Operational Influences Affecting Sawlog Weight and Volume Relationships in the Intermountain West

Jarred D. Saralecos Robert F. Keefe Wade T. Tinkham
Randall H. Brooks Leonard R. Johnson

Abstract

As weight-based timber sales become more common in the Intermountain West, characterizing the factors affecting weight-to-volume relationships for softwood sawlogs has become more important. Several factors are thought to affect sawlog weight and volume (W:V) relationships, but the relative importance of weather, topography, species, and region in the western United States has not been quantified. Analysis was conducted to determine the factors affecting W:V relationships across the state of Idaho for commercial softwood sawlogs. Using 7,929 sorted and scaled sawlog loads sampled throughout Idaho from 2011 to 2013, we studied the relationships between log small-end diameter (SED), region, atmospheric temperature, precipitation, and elevation, to assess changes in W:V. Relationships of W:V using mixed-effects models were strong (R^2 of 0.74 to 0.90, $P < 0.05$) when fitted individually by species, with volume modeled as a function of weight, SED, truckload piece count, percent defect, and seasonal quarter: Y (board foot volume) $= \beta_0 + \beta_1$ (Tons) $+ \beta_2$ (SED) $+ \beta_3$ (Piece Count) $+ \beta_4$ (Length) $+ \beta_5$ (Defect) $+ \beta_6$ (Seasonal Quarter) $+ \beta_7$ (1|Sale Number/Ticket) $+ u$ (Error).

The Intermountain West of the United States forest products industry harvests more than 6.9 million m^3 of wood annually (O'Laughlin 2012). Day-to-day financial transactions of harvested forest logs depend largely upon the accuracy and reliability of log scaling systems. Of the various log scaling methods implemented across North America, most have been derived from diagrammatic or mathematical formulas (Row and Guttenberg 1966, Freese 1973). Traditionally, sawmill inventories have been measured in units of board feet, cubic feet, or cubic meter volumes using conventional log scaling procedures such as the Doyle log rule, International ¼ inch rule, or Scribner log rule. However, with the average sawlog scaling diameter decreasing because of increased industrial harvesting of second growth forest stands and associated increases in scaling costs, the efficiency and affordability of traditional or conventional stick scaling has been questioned (Daniels 2005). Traditional scaling methods require each sawlog delivered to be measured using a predetermined set of rules to establish a gross and net volume for financial and inventory purposes (Bauer and Hogan 2006). Scribner Decimal C short log scaling rule is the most commonly applied log rule in the Intermountain West in the United States. The search for a more efficient and cost-effective alternative scaling method has gradually shifted interest towards performing transactions on a weight basis (Patterson and Doruska 2005).

Weight scaling has been widely adopted within southeastern US forestry practices, where sample check scaling has been shown to validate weight scaling conversion factors, providing a reliable and efficient means of scaling (Guttenberg et al. 1960). This is done by stick scaling a

---

The authors are, respectively, Research Assistant, Dept. of Forest Management, College of Forestry and Conservation, Univ. of Montana, Missoula (jarred.saralecos@umontana.edu [corresponding author]); Assistant Professor of Forest Operations, Dept. of Forest, Rangeland, and Fire Sci., College of Natural Resources, Univ. of Idaho, Moscow (robk@uidaho.edu); Post-Doctoral Researcher, Dept. of Forest and Rangeland Stewardship, College of Natural Resources, Colorado State Univ., Fort Collins (wade.tinkham@colostate.edu); and State Forestry Extension Specialist and Professor Emeritus of Forestry, Dept. of Forest, Rangeland, and Fire Sci., College of Natural Resources, Univ. of Idaho, Moscow (rbrooks@uidaho.edu, lrjohnson@uidaho.edu). This paper was received for publication in September 2014. Article no. 14-00087.
©Forest Products Society 2015.
Forest Prod. J. 65(5/6):198–208.
doi:10.13073/FPJ-D-14-00087

