APPLIED RESEARCH

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harvesting & utilization

Predicting Logging Residue Volumes in the Pacific Northwest

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Pacific Northwest forest managers seek estimates of post-timber-harvest woody residue volumes and biomass that can be related to readily available site- and tree-level attributes. To better predict residue production, researchers investigated variability in residue ratios, growing-stock residue volume per mill-delivered volume, across Idaho, Montana, Oregon, and Washington. This project presented unique sample design challenges, and the authors adopted model-based sampling to calculate the growing-stock logging residue ratio for the four-state region and produced models that relate the residue ratio to individual tree- and stand-level variables meaningful to land managers. The regionwide residue ratio was 0.0269, i.e., 26.9 ft^3 of growing-stock logging residue per 1,000 ft^3 (26.9 m^3 per 1,000 m^3) of mill-delivered volume. Residue ratios were related to tree- and site-level variables with predictive models. Residue ratios were predicted to increase with larger small-end used diameter and decline exponentially with increasing dbh. Ratios were predicted to drop when pulp logs were removed and when timber was mechanically felled. Results from this study could be used to produce or improve residue prediction tools for land managers.

Keywords: growing-stock removals, residue ratio, timber harvest

The US Department of Agriculture (USDA) Forest Service's Forest Inventory and Analysis (FIA) program provides information on the condition and changes in the timber resource throughout the United States. This information derives from three interrelated sources: multiresource inventory based on remeasurement of a network of permanent plots (e.g., Donnegan et al. 2008, Menlove et al. 2012); timber product output (TPO) mill surveys, which measure timber-processing facilities to quantify the volume of timber products harvested and delivered to mills (e.g., Gale et al. 2012, McIver et al. 2015, Simmons et al. 2014a); and TPO logging utilization studies, which characterize timber harvest operations and determine what proportion of felled timber is left in the forest as logging residue versus delivered to mills (e.g., Morgan et al. 2005, Morgan and Spoelma 2008, Simmons et al. 2014b).

The components of forest inventory change (i.e., growth, mortality, and removals) are captured by the FIA plot network. Removals consist of volume harvested for products, logging residue, and "other removals" due to changes in land-use designation. Only through the TPO mill surveys and logging utilization studies can removals for various timber products (e.g., sawlogs, veneer logs, or pulpwood) delivered to mills be quantified and distinguished from removals that are left in the forest or at the landing as logging residue (i.e., material that is cut or killed during commercial harvest but not used).

This study and others like it (Bentley and Harper 2007, Morgan and Spoelma 2008, Simmons et al. 2014b) make those direct connections among timber harvested for products, the associated logging residue, and the impacts on growing-stock volume. There are several other studies (e.g., Howard 1978, 1981) that quantify slash or logging residue; however, they do not directly associate the residue volume to harvest volumes and FIA inventory parameters (e.g., growing-stock versus nongrowing-stock volume).

Logging utilization studies provide estimates of logging residue volumes without the need for detailed inventories or tree lists. Study results include calculation of the growing-stock[1] (Figure 1) residue ratio, defined as the growing-stock logging residue volume divided by the mill-delivered volume. This ratio can be used to quickly estimate growing-stock residue volumes simply by applying timber harvest volumes at the stand, landscape, or state levels (Morgan and Spoelma 2008). Nongrowing-stock (i.e., tree top and branch) residue can then be estimated with allometric equations (Woodall et al.

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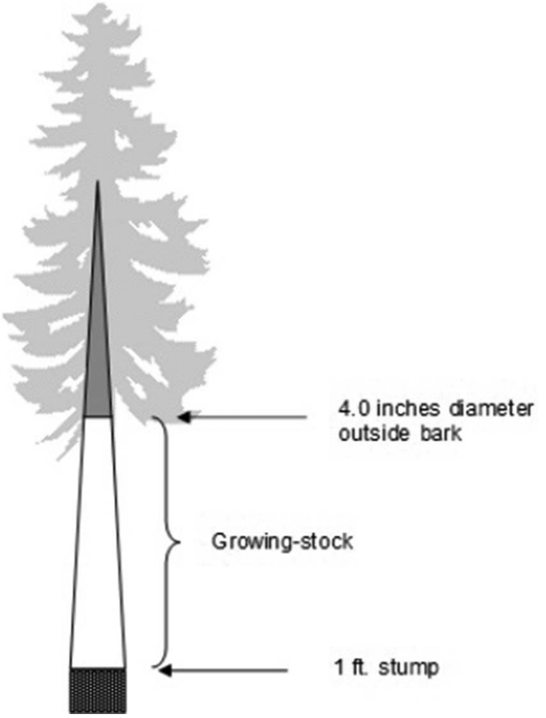

Figure 1. Individual tree growing stock. Growing stock includes live tree sections from the 1-ft (0.30 m) stump to the 4.0-in. (10.2 cm) outside bark top diameter.

2011) to provide a more complete accounting of total logging residue.

The residue ratio is used in the calculation of logging residue volumes published in the Timber Product Output (TPO) database (USDA Forest Service 2015) maintained by the FIA Program of the USDA Forest Service. This Internet-housed database utility, often referred to as "Resource Planning Act (RPA)-TPO," is used to periodically assess nationwide changes in timber products and logging residue as components of removals from inventory. Recent logging utilization studies in Idaho (Simmons et al. 2014b) and Montana (Morgan et al. 2005) have provided updated residue information for the inland northwest. However, similar studies that link logging residue to TPO and FIA removals have not been conducted in Oregon or Washington, and the most recent investigations in these states were published nearly 35 years ago (Howard 1981).

