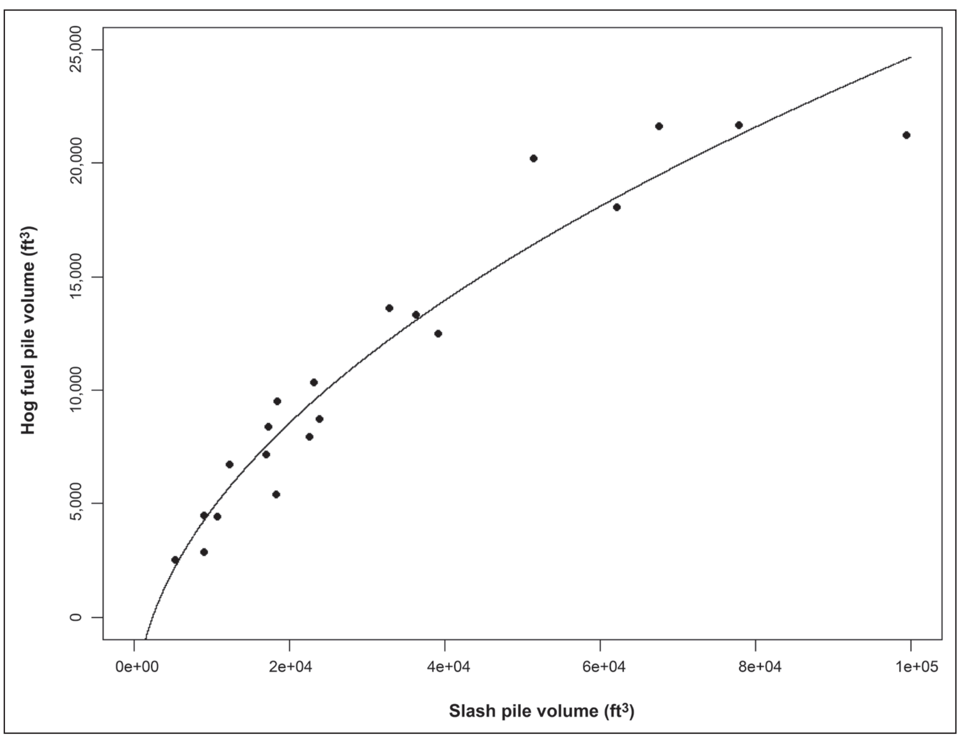

Figure 7—Hog fuel pile volume versus slash pile volume with regression line. The function describing the regression line is $92.18V_s^{1/2} - 4,468$.

As both *a* and G_b are unitless, equation (5c) can be simplified to:

$$\text{Bone-dry density} = 9.05 \text{ lbs/ft}^3 \qquad (5d)$$

Discussion and Applications to Management

Equations (4a) and (5d) can be substituted into equation (1) to yield:

$$\text{Bone-dry mass} = (92.18V_s^{1/2} - 4{,}468) \text{ x } 9.05 \text{ lbs/ft}^3 \qquad (1a)$$

where bone-dry mass is in pounds. Equation (1a) is only meaningful for slash piles greater than 2,350 ft^3. The implication of the negative intercept is that processing (grinding) slash piles sufficiently small in size yields negligible amounts of hog fuel; or at least volumes that cannot be estimated with the geometric solid indicated by equation (3). In situations where it is necessary to estimate V_h yielded by very small slash piles, it may be reasonable to use the slope from the linear model (0.3324), which had an adjusted R^2 of 0.94, although it should be noted that this estimator is based on only 19 piles, as one pile highly leveraged the estimate and was ejected using Quenouilles jackknife (Cochoran 1977).

The nonlinear relationship between volumes of slash and hog fuel piles suggests that increasingly larger increments of slash volume are required to yield a constant increment of hog fuel. This may be explained by the onsite operational methods: As slash is piled for processing, the pile diameter is limited by the length of the loader's boom arm. To concentrate material as much as possible—so that the maximum amount of slash can be processed without moving the grinder—the loader will grow the pile in height, with more material in the center. The result is a breakdown between the actual shape of very large slash piles and the necessity of selecting a shape from a discrete list that is measurable. The selection of a parabolic solid may be the best fit, but the slash is concentrated down the center and around the bottom, with more air space in the outer mid-section of the solid. A nonlinear relationship may also explain Little's (1982) data plot, although the lack of large-volume slash piles makes it difficult to state with certitude that a similar residual pattern exists.

Note that with respect to pile composition, the average green specific-gravities of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Sitka spruce (*Picea sitchensis* (Bong.) Carriere), and western redcedar (*Thuja plicata* Donn ex D. Don) are 0.53, 0.46, 0.35, and 0.32, respectively. Given that the mean specific gravity among the 20 piles was 0.38 and that moisture content was sufficient to ensure mean or higher values, there was likely a significant component of western redcedar in the piles; based on these values and the observed ranges, there were likely significant components of Sitka spruce and western redcedar in the piles. Pure Douglas-fir stands or stands composed mostly of fir and hemlock would have higher specific gravities, and therefore yield higher bone-dry masses for the same volumes.