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

known proportion of sawlog loads from each harvest to help improve the accuracy of weight scaling conversion factors (Amateis et al. 1984). The reduction of total conventionally scaled loads and reduced truck turn-times at mill yards has resulted in improvements over conventional scaling practices (Guttenberg et al. 1960, Guttenberg and Fasick 1973). Research on weight scaling for log inventory and transaction purposes is limited in its application outside of the southeastern United States, where it was originally developed (Daniels 2005, Fonseca 2005). Within the southeastern region, several studies have found that various combinations of diameter, length, and specific gravity best improve the prediction of volume from weight in both pulpwood and sawlogs (Taras 1956, Page and Bois 1961, Row and Guttenberg 1966, Van Deusen et al. 1981). The knowledge has led to several states adopting conversion factors that account for local and regional variation in logs (Dicke and Parker 1999). Small-end diameter (SED) and truckload piece count have also improved prediction of scaled volume from weight (Yerkes 1966, Donnelly and Barger 1977, Markstrom and King 1993). However, these studies are characterized by small sample sizes. Few comprehensive regional assessments that account for the potential influence and relative importance of SED, piece count, species sort, season, and harvest area on weight-to-volume (W:V) relationships exist.

In western North America, there is very little published research on W:V relationships (Donnelly and Barger 1977, Markstrom and King 1993, Briggs 1994), with current literature acknowledging but not accounting for the influence of species sort, piece size, season, and local climatic conditions on W:V relationships. Current regional practices use a single W:V conversion multiplier for each supervisory district, which are updated annually based on sample check scaling. The Intermountain West region of North America commonly experiences large disturbances such as catastrophic wildfires and insect infestations, which can dramatically alter forest structure and composition (Brown and Chojnacky 1996). Large- and fine-scale climatic and soil variation across the region are known to affect forest composition, growth, and even wood density. For example, wood specific gravity is known to range from 0.30 for western redcedar (*Thuja plicata*) to 0.48 for western larch (*Larix occidentalis*) within the region (Alden 1997). These climatic factors are also known to influence the moisture content of felled sawlogs at fine temporal scales, carrying significant implications for W:V conversion factors (Saralecos et al. 2014).

The objectives of this study were to conduct an in-depth analysis of softwood sawlog W:V relationships across the state of Idaho through the coupling of weather, topography, harvest timing, and log scaling data. The primary goals were (1) to identify the most important regional factors affecting W:V relationships and (2) to assess the effect of environmental and topographical variables as predictors in weight scaling applications. In keeping with the concepts of Markstrom and King (1993), we hypothesized that including SED and truckload piece count with net load weight would improve the prediction of sawlog volume. We also hypothesized that species, harvest region, and season would improve the regression model used to establish W:V conversions at the alpha = 0.05 level. Finally, we expected that environmental and topographical data would increase the accuracy of model predictions.

Methods

Study area

The study area encompasses more than 971,000 hectares, largely within the Idaho Panhandle Region (Fig. 1), with harvest unit elevations ranging from 400 to 2,100 m. The fine-scale variation in physical and environmental characteristics within the Intermountain West region produces one of the most spatially diverse collections of forest habitat types found across North America (Benson et al. 1987). At 42 percent of its total land area, Idaho has the largest proportion of forested lands of any Intermountain West state (Brown and Chojnacky 1996). Idaho's forests extend from the Canadian border, south through the rugged central mountains of the Selway-Bitterroots, and Sawtooth Wilderness to the Snake River plain of southern Idaho (Morgan et al. 2001; Fig. 1). State managed forests of the Idaho Department of Lands are broken into 11 supervisory districts that are overseen by northern and southern management regions (Table 1). Although connected longitudinally, the differences across these areas in species composition and growing season length varies widely from low elevation ponderosa pine (*Pinus ponderosa*) savannah to alpine forests habitat types (O'Hara et al. 1996). Approximately 65 percent of the timber volume harvested from state-owned land is extracted from the northern management region.

The region has typical interior mountain climate, with distinct seasonal temperature and precipitation variations (Whitlock and Bartlein 1993; Table 2). Annual average monthly temperature ranges from –8.7°C in January to 24.7°C in August. Average monthly precipitation ranges from 0 to 312 mm, with the third quarter (July through September) being the driest season. Winters are cold, often with heavier snowfall at the higher elevations. The majority of the precipitation occurs during the end of the fourth quarter (October through December) and beginning of the first quarter (January through March). Precipitation amounts vary across the supervisory districts, and the rain shadow effect of the Coastal and Cascade Mountains are noticeable as drought conditions are common (Finklin 1983). The high variability in precipitation and temperature, combined with steep slopes and the moderate storage capacity of the forest soils, results in a hydrologically dynamic area (Goode et al. 2012).