Land managers seek information on how logging residue biomass and volume relate to tree- and stand-level variables to improve their fuels and bioenergy management prescriptions (Morgan et al. 2009). Logging utilization studies could provide the data needed to improve prescriptions and enable managers to make informed site-specific fuels management and biomass utilization decisions. Spurred by bioenergy needs, European investigators have developed models relating logging residue biomass to individual tree and stand attributes (Bouriaud et al. 2013). European scientists have offered land managers tradeoff scenarios of utilization standards, such as minimum small-end used diameter versus residue production (Räisänen and Nurmi 2011). Similar forecasting tools could greatly benefit US land managers.

Because the Pacific Northwest's timber composition, harvest technology, and timber harvest ownership patterns have changed substantially since the 1980s (Gale et al. 2012, Simmons et al. 2014a), comprehensive information that reflects the characteristics and effects of contemporary timber harvesting on residue production is needed to predict how contemporary post-harvest residues vary. To answer these needs the authors investigated logging residue production in Montana, Idaho, Washington, and Oregon from 2008 through 2013. Two specific objectives were to estimate the growing-stock logging residue ratio for the entire four-state region and major geographic subregions, and to produce models that relate the residue ratio to individual tree- and stand-level variables meaningful to land managers.

Methods

The authors sought a sample protocol that would provide data to estimate the residue ratio expressed as the ratio of means (Zarnoch et al. 2004). Design-based sampling requires a priori knowledge of the total number of primary sampling units in the population (Lohr 2009). In this study, the primary sampling unit was the logging site where trees were being commercially harvested. However, as Morgan and Spoelma (2008) outlined, it is not possible to know in advance the total population of logging sites in a state or region for a given year. Northwestern government and forest management organizations do not maintain comprehensive lists of active logging sites. It was therefore impossible to identify the sampling frame. This created a problem: without a comprehensive list of logging sites (the sampling frame) to draw sample sites at random, it was not possible to conduct probabilistic design-based sampling (Lohr 2009).

Model-based sampling offered an alternative method of estimating population parameters without a sampling frame through regression modeling (Sterba 2009). Model-based sampling has been shown to be a viable alternative for fisheries and wildlife biologists, geologists, hydrologists, and other investigators who lack sampling frames (Chambers and Clark 2012, Thompson 2012). The means of incorporating randomization or stochastic features differs between design and model-based sampling. The stochastic feature of model-based sampling as explained by Chambers and Clark (2012) was essential in the current study because it was impossible to select sample logging sites at random. Some statisticians have criticized model-based sampling because it may yield biased parameter estimates (Lohr 2009). Berg et al. (2015) analyzed the potential bias in model-based sampling estimates using the current study's "real" and simulated residue data. These researchers found that the model-based residue ratio exhibited less than 0.5% bias, i.e., the difference between the simulated data parameter estimate and the real data parameter estimate for the entire region.

Model-based sampling was used in the current study. Sterba (2009) outlined the need to stratify the population and weight data if sampling was disproportionate by strata when model-based sampling is used. These provisions were accounted for in this investigation. The population was stratified by subregions and disproportionate sampling within strata was corrected by weighting. A stratification was sought that would partition the four-state region by geographic differences in site quality, a criterion strongly related to individual tree form and volume (Weiskittel et al. 2011), and therefore probably related to the residue ratio. Bailey's Ecoregion Provinces (Bailey 2009), a land classification system based on broad differences in soil order, landform, vegetation, and climate and therefore related to site quality, was used to stratify the project area into the following subregions (Figure 2).