Pure Douglas-fir stands or stands composed mostly of fir and hemlock would have higher specific gravities, and therefore yield higher bone-dry masses for the same volumes.

Supply Curves

Interest in using biomass to produce energy is increasing. In April 2011, House Bill 1422 authorized the Washington State Department of Natural Resources to develop aviation fuels from forest biomass. Previously in 2006, Washington voters approved Ballot Initiative 937, requiring large utilities to obtain at least 15 percent of their electricity from new renewable resources, including biomass. Where and how biomass will be utilized will depend, in part, on the available supply and cost of delivery.

Supply curves describe the behavior of average unit cost as cumulative supply increases. Kerstetter and Lyons (2001) demonstrated a straightforward methodology for constructing supply curves for logging and agricultural residues in Washington, Oregon, and Idaho: Factor analyses of site production, in-woods cost of recovery, and transportation cost to specified delivery center, where the delivered price is the sum of recovery and transportation factors.

The purpose of this analysis is to use a similar methodology and construct updated supply curves for delivery centers on Washington's Olympic and Kitsap Peninsulas: Aberdeen, Forks, Port Angeles, Port Townsend, and Shelton.

Methods

Residue production—

The production study described the criteria for residue-producing parcels on the Olympic and Kitsap Peninsulas: Timberlands greater than 15 ac excluding federal and tribal lands; also excluded were single-tree sales, right-of-way, and salvage operations. The Washington State Forestland Database (Rogers and Cooke 2010) delineated 1,963,352 ac within the study area meeting these criteria; total harvest acreage over the 2-year study period (66,729) suggests an annualized harvest rate of 1.7 percent. Using the Forestland Database, parcels were directly stratified by forest location and ownership type factors, and aggregated by 10-minute delivery interval to a specific delivery center. Harvest intensity was imposed on each location/ownership group in the same proportion as table 1. Harvest method was not considered as it was not found to be associated with distinct production rates. The acreage in each forest location, harvest intensity, and ownership type stratum within a delivery interval was assigned its corresponding residue production rate from table 5.

To illustrate, there are 15,016 ac of timberland between 10 and 20 minutes of delivery time from Port Angeles, of which 5,069 ac is located on the west side of the Olympic Peninsula and has public ownership (L_wO_p). According to table 1, 87.9 percent (4,410 ac) of L_wO_p lands were clearcut, of which approximately 1.7 percent (75 ac) would be expected to be harvested in a given year. The average residue produced per clearcut acre of public land on the west side of the Olympic Peninsula ($L_wI_cO_p$) is 1,913 ft^3 (see table 5), yielding a total of 143,000 ft^3. Applying a bone-dry density of 24.18 lbs/ft^3, this volume is equivalent to 1,729 BDTs. These calculations were repeated for each stratum for each delivery interval for each delivery center.

In woods recovery costs—

Recovery operations consist of one or two loaders that gather material about the harvest unit, their operators, and a grinder located near a road. Current operational procedures apply a base processing rate around $35/BDT that covers labor, capital, and a small margin.[8] A fuel surcharge is applied at the rate of 1 percent of the base rate for every 10 cent increase in the price of diesel fuel.[9]

Transportation—

Parcels were aggregated into 10-minute intervals of delivery time;[10] however, transportation also includes load and unload times, and the return trip. Han (2011) estimated the loading and unloading times at around 30 minutes each. Total transportation costs are the sum of loading, unloading, and twice the interval time; an hourly base transportation rate of $65 was found to represent the region. A fuel surcharge is applied in the same manner as for recovery operations. Assuming a full truck load is 29 green tons of hog fuel at 53 percent moisture (see *x*, in the “Volume-to-weight ratios” section), transportation cost is calculated at $1.59/BDT/10-minute interval.

---

[8] Both Port Townsend Paper Corporation and Hermann Brothers Logging and Construction, Inc. collaborated with the Olympic Natural Resources Center on this project and agreed to share information. Consequently, we were able to capture costs and procedures that reflect current operations.

[9] The U.S. Energy Information Administration posts regional on-highway diesel fuel prices each week. The base price on which a surcharge is calculated is $1.21 from March 21, 1994. Therefore if diesel prices post at $4.21 for a given week, then a 30 percent surcharge is applied to the base rate.

[10] Transportation time estimates were derived from a combination of Environmental Systems Research Institute’s Streetmap North America 2010 that has speed limits for interstates, highways, urban roads, and surface streets. The transportation layer from the Washington State DNR was used for all other roads, with an assumed average speed of 15 mph. Aggregations were constructed within the Washington State Forestland Database.

Supply Curves

Supply curves were developed for Aberdeen, Forks, Port Angeles, Port Townsend, and Shelton. Price represents the cumulative average delivered base price; cumulative supply is denoted in MBDTs. The length of the curve represents total accessible biomass within 180 minutes (one-way) delivery time. Residue production within delivery intervals will differ with the distribution of stratified factors; costs are expected to remain constant within a delivery interval—marginal increases reflect increased distance. Aggregate supply curves are presented in figure 8 for comparison purposes, followed by individual curves in figures 9 through 13.