Scaled data

Information from scaled sawlog truckloads was collected from across Idaho, representing a range of harvest areas, elevations, species sorts, and climatic conditions from 2011 to 2013 (Table 2). The truckloads sampled included only pure sorted loads, consisting of five species sorts common to the Intermountain West: (1) Douglas-fir (*Pseudotsuga menziesii*) and western larch (*Larix occidentallis*); (2) grand fir (*Abies grandis*), western hemlock (*Tsuga heterophylla*), and sub-alpine fir (*Abies grandis*); (3) lodgepole pine (*Pinus contorta*) and ponderosa pine (*Pinus ponderosa*); and (4) western redcedar (*Thuja plicata*). A fifth sample of loads containing western white pine (*Pinus monticola*) and Engelmann spruce (*Picea engelmannii*) were excluded as there were insufficient representative samples for analysis.

A total of 7,929 pure sorted truckloads of sawlogs covering the entirety of the state of Idaho were sampled (Table 3). Sample loads were proportionally distributed

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

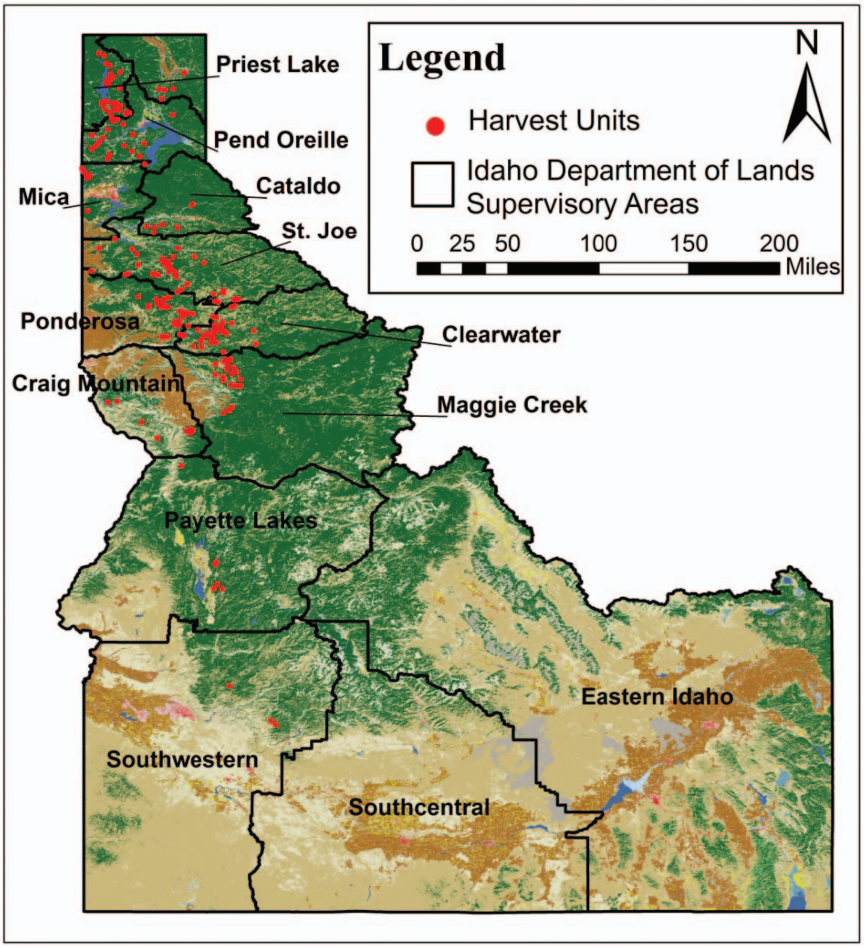

Figure 1.—Regional map showing the location and distribution of harvesting units containing sample loads across the state of Idaho.

across the state supervisory districts based on each supervisory area's harvest volume in proportion with the total statewide harvest volume (Table 1). For each truckload, gross and net volume (board feet), truck payload (tons), average SED (inches), average log length (feet), load piece count (number), species, and harvest quarter were collected. As board feet is the current industry standard for assessing volume in North America, all analysis and results have retained that unit of measure. All other measurements have been converted into SI units.