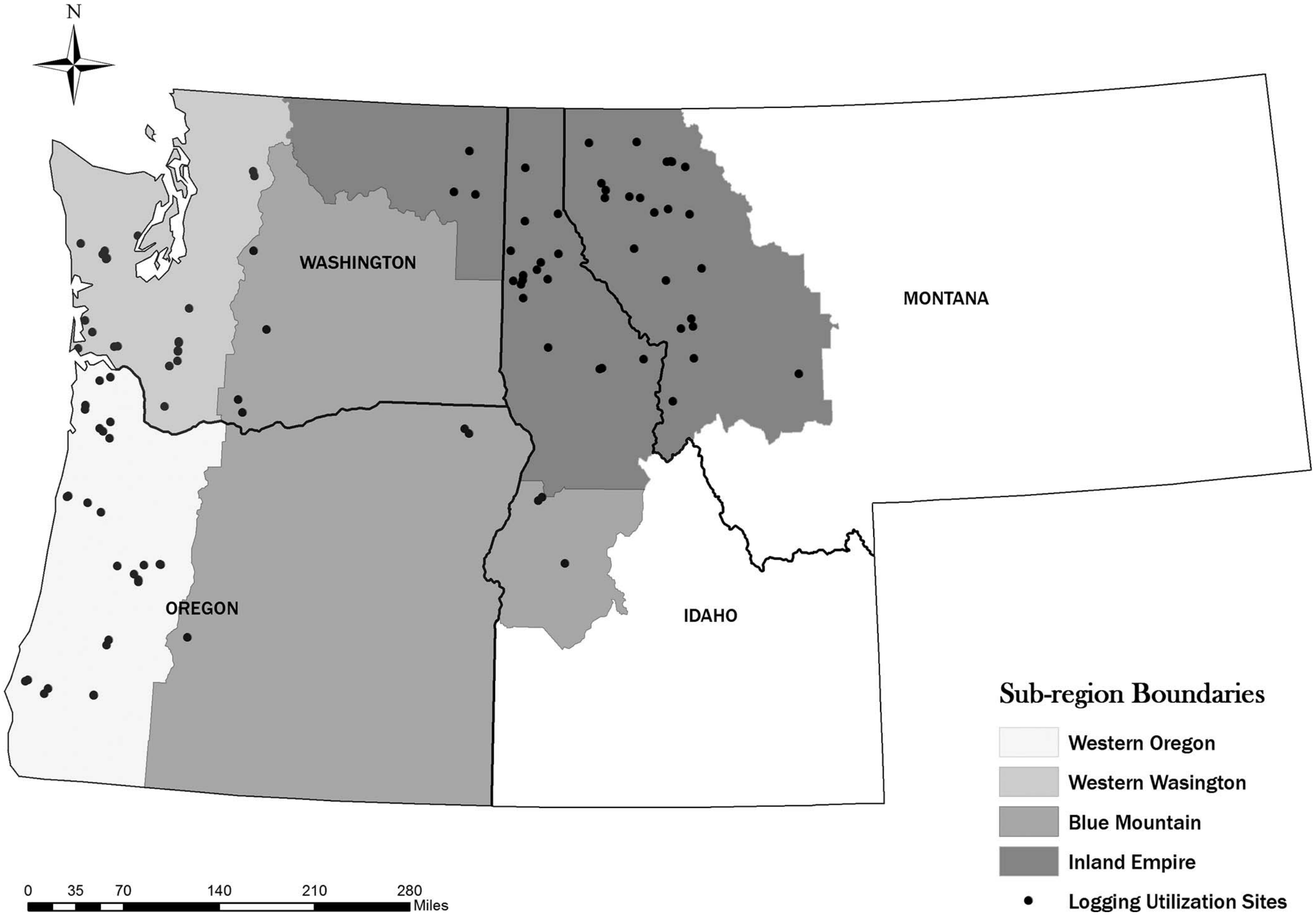

Figure 2. Subregions, largely defined by Bailey's Ecoregion Provinces (Bailey 2009), and sample logging site locations.

Inland Empire: "Northern Rocky Mountain Forest-Steppe-Coniferous Forest-Alpine Meadow Province." (in northeastern Washington, northern Idaho, and western Montana).

Blue Mountains: "Middle Rocky Mountain Steppe-Coniferous Forest-Alpine Meadow Province." Characterized by sites generally less mesic than those within the Inland Empire subregion (in southcentral Idaho, eastern Oregon, and southeastern Washington).

Western Washington: "Cascade Mixed Forest-Coniferous Forest-Alpine Meadow Province." Includes highly mesic mountainous forest sites spanning the Cascade Crest to the Pacific Ocean in Washington.

Western Oregon: "Cascade Mixed Forest-Coniferous Forest-Alpine Meadow Province." Identified by mountainous forested sites from the Cascade Crest to the Pacific Ocean in Oregon.

The stratified cluster sampling design consisted of logging sites stratified by subregion with felled trees clustered within logging sites. Timberland owners and managers were asked to identify potential commercial logging sites where field crews could safely measure felled trees. Sample sites were chosen regardless of the logging system used, tree species, silvicultural prescription, or other attributes. Sample sites could not be selected at random because researchers lacked a sampling frame from which to pick sites. Sampling elements consisted of felled trees at each logging site that met the following requirements to qualify as a potential measurement tree. The tree had to be alive before harvest, had to be at least 5.0 in. (12.7 cm) dbh, and had to contain at least one merchantable log, and the entire bole (stump to top) had to be measureable (Morgan and Spoelma 2008).

Sample sizes for trees and logging sites were guided by previous utilization studies. Zarnoch et al. (2004) found that standard errors for the residue ratio dropped substantially by increasing the number of sampled logging sites from 10 to 20 per region or state. Previous logging utilization studies in California and Idaho garnered low standard errors by measuring 25–35 trees on each of 30–45 logging sites (Morgan and Spoelma 2008, Simmons et al. 2014b). Based on this information, researchers decided that measuring 25 trees on each of approximately 100 sites should yield standard errors less than a desired 20% of estimated residue ratio values for the region.

Data Collection

At each logging site, foresters and/or loggers provided information on tree species, products merchandised, and preferred and acceptable small-end diameters and log lengths—information reported on the "cutting card" or list of tree merchandising specifications. Field crews were then able to discriminate between used versus nonutilized (residue) felled tree sections. Field crews checked residue piles and log decks to ensure that cutting card guidelines were being followed. County of harvest, landownership class, felling method, yarding/skidding method, and log merchandising location and method were recorded for each site.

Field crews selected felled trees with systematic sampling grids using randomized starting points. Individual trees were scattered

Table 1. Subregion summary statistics.

Subregion	No. of logging sites sampled	No. of trees sampled	5-yr timber harvest volume (Scribner MBF)	Weighting factors	Residue ratio of means	Residue ratio SE
Blue Mountains	7	173	2,855,205	0.087	0.0319	0.0049
Inland Empire	53	1324	6,400,383	0.195	0.0248	0.0032
Western Oregon	21	519	12,638,795	0.384	0.0298	0.0053
Western Washington	20	486	11,060,569	0.336	0.0263	0.0045
Total project	101	2502	32,954,954		0.0269	0.0024

MBF, thousand board feet.

Table 2. Variables used in residue ratio modeling.

Variable	Categorical or continuous	Explanation	Range/frequency for 2,502 felled sample trees[a]
DBH	Continuous	Tree dbh; to nearest 0.1 in.	5.0–37.2
FELLING	Categorical	0 = hand felling; 1 = mechanical; 2 = mix of hand and mechanical	0 = 840; 1 = 1,287; 2 = 375
OWNERSHIP	Categorical	1 = federal; 2 = state; 3 = nonindustrial private; 4 = industry; 5 = other	1 = 121; 2 = 469; 3 = 100; 4 = 1,724; 5 = 88
PULPALLSOURCES	Categorical	n = pulp not utilized; y = pulp utilized for the logging site	n = 877; y = 1,625
RESIDUE RATIO	Continuous-ratio	Response variable; ratio = growing-stock residue cubic foot volume/mill-delivered cubic foot volume	0.0000–0.1023 for 101 logging sites; 0.0000–1.1456 for individual felled trees (1 high-influence outlier = 3.8422 was deleted)
SEDMIN	Continuous	Smallest top-end DOB of utilized bole; to nearest 0.1 in.	0.1–21.0
Species: ALDER,WRC	Categorical	Red alder (ALDER), western redcedar (WRC); yes or no	WRC = 105; ALDER = 57
STUMPHT	Continuous	Stump height; to nearest 0.1 ft	0.0–1.5
SUBREGION	Categorical	Geographic subregions for the project area	BL = 173; IE = 1,324; WO = 519; WW = 486

IE, Inland Empire; BL, Blue Mountain; WO, Western Oregon; WW, Western Washington.