Applications to Management

Recovery and transportation—

Much effort has been devoted in other analyses to precisely quantify the cost of recovery. Although piece size, yarding method, and yarding distance most certainly affect the delivered cost of a BDT, the precision achieved in accounting methods belies operational realities: once material is processed and in a van, it becomes impossible to dissect the load into constituent costs. This presents an auditing problem for buyers and inefficiencies in the field. The simplicity achieved with a base rate also reflects the compromise that is being struck with landowners for access. Direct pay to landowners is essentially forgone (≤ $4 BDT) in exchange for operations that cover an entire unit. Landowners realize a gain in reduced (or even

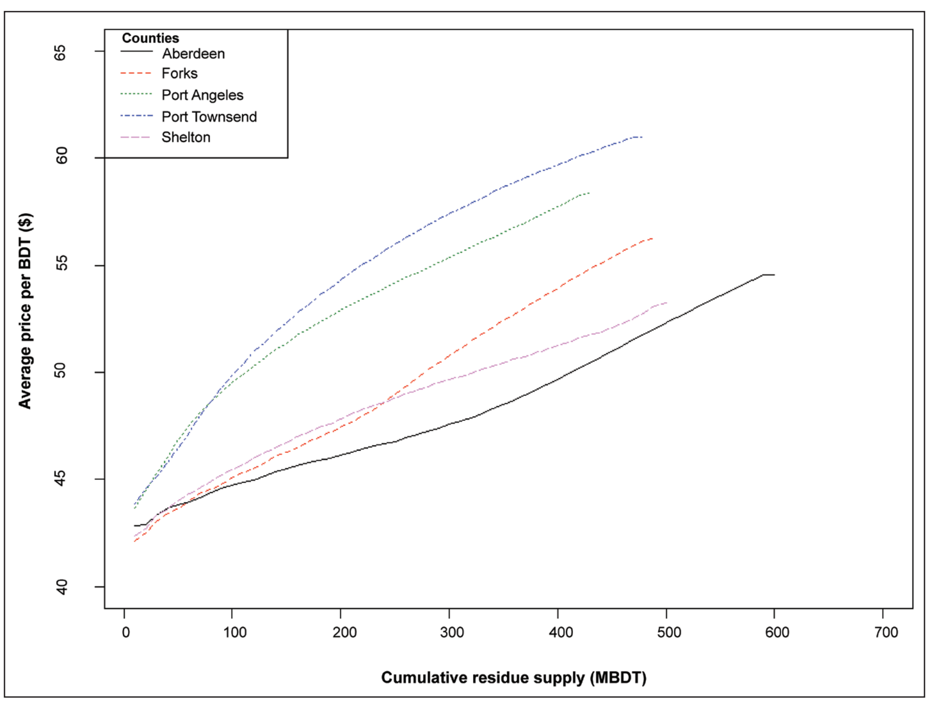

Figure 8—Supply curves for all delivery centers. BTD = bone dry ton. MBDT = thousand bone dry tons.

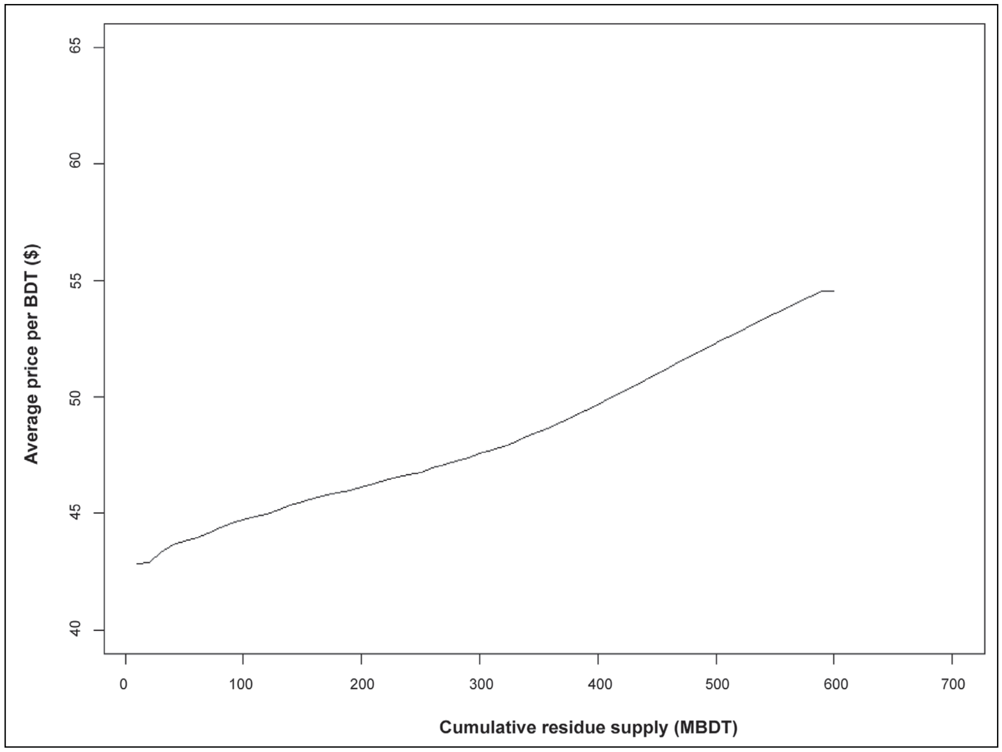

Figure 9—Aberdeen supply curve. BTD = bone dry ton. MBDT = thousand bone dry tons.