Additionally, for each sample load, latitude and longitude corresponding to the centroid of each harvest unit were overlaid on a national 30-m digital-elevation model to

Table 1.—Average supervisory area harvest volumes from 2011 to 2013 in relation to Idaho Department of Lands statewide annual harvest volume and sample allocation across each supervisory area.

Supervisory area[a]	Mean harvest volume 2011–2013 (mmbf)[b]	Percentage of state harvest	Percentage of sample loads
Cataldo (N)	7.3	3.1	1.9
Clearwater (S)	40.3	17.0	18.6
Craig Mountain (S)	9.3	3.0	8.0
Maggie Creek (S)	21.0	9.0	14.9
Mica (N)	7.7	3.0	2.2
Payette Lakes (S)	16.3	6.0	5.6
Ponderosa (N)	36.7	17.0	17.5
Priest Lake (N)	16.3	7.0	3.0
Southwest (S)	8.3	3.5	2.0
St. Joe (N)	48.3	20.3	23.0
Pend Oreille Lake/ Kootenai Valley (N)	22.4	9.4	3.3

[a] N and S denote whether the supervisory area is located in the Northern or Southern management region of the state.

[b] mmbf = million board feet

Table 2.—Characteristics collected for each scaled sample load and the coincident Idaho Department of Lands harvest locations.

	Range	Mean (SD)
Scaling		
Net Scribner volume (board ft)	3.0–7.9	5.0 (0.8)
Net weight (tons)	11.5–35.0	27.3 (2.2)
Small-end diameter (in.)	6.0–27.2	10.5 (3.0)
Length (ft)	14.1–50.0	29.2 (4.5)
Piece count	10.0–359.0	49.7 (31.0)
Defect (%)	0.0–22.0	7.7 (0.03)
Climate and topographic factors		
Elevation (m)	562.2–2,003.0	1,073.0 (241.3)
Precipitation (mm)	0.0–312.0	96.3 (68.4)
Temperature (°C)	−7.7–23.7	7.6 (8.1)

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

Table 3.—Distribution of sample loads by supervisory area, species, and quarter.

	No. of sample loads
Supervisory area	
Cataldo	61
Clearwater	1,472
Craig Mountain	665
Maggie Creek	1,309
Mica	93
Payette Lakes	420
Ponderosa	1,464
Priest Lake	233
Southwest	94
St. Joe	1,812
Pend Oreille/ Kootenai Valley	257
Species[a]	
WRC	1,390
DFL	2,260
GFHAF	3,536
LPPP	694
Quarter	
1	1,768
2	1,571
3	2,634
4	1,907

[a] WRC = western redcedar; DFL = Douglas-fir and western larch; GFHAF = grand fir, western hemlock, and sub-alpine fir; LPPP = lodgepole pine and ponderosa pine.

determine elevation and supervisory district. Furthermore, total precipitation (millimeters) and average temperature (°C) for the 30 days prior to the mill delivery date of each sample load was extracted from the nearest Natural Resource Conservation Service SNOTEL site record (US Department of Agriculture–National Resources Conservation Service 2013).

Statistical analysis

All statistical analysis was completed using R (R Core Team 2013). Data from the Idaho Department of Lands scaling records collected from 2011 to 2013 were combined and statistical tests of harvest area, species, and seasonal differences in W:V relationships were conducted. Prior to analysis, all variables were evaluated using the Shapiro-Wilk test for normality (Royston 1982). SED and piece count were ln transformed, in order to meet the linear regression assumption of normality. To evaluate any potential interdependence among predictors, a Pearson chi-square test for multicollinearity was conducted. Once all variables had been evaluated for both normality and collinearity, the model improvement ratio (MIR; Murphy et al. 2009; Tinkham et al. 2013, 2014) commonly implemented in the Random Forest machine learning algorithm (RF; Breiman 2001) was implemented to evaluate variable importance. Variable importance and MIR have been used to identify important factors correlated with a target parameter (Ahmed et al., submitted for publication). The RF algorithm was used to produce 10,000 random decision trees for use in determining variable importance. The MIR procedure, which operates by standardizing the decrease in mean squared error achieved by adding a variable across all the trees from zero to one, was used as the primary variable selection criteria for subsequent analysis (Ahmed et al., submitted for publication).