[a] Range is presented for continuous variables and frequency is presented for categorical variables.

throughout the logging site or accumulated in piles for skidding. Species was recorded; outside bark diameter and section length measurements were taken at the cut stump height, at 1 ft aboveground (uphill side of the tree), at dbh, at 7.0 in. (17.8 cm) and 4.0 in. (10.2 cm) diameter outside bark (DOB), and at the end of utilization. DOB and length were measured for each tree section along the bole at intervals corresponding to cutting card prescribed log lengths with a maximum section length of 16 ft (4.8 m). Thus, for each bole section, lower and upper DOB and length were recorded. Each tree typically had DOB measured at 8–15 locations along the bole. The percent cubic cull defect for each section was recorded, and each section was identified as used (delivered to the mill) or unutilized (logging residue). Sections damaged and made unmerchantable by logging activities (e.g., felling breakage) were coded unutilized.

Twenty to 32 felled trees were measured at each Idaho logging site in 2008 and 2011 and at Washington, Oregon, and Montana sites in 2011, 2012, and 2013 (Table 1). Sampling of sites was rotated among states over this 5-year period to dilute spot market influences on tree utilization. Cubic foot volumes for each tree section were calculated using Smalian's formula, and section volumes were summed for each tree by category (e.g., used versus unutilized stump, bole, and upper stem sections of the trees). The residue ratio was calculated for each tree and site.

Data Analysis

Objective 1—Regional and Subregional Residue Ratio Estimation

Region and subregion residue ratios of means and standard errors were computed with a linear mixed model. The response variable, the residue ratio of means for a site, equaled the sum of the site's growing-stock residue volume divided by the sum of the site's mill-delivered volume. The sole covariate was a categorical variable representing the four subregions. Sample weights equaled the proportions of subregion versus total region 5-year timber harvest volumes (Table 1).

Objective 2—Relationship of the Residue Ratio to Variables of Interest to Land Managers

The authors developed two multilevel mixed models that related individual tree residue ratios (not the ratio of means) to covariates of interest to land managers (Table 2). One model related individual tree residue ratios to tree-level attributes designed to inform land managers how residues vary by tree characteristics such as dbh and utilization standards. The second related individual tree residue ratios to readily obtainable logging site-level attributes to enable land managers to easily predict residues on any specific site. Goodness of model fit was gauged by information theoretic metrics based on the Akaike information criterion (AIC) and the proportion of variance explained by the model.

Results

Objective 1—Regional and Subregional Residue Ratio Estimation

The logging site residue ratio distribution followed an exponential decay pattern and was strongly skewed to the right with many observations less than 0.0100 (Figure 3). The residue ratio of means = f(subregion) model was parameterized using SAS PROC GENMOD (SAS Institute, Inc. 2013) with the normal distribution. Logging sites were nested within subregions in a multilevel structure. Use of the log-normal, beta, inverted Gaussian, power, and exponential distributions, often used with strongly skewed data, did not improve this or any other study model's performance, i.e., convergence and computation of errors, compared with the normal. Parameterizing mixture models also did not improve performance.

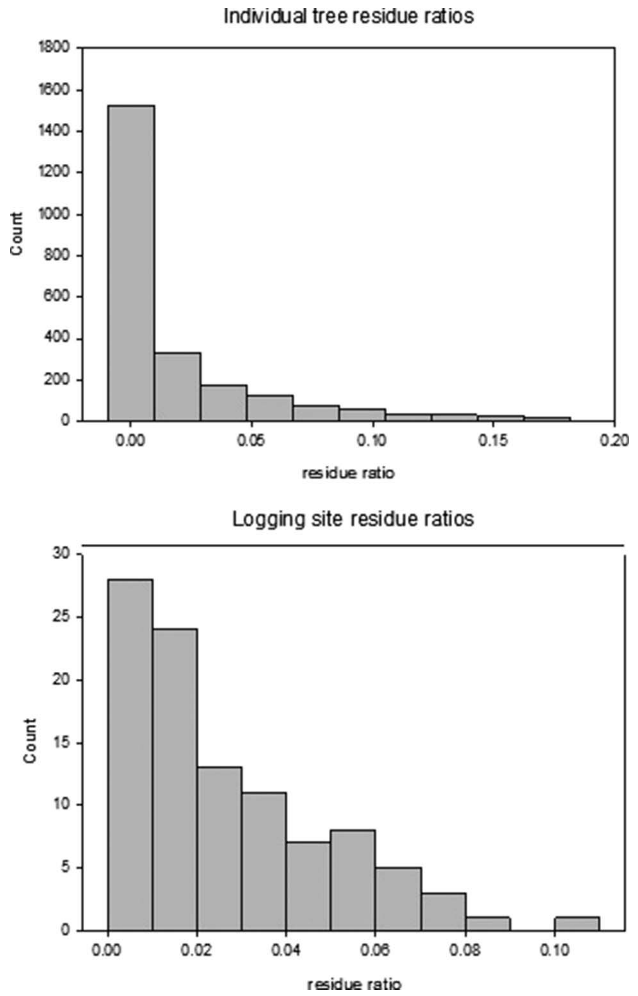

Figure 3. Top. Histogram of 2,501 individual felled tree residue ratios (truncated for values >0.18). Bottom. Histogram of residue ratios for 101 logging sites.