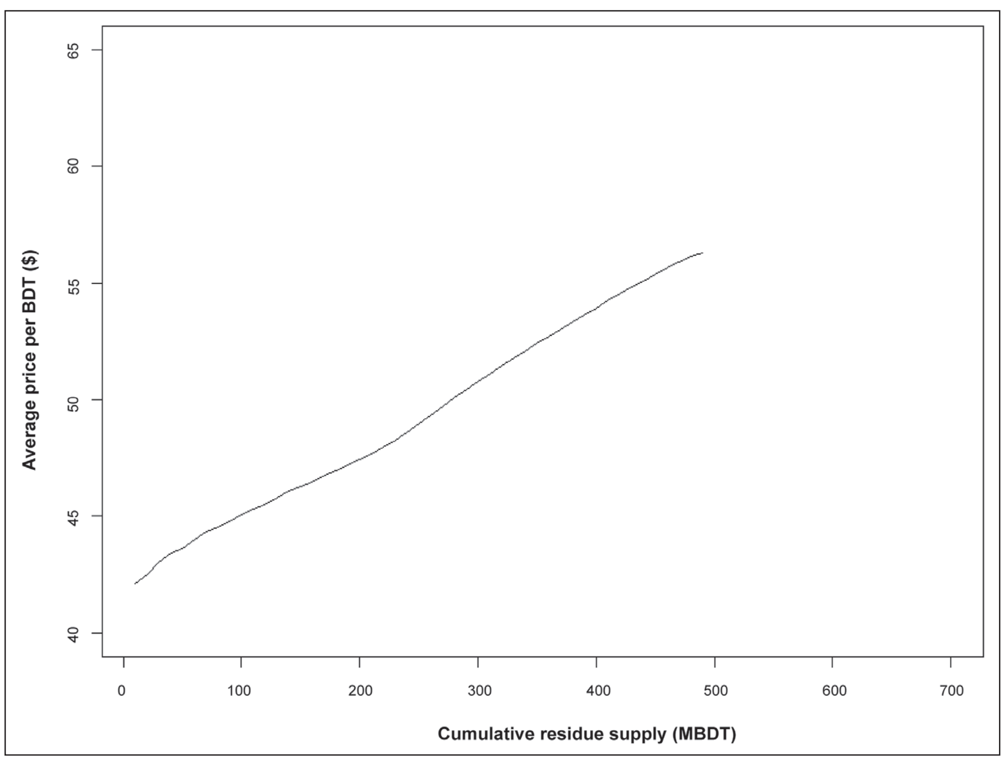

Figure 10—Forks supply curve. BTD = bone dry ton. MBDT = thousand bone dry tons.

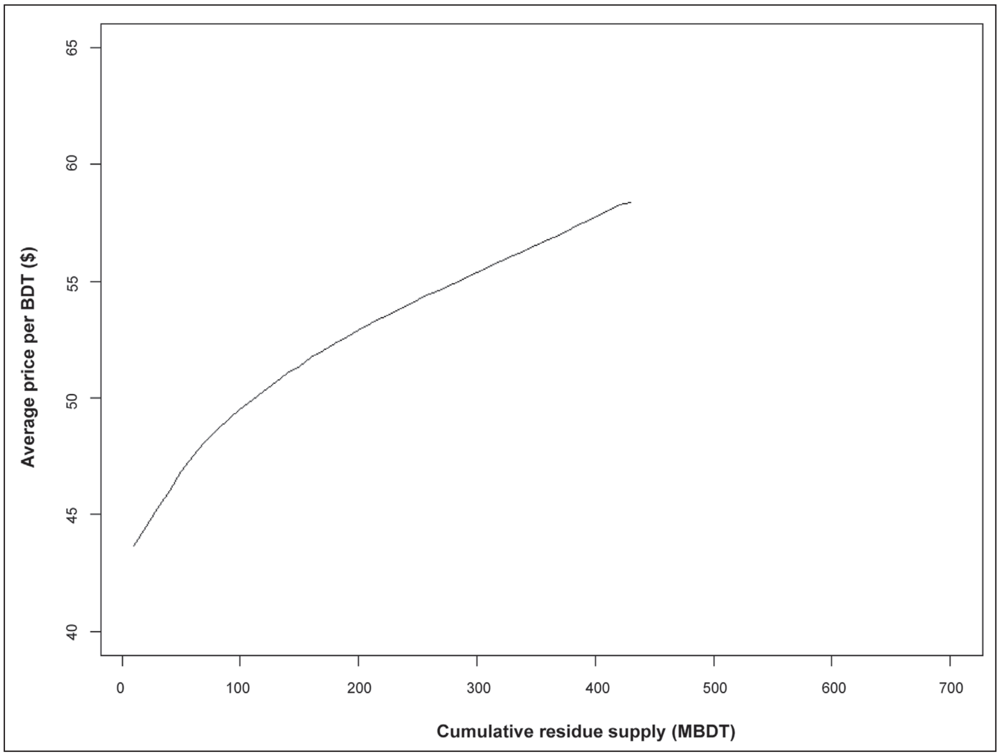

Figure 11—Port Angeles supply curve. BTD = bone dry ton. MBDT = thousand bone dry tons.