Based on the outcome of variable importance ranking using MIR from Random Forest, a series of linear mixed-models were fitted to predict net volume using the lme4 package (Bates et al. 2013) in the R statistical programming environment (R Core Team 2013). The linear mixed-models were separated by species sort. Individual timber sales and scaling ticket numbers were implemented as random effects, and tons, SED, piece count, length, defect, and seasonal quarter as fixed covariates. The variables identified using the MIR and implemented in the mixed-models were further evaluated with Akaike's Information Criterion (AIC; Akaike 1974), for which R^2 values were derived from the conditional R^2, using procedures established in Nakagawa and Schielzeth (2013). AIC evaluates the statistical quality of a model in comparison to others by balancing goodness of fit against model complexity (Akaike 1974). Single AIC values contain no meaning. Although when compared between models, lower values indicate better fitting models (Breck et al. 2003). In the case of negative reported values it is the highest negative value that identifies the best model. The AIC and R^2 values from the models were later used with a Tukey's honestly significant difference test to evaluate differences between the independent variables. The difference testing was applied with Tukey's DTK package (Lau 2013) because of unequal sample sizes of species and harvest area. All significance tests were evaluated at the alpha = 0.05 level.

The best model was fitted using a liner mixed-model design using the lme4 package and lmer regression function. The purpose of including load ticket and timber sale number as nested random effects was to account for the lack of independence between sample loads from the same timber sale location (Bates et al. 2013). While sale numbers are unique to each harvest, ticket numbers are repeated. Therefore, to meet the linear regression assumption of independent errors and constant variance, a mixed-effects model was used. The interaction of sale number × ticket assured that each sample load would be unaffected by loads of similar structure by accounting for correlated error.

Fixed-effects variables were used to predict net volume (Scribner board foot) separately for each species sort (Table 3). The fitted model had the following form (Eq. 1: $Y = \beta_0 + \beta_1$ (Tons) $+ \beta_2$ (SED) $+ \beta_3$ (Piece Count) $+ \beta_4$ (Length) $+ \beta_5$ (Defect) $+ \beta_6$ (Quarter) $+ \beta_7$ (1|Sale Number/Ticket) $+ u$ (Error), where Y is net volume (Scribner board foot, converted to m^3), SED is small-end diameter (cm, diameter inside bark), piece count is the number of logs in the load, defect is the difference between gross and net volume (%), and seasonal quarter (quarter) was grouped as follows: Q1, January through March; Q2, April through June; Q3, July through September; Q4, October through December. Seasonal fluctuations in W:V relationships were assumed to be represented through the variables seasonal quarter, precipitation, temperature, and elevation. Mixed-effects models are used widely in natural resources analysis, but have not been previously applied to W:V analysis.

Results

Weight–volume

When assessing overall trends using exploratory data analysis, seasonal patterns in the W:V relationship were

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

evident across all supervisory districts and species sorts, with decreases in the second and third quarters (April through September) observed for all supervisory districts and species combinations, followed by increases during the fourth quarter (October through December). Specifically, W:V decreased by 12 percent for western redcedar between the first and third quarters, while Douglas-fir–larch and grand fir–hemlock each showed a 9 percent reduction. This seasonal dependence of the W:V relationships, compared with a yearly mean, is shown in Table 4. The trends identified in W:V during the year are tied closely to seasonal changes in mean temperature.

The species with the greatest yearly range (tons per mbf) in W:V was Douglas-fir–larch (4.00 to 9.52). The smallest change occurred for redcedar (2.56 to 6.94). Yearly averages show that Douglas-fir–larch, grand fir–hemlock, and lodgepole–ponderosa pine sorts were not significantly different at the alpha = 0.05 level. However, redcedar was significantly different with a yearly average W:V conversion 21 percent less than the other sorts. When separated into quarters, each sort differed between the second and third quarters of the year. Whereas season and species had different conversion factors, the effect of harvest region was much less.