This and all models exhibited substantial heteroscedasticity which was probably an artifact of having strongly skewed distributions with many observations close to or equal to 0.0000. Log, arcsine, and inverse transformations of the residue ratios did not markedly reduce heteroscedasticity. The GENMOD analysis yielded a regional residue ratio of means of 0.0269. Ratios varied little across subregions with Blue Mountain (ratio = 0.0319) and western Oregon (ratio = 0.0298) exhibiting slightly higher values (Table 1). Standard errors were less than 19.0% of parameter estimates for both regional and subregional estimates, less than the targeted 20.0%. Residue ratios of means varied little among subregions, and differences did not reflect a clear east (lower productivity) versus west (higher productivity) of the Cascade Crest trend (Table 1). This suggested that subregional site productivity differences were weakly related to logging residue ratios.

Objective 2—Relationship of the Residue Ratio to Variables of Interest to Land Managers

Tree-Attribute Model

As with logging site residue ratios, individual tree residue ratios also followed an exponential decay pattern and were strongly skewed to the right; 1,007 of 2,501 observations had values of 0.0000 (Figure 3). The best nonlinear multilevel model (trees nested within logging sites) was parameterized with covariates dbh and minimum outside bark small-end diameter of the used bole (SEDMIN) (Table 2) using PROC NLMIXED (SAS Institute, Inc. 2013) with the normal distribution (Table 3).

Table 3. Tree-attribute model.

Parameter	Estimate	SE	*t* value	$P > \lvert t \rvert$	95% confidence limits
Intercept (B_0)	0.0015	0.0004	04.06	<0.0001	0.0008–0.0022
B_1	1.8846	0.1012	18.63	<0.0001	1.6839–2.0853
B_2	0.3878	0.0102	37.92	<0.0001	0.3675–0.4081
S2U	0.0008	0.0001	05.66	<0.0001	0.0006–0.0011
S2E	0.0040	0.0001	34.53	<0.0001	0.0038–0.0043

Model: predicted residue ratio = $B_0(\text{SEDMIN})^{B_1} + e^{(-B_2(\text{dbh}))}$. $n = 2{,}501$ felled trees, nested within 101 logging sites. Covariates (Table 3): SEDMIN, the minimum utilized small-end DOB in inches; DBH, diameter at breast height in inches. The proportion of variance is explained by the full versus the null model = (null model S2E − full model S2E)/(null model S2E) = 0.17. S2U is the variance of the random effects; S2E is the conditional variance of the response.

$$\text{Predicted residue ratio} = B_0(\text{SEDMIN})^{B_1} + e^{(-B_2(\text{dbh}))}$$

Although this model was ranked number 1 for explanatory strength (Table 4), the proportion of model variance explained was only 0.17 (Table 3), which suggested that the model had low explanatory power. However, all multilevel models have the same problem: clustering comes with a statistical price—goodness of fit drops compared with that for single-level models (Raudenbush and Bryk 2002).

Small-end used diameter (SEDMIN) was the most influential of all single variable models as judged by its model rank of 2 (Table 4). SEDMIN values were the actual small-end diameters measured during field sampling not the nominal values given on the cutting card. The residue ratio increased at an increasing rate with larger values of SEDMIN in the SEDMIN, DBH model. The opposite was true of dbh. The residue ratio declined exponentially with progressively larger values of dbh to approximately 15.0 in (38.1 cm). The relationship was then linear with essentially no change in the predicted residue ratio when dbh exceeded 15.0 in. (Figure 4). The residue ratio (individual tree residue volume divided by its used volume) was highly sensitive to changes in used volume, but changes in residue volumes yielded only minor differences in predicted ratios for most trees sampled.

Stump height and tree species variables were evaluated but not included in the final SEDMIN, DBH model (Table 4). Increases in stump height (STUMPHT) resulted in higher residue ratio values. But STUMPHT proved to be a weak covariate with a Pearson correlation coefficient of only 0.08 and rank of 6 among all candidate models (Table 4). There are two likely reasons for this weak showing. First, most sample trees were machine-felled, which often produced stumps of similar height (generally 0.3–0.5 ft [0.09–0.15 m]), resulting in little tree-to-tree variability. Second, only stumps greater than 1.0 ft (0.30 m) in height impacted growing-stock (Figure 1) residue and only 75 of 2,501 trees had stumps greater than 1.0 foot in height.

Residue ratios varied little by species. Notable exceptions were red alder (*Alnus rubra Bong.*) and western redcedar (*Thuja plicata* Donn ex D. Don.) (Table 2). Alder was strongly related to the residue ratio with a model rank of 3 (Table 4). Higher residue ratios of the 57 measured alder trees probably reflected their smaller dbh, substantial top branching, and sinuous bole form compared with those of other species. Western redcedar was moderately related to

Table 4. Information theoretic metrics for tree (Table 3) and site-attribute (Table 5) models and individually modeled covariates.

Model	AIC	DELTA AIC	Akaike weight	Evidence ratio	Rank
TREE-ATTRIBUTE					
SEDMIN, DBH	−6497.00	0.00	1	1	1
SEDMIN	−6308.00	189.00	9.1027E−42	1.09857E + 41	2
ALDER	−6173.00	324.00	4.4085E−71	2.26833E + 70	3
DBH	−6145.00	352.00	3.6658E−77	2.7279E + 76	4
WRC	−6077.00	420.00	6.2829E−92	1.59163E + 91	5
STUMPHT	−6046.00	451.00	1.1657E−98	8.57839E + 97	6
NULL (INTERCEPT ONLY)	−6044.00	453.00	4.288E−99	2.33185E + 98	7
SITE-ATTRIBUTE					
PULPALLSOURCES	−6055.34	0.00	0.99663146	1	1
PULPALLSOURCES, FELLING	−6043.93	11.40	0.00332943	299.3399847	2
NULL (INTERCEPT ONLY)	−6034.94	20.40	3.7095E−05	26867.02561	3
OWNERSHIP	−6028.64	26.70	1.5896E−06	626970.6448	4
FELLING	−6026.01	29.33	4.2708E−07	2333582.037	5

AIC, Akaike's information criterion (smaller AIC values indicate superior fit); DELTA AIC, difference in AIC values between the subject model and the model with lowest AIC; Akaike weights, relative likelihoods of the candidate models; evidence ratios, ratios of the best model's Akaike weight versus the candidate model's Akaike weight (smaller numbers indicate superior models). Rank is based on evidence ratios, e.g., 1 = best overall model.