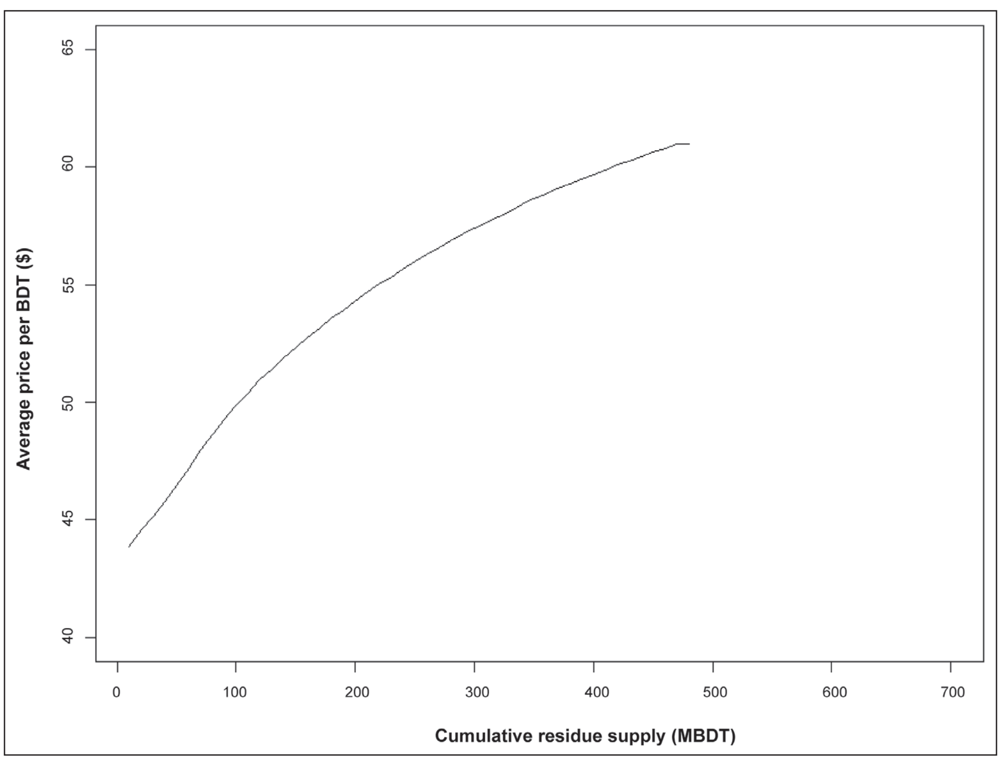

Figure 12—Port Townsend supply curve. BTD = bone dry ton. MBDT = thousand bone dry tons.