W:V relationships were generally not significantly different among supervisory districts. While several districts proved different from each other, the difference was attributed to distinct variations between habitat types and species harvest volumes and not further investigated. Conversion factors consisting of all sorted species also did not produce different results. However, when tabulated by species and region, harvest area differences were observed between only a few areas. The combinations of area and species that experienced the greatest differences were found within the species sorts containing the largest seasonal fluctuation. Subsequently, these differences were highly correlated with local weather observed in each location as well as defect quantities.

Table 4.—Seasonal variation in weight–volume relationship of softwood sawlogs relative to various species sorts common to the Intermountain West region.

Species and quarter[a]	Defect (%)	Weight–volume (tons/mbf)
WRC	9.7	4.55
Quarter 1	8.7	4.85
Quarter 2	8.9	4.64
Quarter 3	11.0	4.25
Quarter 4	9.5	4.70
DFL	8.8	5.74
Quarter 1	8.6	6.03
Quarter 2	8.7	5.70
Quarter 3	9.0	5.51
Quarter 4	8.8	5.90
GFHAF	6.6	5.71
Quarter 1	6.9	6.01
Quarter 2	8.0	5.59
Quarter 3	6.7	5.49
Quarter 4	6.6	6.00
LPPP	6.0	5.80
Quarter 1	5.9	6.01
Quarter 2	5.7	5.81
Quarter 3	6.1	5.62
Quarter 4	6.4	5.83

[a] WRC = western redcedar; DFL = Douglas-fir and western larch; GFHAF = grand fir, western hemlock, and sub-alpine fir; LPPP = lodgepole pine and ponderosa pine.

Mean defect for different supervisory districts, species, and seasonal quarters was similar. Cedar sawlogs had the highest mean defect percentage over the entire year, as well as in each seasonal quarter. While cedar showed the greatest mean defect overall, the mean defect volume per load of each species increased during the second and third quarters; however, no statistical difference in defect was observed. This increase occurred during the seasonal period with the most delivered loads. Finally, the predictability of defect was greater than most other variables evaluated (Fig. 2). This ability to accurately predict variation due to season, supervisory district, species, and defect creates a strong base from which to develop W:V relationships for commercial weight scaling.

Climate variables

Impacts of climatic and topographic variables, including precipitation, atmospheric temperature, latitude, longitude, and elevation, were assessed as potential predictors of W:V relationships. Initial results from a model improvement ratio using RF indicated that all factors were significant predictors of W:V. In comparison, the effects of temperature, latitude, and elevation were identified as stronger predictors of W:V relationships than precipitation and longitude.

Predicting volume using mixed-effects models

The variables precipitation and temperature had collinearity with seasonal quarter, as did the topographic variables elevation and harvest area. The analysis of variance (ANOVA) indicated significant collinearity between seasonal quarter and temperature (0.52), and between seasonal quarter and precipitation (0.62). Therefore, the climatic and topographic variables were withheld from further analysis. Finally, the MIR was run again, including the reduced variable list. Final variables in the model were species, SED, piece count, length, defect, quarter, and harvest area (Fig. 3).

Results from the MIR indicated strong model improvement due to inclusion of species. The subsequent AIC testing then separated the analysis into four models representing one for each species sort. Using species sort as a random variable in place of using separate models did not improve the AIC results. Individual species sorts were closely tied to levels of defect. The combined testing of independent variables through the RF model improvement ratio and AIC tests showed the strongest model as follows:

$$\begin{aligned} Y = \beta_0 &+ \beta_1(\text{Tons}) + \beta_2(\text{SED}) + \beta_3(\text{Piece Count}) \\ &+ \beta_4(\text{Length}) + \beta_5(\text{Defect}) + \beta_6(\text{Quarter}) \\ &+ \beta_7(1|\text{Sale Number/Ticket}) + u(\text{Error}) \end{aligned} \tag{1}$$

This model independently predicted net volume (board feet) for each species sort (Table 5). The addition of harvest area, while improving the model, did not significantly improve the model at the alpha = 0.05 level.