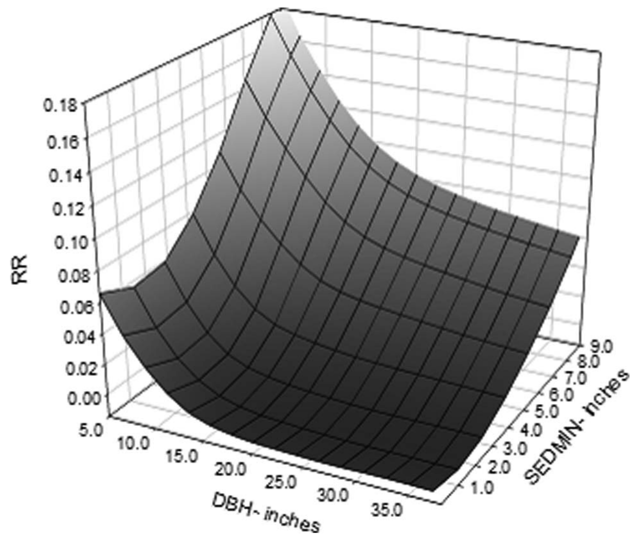

Figure 4. Predicted residue ratio (RR) (individual tree cubic foot residue volume/mill delivered cubic foot volume) versus dbh and small-end used DOB (SEDMIN), truncated for residue ratio >0.1800 and SEDMIN >9.0 in (22.9 cm).

the residue ratio (model rank of 5; Table 4). Because sampled redcedars and alders were located in only a fraction of the sampled logging sites (13 sites for alder and 24 sites for redcedar) and many sites East of the Cascade crest cannot support the survivorship and growth of these two species, covariates for these species would have limited informative value to many land managers and so were not included in the final tree-attribute model.

The number one-ranked tree attribute model [residue ratio = *f*(SEDMIN, DBH)] exhibited reasonably good predictive capabilities throughout the range of measured dbh as evidenced by relatively narrow confidence limit bands around the predicted residue ratio (Figure 5). Confidence limits were also narrow for SEDMIN values of 2.0 in. (5.08 cm) to approximately 10.0 in. (25.4 cm); confidence limits then expanded sharply above this range (Figure 5).

Site-Attribute Model

The residue ratio was predicted using site-attribute covariates in a multilevel linear mixed model parameterized with SAS PROC HPMIXED (SAS Institute, Inc. 2013) (Table 5). Trees were nested within sites that were nested within subregions.

$$\text{Predicted residue ratio} = B_0 + B_1\,(\text{PULPALLSOURCES}) + B_2\,(\text{FELLING})$$

Despite its simplicity, the above model explained 30% of the variation in the predicted residue ratio (Table 5). PULPALLSOURCES is a logging site-level dichotomous covariate for whether or not the logger removed any live tree pulp products from the logging site (Table 2). Pulp logs, generally 10–20 ft (3.05–6.10 m) in length, were bucked from felled tree tops with pulp product SEDMIN ranging from 0.1 to 4.0 in. (0.25–10.16 cm). Entire green trees were seldom merchandised into pulp products. The residue ratio was strongly related to whether or not pulp was removed (PULPALLSOURCES) with model rank of 1 (Table 4).

Tree felling methods were weakly related to the residue ratio with the covariate FELLING (Table 5), which represented three categorical values: hand, mechanical, or a combination of hand and mechanical in the same logging site. Hand-felled timber showed the most breakage and resulted in higher residue ratio values. But breakage sometimes spiked in combination sites. For example, extensive breakage was observed in three western Washington sites with combined mechanical and hand felling. Mechanically felled trees in these units were carefully laid undamaged into bunched piles ready for skidding. Loggers then hand-felled larger-diameter trees onto the piles, resulting in substantial breakage and a residue ratio more than double the mean residue ratio for western Washington. Adding FELLING to the site-level model proved statistically inefficient as a PULPALLSOURCES, FELLING model ranked 2 compared with the rank of 1 for PULPALLSOURCES alone (Table 4). But FELLING was kept in the model because of its explanatory benefits to managers and its direct relationship to breakage and residue creation. Figure 6 summarizes the tradeoffs in predicted residue ratios by varied values of the PULPALLSOURCES, FELLING model. The smallest predicted residue ratio (0.01692) was found to be the combination of taking pulp plus mechanized felling, and the largest (0.06921) was not taking pulp in hand-felled units, nearly a 4-fold difference in the residue ratio between these two variable combinations.

The site-level felled tree quadratic mean diameter (QMD) was not related to the residue ratio ($P = 0.8412$ computed with PROC HPMIXED). The variability of individual felled-tree dbh within each logging site was enormous, often ranging from 5.0 in. (12.7 cm) to more than 35.0 in. (88.9 cm). This variability produced