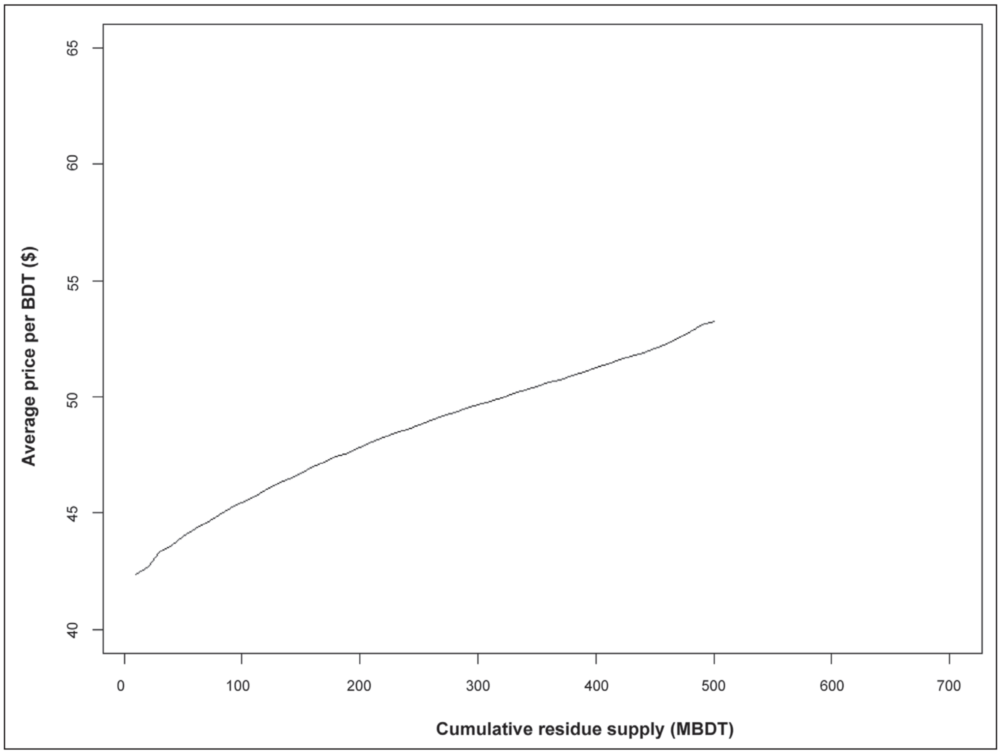

Figure 13—Shelton supply curve. BTD = bone dry ton. MBDT = thousand bone dry tons.

perhaps eliminated) site preparation, fire, and smoke management costs and concerns. Therefore, operators agree to take material from the entire unit—even if some of the unit's slash would not otherwise be economical to extract—in exchange for permission to remove residues. A single rate for recovery operations will reflect this compromise; purchasers understand that in order to access the low-cost residues, they must be willing to purchase some quantity at a higher cost.

Supply—

Forks is the most competitive delivery center up to approximately 50 MBDT; equivalent to roughly 6 megawatt-years of power.[11] Aberdeen, Forks, and Shelton demonstrate relatively similar behavior up to 250 MBDT, beyond which delivery to Forks is noticeably more expensive and to Aberdeen noticeably less. Port Angeles and Port Townsend are at a decided disadvantage with respect to total quantity of biomass accessible and average price; however, barge delivery of hog fuel from outside sources is possible at both locations, but accounting for any such sources was

[11] The average energy value of piled residue in the study was about 9,000 BTUs per bone-dry pound (Howard 1988). Therefore, one BDT is equivalent to 5.3 megawatt hours (MWH) of energy. The U.S. Department of Energy estimates 75 percent combustion efficiency, and 40 percent generation efficiency (http://www.ornl.gov), resulting in 1.6 MWH of electricity per BDT of biomass that may be rounded conservatively to 1 MWH. If one megawatt year consists of approximately 8,000 MWH, then total electrical production from biomass can be calculated by dividing the available supply (BDT) by 8,000.

was beyond the scope of this investigation. Aberdeen has access to the greatest quantities of logging residue at the lowest average price; both Aberdeen and Shelton are likely to have access to additional residues in Thurston, Lewis, and Pacific Counties (not included here), counties that would increase their overall supply and competitiveness. Listed below (in decreasing order) is the annual quantity of hog fuel available to each delivery center at an average cost of $50/BDT:

1. Aberdeen (410 MBDT/year)
2. Shelton (320 MBDT/year)
3. Forks (280 MBDT/year)
4. Port Angeles (110 MBDT/year)
5. Port Townsend (100 MBDT/year)

The average price for each supply curve represents the base recovery and transportation rate, on which a fuel surcharge must be levied. The effect of the surcharge is to shift each curve up, but does not affect the shape or relative position of each curve.

Conclusion

The investigation of the quantity of slash produced by timber harvest operations for calendar years 2008 and 2009 included 975 FPAs accounting for 66,729 ac of land on the Olympic and Kitsap Peninsulas of Washington. In total, nearly 30 mi of transect surveys and a census of more than 3,000 slash piles isolated mean production within 3 percent of the mean production rate of 1,599 ft^3/ac, with 80 percent confidence. Four factors were thought to be associated with difference slash production rates: forest location, ownership type, harvest intensity, and harvest method. For slash measured by transects, only ownership type was associated with different production rates. Public lands produced an average of 1,588 ft^3/ac compared with 1,155 ft^3/ac on nonpublic lands. Several factors were associated with different production rates for pile residues: forest location, harvest intensity, ownership type, and the interaction between intensity and ownership. Further analysis found two distinct levels of piled residue production ranging from 65 ft^3/ac to 325 ft^3/ac.

An updated analysis of slash piles found significantly less wood per unit volume than previous estimates, likely owing to changes in forest types and harvest methods between studies.

An updated analysis of slash piles found significantly less wood per unit volume than previous estimates, likely owing to changes in forest types and harvest methods between studies. The bone-dry mass (in pounds) of wood in a pile of slash was related to its gross volume (V_s) with the equation: bone dry mass = $(92.18V_s^{1/2} – 4,468) \times 9.05$ lb/ft^3. This equation reflects the specific gravities (i.e., the types and mix of species) in the sampled piles, and the moisture content at the time of sampling. As species and moistures differ among piles, so will this relationship.