Seasonal variation of predictions from the linear mixed-effects model (Eq. 1) is shown in Figure 4. This model

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

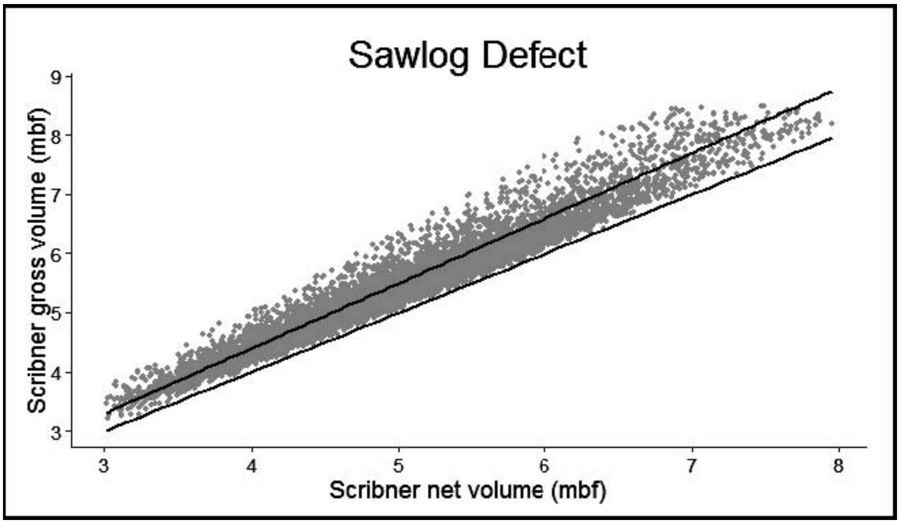

Figure 2.—Changes in truckload defect are shown as a comparison of gross and net scaled board foot volumes. The top line represents average defect per truckload and the lower line represents no defect.

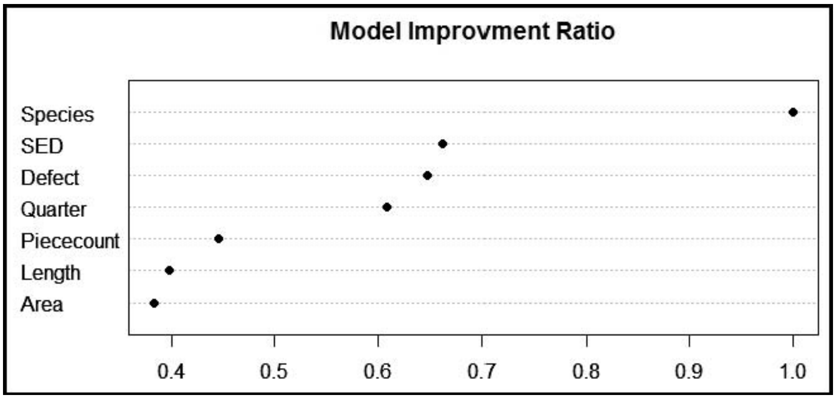

Figure 3.—Results of the model improvement ratio derived from Random Forest explaining the proportion of the time that each variable best explained sawlog weight–volume relationship. SED = small-end diameter.

explained >0.74 of the total variability in the net truckload board foot volume of the sampled loads in all models with a conditional R^2 ranging from 0.74 to 0.90 ($P < 0.05$; 0.74 WRC, 0.90 DFL, 0.85 LPPP, 0.89 GFHAF) (Table 6). The selection of these variables supported the hypotheses that net weight, SED, piece count, and seasonal quarter affect net volume (board feet). Variability in temperature (°C), precipitation (millimeters), elevation (meters), latitude, and longitude were explained by quarter and harvest area, so these terms were removed from the model, supporting our initial hypothesis. We failed to reject the null hypothesis that species does not affect W:V. While not all harvest areas were significant, differences among individual supervisory areas were evident, based on ANOVA tests.

Table 5.—The results of Akaike's Information Criterion (AIC) testing to determine the best fit model applying the factors derived from the Random Forest model improvement ratio.