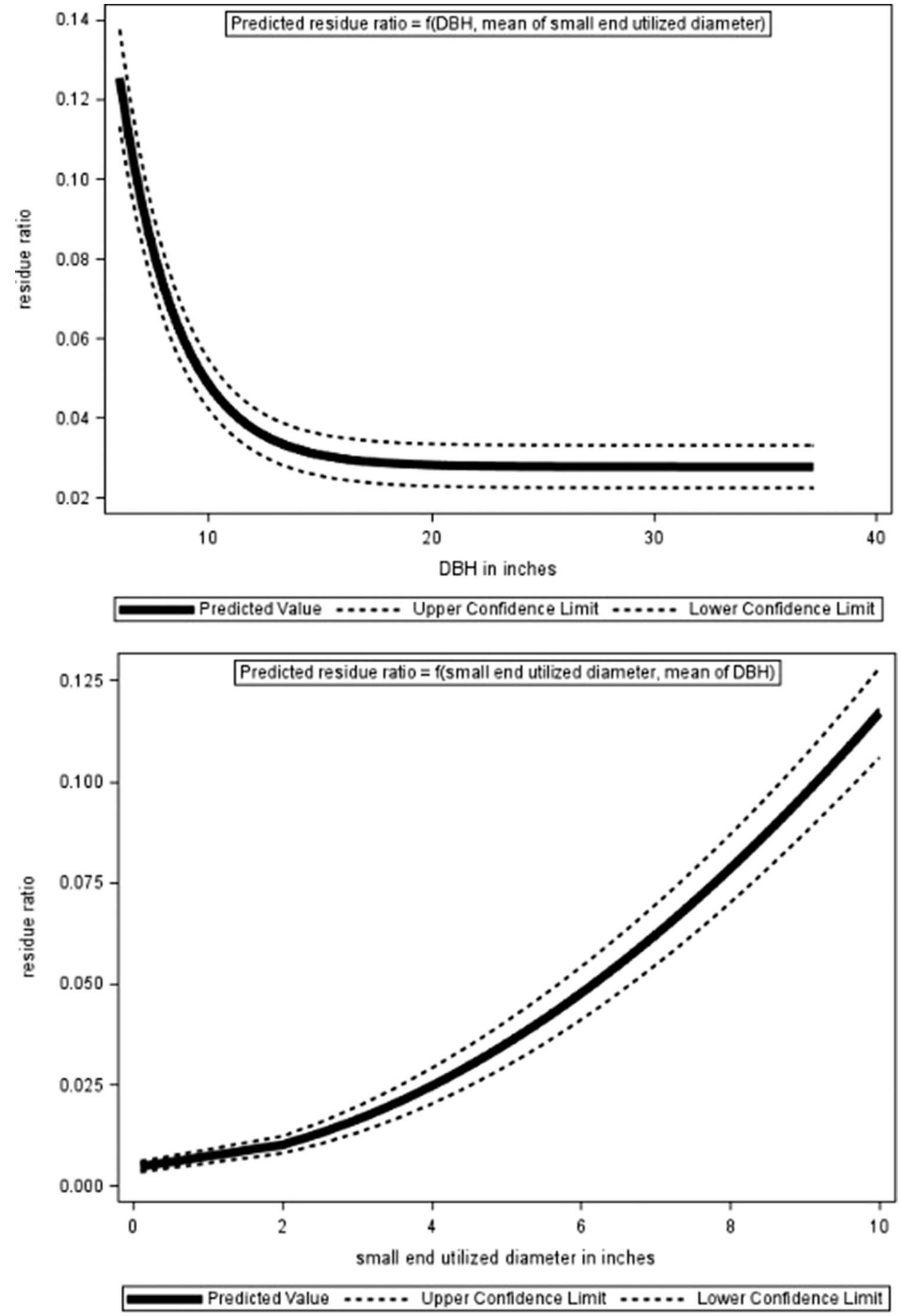

Figure 5. Predicted values and 95% confidence limits for the mean of the residue ratio versus dbh and small-end used diameter (SEDMIN).

QMDs that were simply not related to residue ratios. OWNERSHIP (Table 2) was not included in the site-level model because it was highly collinear with FELLING and with PULPALLSOURCES ($P = 0.001$ for all levels of both variables computed with SAS PROC HPMIXED). Because land managers frequently asked field crews about the impacts of ownership on residue creation during field sampling, the authors calculated the OWNERSHIP residue ratio least-squares means: 0.02626 on industrial sites, 0.04279 on federal, 0.0516 on nonindustrial private, 0.06471 on state, and 0.06632 on all other ownerships.

Individual tree- and site-attribute models were moderately successful in predicting the variability in the residue ratio. Lack of predictive capability was largely a function of high standard errors commonly experienced with multilevel models, variability in tree-level residue ratios within and among logging sites, and a strongly skewed residue ratio distribution with many observations equal to zero (Anderson 2010). However, the authors repeatedly tested models with varied values of the covariates and suggest that the models could serve land managers as realistic forecasting tools.

Table 5. Site-attribute model.

Covariate (parameter)	Covariate level	Parameter estimate	SE	t value	$P > \lvert t \rvert$
Intercept (B_0)		0.0550	0.0067	8.26	<0.0001
PULPALLSOURCES (B_1)	n	0.0000			
PULPALLSOURCES (B_1)	y	−0.0380	0.0070	−5.44	<0.0001
FELLING (B_2)	0	0.0143	0.0073	1.94	0.0525
FELLING (B_2)	1	0.0000			
FELLING (B_2)	2	0.0109	0.0097	1.13	0.2604

Model: predicted residue ratio = $B_0 + B_1$(PULPALLSOURCES) + B_2 (FELLING). $n = 2{,}501$ felled trees, nested within 101 logging sites; sites were nested within 4 subregions. Covariates (Table 3): PULPALLSOURCES, taking pulp from the logging site, yes (y) or no (n); FELLING, by hand (chainsaw) = 0, mechanized = 1, combination hand and mechanized within same logging site = 2. The proportion of variance is explained by the full versus null model = (null model variance − full model variance)/(null model variance) = 0.30.

Summary Findings

1. The residue ratio of means for the four-state region was 0.0269 (i.e., 26.9 ft^3 of growing-stock logging residue generated per 1,000 ft^3 of mill-delivered volume).
2. There was little difference in predicted residue ratios of means by geographic subregion.
3. Individual tree residue ratios were found to be positively and strongly related to small-end used top diameter (SEDMIN). Residue ratios declined as dbh increased.
4. Predicted residue ratios were lowest when pulp was a product removed from the site and much higher when timber was hand-felled.