Supply curves that detail the quantity available to, and average unit price on, delivery were constructed for the cities of Aberdeen, Forks, Port Angeles, Port Townsend, and Shelton. The in-woods costs for processing slash and transportation were asserted at $35/BDT and $65/hour, respectively. This resulted in a delivered cost of $1.59/BDT/10-minute delivery interval one way. Aberdeen was found to have access to the greatest quantity of slash (600 MBDT/year), and had more than four times the quantity available for delivery (410 MBDT/year) than Port Townsend (100 MBDT/year) at an average price of $50/BDT. Forks was found to have the lowest average unit price for the first 50 MBDT/year, at $43.64/BDT; a quantity that could produce approximately 6 MW of power. The deliverable quantities were based on harvest rates for 2008 and 2009, and would be expected to increase and decrease as harvest rates change.

Acknowledgments

The research team for the production study and updated volume-to-weight ratios included principal investigator Eric Turnblom, associate professor at the University of Washington, College of the Environment, School of Environmental and Forest Sciences; Jason Cross, research coordinator for the University of Washington's Olympic Natural Resources Center (ONRC); John Calhoun, director of the Olympic Natural Resources Center. The research team for the supply curves also included Gregory Ettl, director of the Center for Sustainable Forestry at Pack Forest; Jeff Comnick, research scientist at the ONRC.

Jeff McGinley of Pacific Forest Management in Forks, Washington, helped secure landowners' permissions to access harvest units and collect field data; Reed Wendel, Aaron Brooks, and Scott Jamieson, all from Pacific Forest Management, collected field data. Rebecca Gentry of ONRC conducted the laboratory analyses of hog fuel samples. Updated volume-to-weight ratios would not have been possible without the cooperation of Bill Hermann of Hermann Brothers Logging in Port Angeles, Washington. His willingness to alter production methods allowed for measurements that could not otherwise be taken. George Cave of Port Townsend Paper provided insight into the methods for developing supply curves that tempered a desire for precision with operational realities.

This work was made possible with funding from the Restoration Silviculture Initiative—a partnership between the University of Washington's ONRC and the U.S. Forest Service's Pacific Northwest Research Station. The expanded scope of the analysis was made possible by additional funding from the Northwest Clean Energy Application Center and Washington State University. This report represents the conclusion and fulfillment of the following contracts: 09-CA-11261991-010 (PNW), 09-CA-11261991-007 (PNW), DE-FG02-97ER41020 (WSU).

Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Feet (ft)	.305	Meters
Miles (mi)	1.609	Kilometers
Miles per hour (mph)	.447	Meters per second
Acres (ac)	.405	Hectares
Cubic feet (ft^3)	.0283	Cubic meters
Pounds (lb)	.454	Kilograms
Pounds per acre (lb/ac)	1.12	Kilograms per hectare
Tons (ton)	907	Kilograms
Degrees Celsius (C)	1.8 °C + 32	Degrees Fahrenheit
Cubic feet per acre (ft^3/ac)	.07	Cubic meters per hectare
Pounds per cubic foot (lb/ft^3)	16.02	Kilograms per cubic meter

Literature Cited

Antos, J.A.; Halpern, C.B.; Miller, R.E.; Cromack, K., Jr.; Halaj, M.G. 2003. Temporal and spatial changes in soil carbon and nitrogen after clearcutting and burning of an old-growth Douglas-fir forest. Res. Pap. PNW-RP-552. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 19 p.

Cochran, W.G. 1977. Sampling techniques. New York: John Wiley and Sons, Inc. 428 p.

Edmonds, R.L. 1980. Litter decomposition and nutrient release in Douglas-fir, red-alder, western hemlock, and Pacific silver fir ecosystems in western Washington. Canadian Journal of Forest Research. 10: 327–337.

Edmonds, R.L.; Chappell, H.N. 1994. Relationships between soil organic matter and forest productivity in western Oregon and Washington. Canadian Journal of Forest Research. 24(6): 1083–1294.

Feller, M.C. 1988. Relationships between fuel properties and slashburning-induced nutrient losses. Forest Science. 34(1): 998–1015.

Feller, M.C.; Kimmins, J.P. 1984. Effects of clearcutting and slash burning on streamwater chemistry and watershed nutrient budgets in southwestern British Columbia. Water Resources Research. 20(1): 29–40.

Foley, T.G.; Richter, D.D.; Galik, C.S. 2009. Extending rotation age for carbon sequestration: a cross-protocol comparison of North American forest offsets. Forest Ecology and Management. 259: 201–209.

Glass, S.V.; Zelinka, S.L. 2010. Chapter 04: Moisture relations and physical properties of wood. In: Wood handbook: wood as an engineering material. Gen. Tech. Rep. FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 19 p.

Gregoire, T.G.; Valentine, H.T. 2008. Sampling strategies for natural resources and the environment. Boca Raton, FL: Chapman & Hall/CRC. 458 p.

Grier, C.C.; Cole, D.W.; Dyrness, C.T.; Fredriksen, R.L. 1974. Nutrient cycling in 37- and 450-year-old Douglas-fir ecosystems. In: Integrated research in the coniferous forest biome. CFB Bulletin 5. Seattle: University of Washington, Seattle: 21–34.

Han, S.K. 2011. Managing woody biomass transportation for improved biomass economics. Corvallis, OR: Oregon State University. 171 p. Ph.D. dissertation.