Discussion

Results for the Inland Empire and Blue Mountain subregions concurred with those for other contemporary logging utilization studies: the residue ratio was less than 4% of mill-delivered volume (Table 1). For example, Simmons et al. (2014b) found that the Idaho state residue ratio of means declined from 0.123 in 1965 to 0.024 in 2011 in response to progressively more efficient logging and milling technologies, removal of greater percentages of bolewood, and a shift from logging old-growth to young-growth timber. Morgan et al. (2005) reported a similar rate of decline in Montana: a statewide residue ratio of 0.163 in 1965 and 0.092 in 2002. Without comparable logging utilization studies for Oregon or Washington, direct comparisons of this study's results to those of previous research in western Washington or western Oregon were not possible.

The lack of variability in residue ratios among Pacific Northwest subregions was unique to this study. Berg et al. (2012) found that adding a dichotomous covariate for northern versus southern Idaho to a multilevel regression model accounted for more than 10% of the variability in the predicted residue ratio. Gedney and Henley (1971) discovered significant differences in regional residue production, with higher residue ratios in western Oregon and Washington versus eastern Oregon and Washington. Howard (1981) reported the opposite trend: significantly higher residue ratios in eastern Oregon and eastern Washington than in west-side sites.

The likely cause for residue ratio conformity among subregions is lack of variability in current utilization standards and logging systems, as the timber-using industry has dramatically downsized, moved away from harvesting old-growth timber, and shifted more to mechanized harvesting. Trees were often mechanically felled with stump heights less than 1 ft (30.5 cm) and SEDMIN of 4.0–6.0 in. (10.16–15.24 cm) throughout the region. Further, 1960s timber age and condition often differed among regions. Felled trees sampled in this study were consistently second- or third-growth timber with little defect.

This study's key findings of the relations of residue ratios to dbh and SEDMIN dovetailed with those of other investigations. For example, Räisänen and Nurmi (2011) developed prediction equations and lookup tables relating a residue ratio (similar to this study's residue ratio) to SEDMIN. They found that total logging residue (including tops and limbs) biomass per hectare for Scots pine (*Pinus sylvestris* L.) increased at an increasing rate with SEDMIN. They also found that residue ratios declined exponentially with increasing dbh. Harmon et al. (1996) discovered that the SEDMIN and the minimum dbh of harvested trees had been the most important variables in predicting the proportion of used versus unutilized Pacific Northwest harvested timber volume from 1910 to the mid-1990s.

Simmons et al. (2013) summarized the impacts of felling methods on Idaho, California, and Montana state-level residue ratios. Hand felling was found to produce twice the growing-stock residue as mechanized felling in Idaho (0.0400 versus 0.0200). Residue ratios for California and Montana averaged 0.0600 on hand-felled logging sites compared with 0.0500 on mechanized felling sites. The current study results aligned with those of California and Montana.

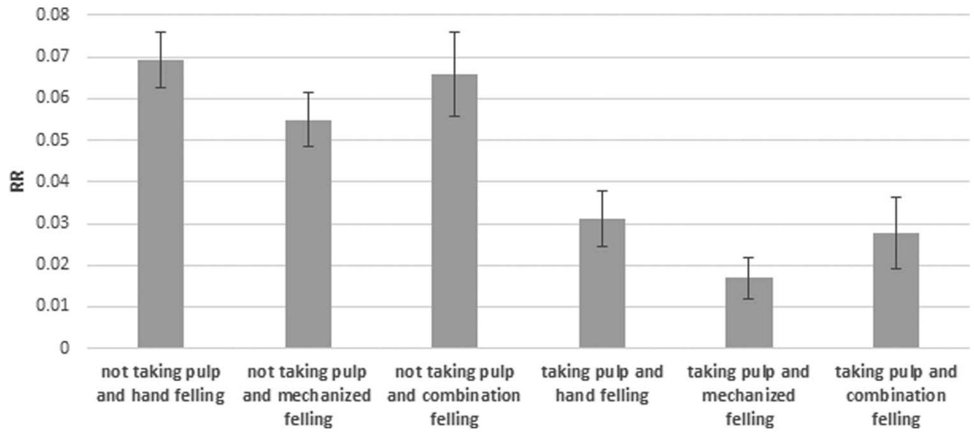

Figure 6. Predicted residue ratio (RR) by pulp removal and felling method.

The individual tree residue ratio was predicted to increase by 0.0143 in hand-felled sites compared with that in mechanized felling sites (Table 5). Breakage caused by tree felling was found to account for more than 90% of individual tree growing-stock residue in an ancillary study that used this study's four-state data set (Berg 2014).

The predicted residue ratio was substantially lower on industry lands than on other ownerships largely because industrial sites more frequently had pulpwood products removed from logging sites and almost exclusively used mechanical felling. Cross et al. (2013) found a similar residue by ownership trend; postyarding mean residue production was 1,588 ft^3/acre (111.1 m^3/ha) on public lands compared with 1,155 ft^3/acre (80.8 m^3/ha) on private lands in western Washington.

Conclusions

This study's regional and subregional residue ratio models could be used to estimate regional- or state-level logging residues. Individual tree predictive models provide the groundwork for tradeoff scenarios of how dbh and small-end used top diameter change the growing-stock residue ratio in the Pacific Northwest. Land managers can quickly gauge the impacts of taking pulp and felling method on the residue ratio by referring to Figure 6, which summarizes residue ratio estimates for combinations of these two variables. However, land managers need to know how these outcomes impact total residue, including boles, tops, and branches. Web-based residue prediction tools to guide fuel management plans, estimate biomass availability, and complete life cycle analyses would be helpful and a logical next step. Creating these Internet-based applications concurrently with fundamental research could be the focus of future logging utilization research efforts.

Endnote

1. Live trees ≥5.0 in. (12.7 cm) dbh; measured from a 1-ft (30.5 cm) stump height to a 4-in. (10.2 cm) diameter top outside bark (DOB).

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