Hardy, C.C. 1996. Guidelines for estimating volume, biomass and smoke production for piled slash. Gen. Tech. Rep. PNW-GTR-364. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 17 p.

Harmon, M.E.; Marks, B. 2002. Effects of silvicultural practices on carbon stores in Douglas-fir–western hemlock forests in the Pacific Northwest, U.S.A.: results from a simulation model. Canadian Journal of Forest Research. 32: 863–877.

Harmon, M.; Ferrell, W.K.; Franklin, J.F. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science. 247: 699–702.

Howard, J.O. 1978. A technique for predicting logging residue volumes in the Douglas-fir region. Res. Pap. PNW-RP-225. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 14 p.

Howard, J.O. 1981. Ratios for estimating logging residue in the Pacific Northwest. Res. Pap. PNW-RP-288. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 26 p.

Howard, J.O. 1988. Energy values for whole trees and crowns of selected species. Res. Note PNW-RN-480. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 6 p.

Jacobs, K.M.; Luoma, D.L. 2007. Small mammal mycophagy response to variations in green-tree retention. Journal of Wildlife Management. 72: 1747–1755.

Janisch, J.E.; Harmon, M.E. 2002. Successional changes in live and dead wood carbon stores: implications for net ecosystem productivity. Tree Physiology. 22: 77–89.

Jurgensen, M.F.; Harvey, A.E.; Graham, R.T.; Page-Dumroese, D.S.; Tonn, J.R.; Larsen, M.J.; Jain, T.B. 1997. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland Northwest forests. Forest Science. 43(2): 234–251.

Kerstetter, J.D.; Lyons, J.K. 2001. Logging and agricultural residue supply curves for the Pacific Northwest. Pullman, WA: Washington State University. U.S. Department of Energy. Contract #DE-FC01-99EE50616. 45 p.

Kraemer, J.F.; Hermann, R.K. 1979. Broadcast burning: 25-year effects on forest soils in the western flanks of the Cascade mountains. Forest Science. 25(3): 427–439.

Lee, C.; Erickson, P.; Lazarus, M.; Smith, G. 2010. Greenhouse gas and air pollutant emissions of alternatives for woody biomass residues. Report to Olympic Region Clean Air Agency. Stockholm: Stockholm Environment Institute. 89 p. http://sei-us.org/publications/id/359. (August 23, 2011).

Little, S.N. 1982. Estimating the volume of wood in large piles of logging residue. Administrative Report Ar-1. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 7 p.

Little, S.N.; Ohmann, J.L. 1988. Estimating nitrogen lost from forest floor during prescribed fires in Douglas-fir/western hemlock clearcuts. Forest Science. 34(1): 152–164.

Lohr, S.L. 1995. Hasse diagrams in statistical consulting and teaching. American Statistician. 49: 376–381.

Mroz, G.D.; Jurgensen, M.F.; Harvey, A.E.; Larsen, M.J. 1980. Effects of fire on nitrogen in forest floor horizons. Soil Science Society of America Journal. 44: 395–400.

National Council for Air and Stream Improvement, Inc. [NCASI]. 2000. Riparian vegetative effectiveness. Technical Bulletin No. 799. Research Triangle Park, NC: 26 p.

Oehlert, G.W. 2000. A first course in design and analysis of experiments. New York: W.H. Freeman & Company. 659 p.

Palosuo, T.; Wihersaari, M.; Liski, J. 2001. Net greenhouse gas emissions due to energy use of forest residues—impact of soil carbon balance. In: Pelkonen, P.; Hakkila, P.; Karjalainen, T.; Schlamadinger, B., eds. Woody biomass as an energy source—challenges in Europe. European Forest Institute Proceedings. 39: 115–122.

Peterson, C.E., Jr.; Gessel, S.P. 1983. Forest fertilization in the Pacific Northwest: results of the regional forest nutrition research project. In: International Union of Forest Research Organizations symposium on forest site and continuous productivity. Ballard, R.; Gessel, S.P., eds. Gen. Tech. Rep. PNW-GTR-163. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 404 p.

Pregitzer, K.S.; Zak, D.R.; Burton, A.J.; Ashby, J.A.; MacDonald, N.W. 2004. Chronic nitrate additions dramatically increase the export of carbon and nitrogen from northern hardwood ecosystems. Biogeochemistry. 68: 179–197.

Rogers, L.W.; Cooke, A.G. 2010. The 2007 Washington State Forestland Database. Seattle: University of Washington. 81 p.

Titus, B.D.; Prescott, C.E.; Maynard, D.G.; Mitchell, A.K.; Bradley, R.L.; Feller, M.C.; Beese, W.J.; Benton, R.A.; Senyk, J.P.; Hawkins, B.J.; Koppenaa, R. 2006. Post-harvest nitrogen cycling in clearcut and alternative silvicultural systems in a montane forest in coastal British Columbia. The Forestry Chronicle. 82(6): 844–859.

Wright, C.S.; Vihnanek, R.E. 2009. Estimating the biomass of hand-piled fuels for smoke management planning. Project No. 07-2-1-57. Pacific Wildland Fire Sciences Laboratory. 15 p.

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