AIC model[a]	AIC for each species sort[b]			
	LPPP	DFL	GFHAF	WRC
$Y = \beta_0 + \beta_1\ _{\text{Tons}} + \beta_2\ _{(1\mid\text{Sale Number/Ticket})} + u$	1,661	4,311	6,941	3,423
$Y = \beta_0 + \beta_1\ _{\text{Tons}} + \beta_2\ _{\text{SED}} + \beta_{3(1\mid\text{Sale Number/Ticket})} + u$	1,012	2,742	5,012	2,687
$Y = \beta_0 + \beta_1\ _{\text{Tons}} + \beta_2\ _{\text{SED}} + \beta_3\ _{\text{PC}} + \beta_4\ _{(1\mid\text{Sale Number/Ticket})} + u$	871	2,678	5,001	2,667
$Y = \beta_0 + \beta_1\ _{\text{Tons}} + \beta_2\ _{\text{SED}} + \beta_3\ _{\text{PC}} + \beta_4\ _{\text{Length}} + \beta_5\ _{(1\mid\text{Sale Number/Ticket})} + u$	863	2,669	4,997	2,631
$Y = \beta_0 + \beta_1\ _{\text{Tons}} + \beta_2\ _{\text{SED}} + \beta_3\ _{\text{PC}} + \beta_4\ _{\text{Length}} + \beta_5\ _{\text{Defect}} + \beta_6\ _{(1\mid\text{Sale Number/Ticket})} + u$	807	2,267	4,399	2,569
$Y = \beta_0 + \beta_1\ _{\text{Tons}} + \beta_2\ _{\text{SED}} + \beta_3\ _{\text{PC}} + \beta_4\ _{\text{Length}} + \beta_5\ _{\text{Defect}} + \beta_6\ _{\text{Quarter}} + \beta_7\ _{(1\mid\text{Sale Number/Ticket})} + u$	803	1,893	2,951	2,547

[a] PC = piece count.

[b] Species sorts: LPPP = lodgepole pine and ponderosa pine; DFL = Douglas-fir and western larch; GFHAF = grand fir, western hemlock, and sub-alpine fir; WRC = western redcedar.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

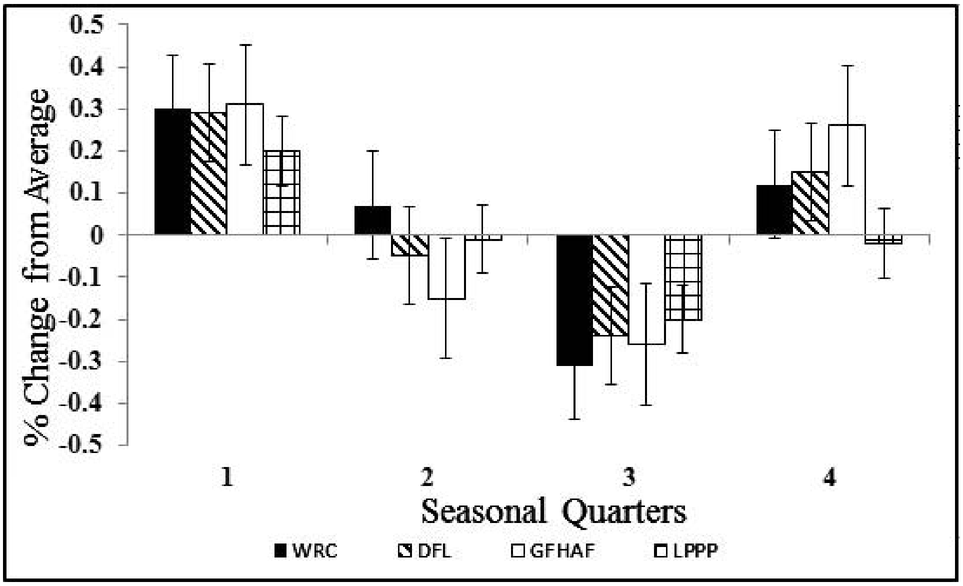

Figure 4.—Seasonal percent change from individual species yearly average weight–volume relationship for each species sort. WRC = western redcedar; DFL = Douglas-fir and western larch; GFHAF = grand fir, western hemlock, and sub-alpine fir; LPPP = lodgepole pine and ponderosa pine.

After fitting each individual species-level model, individual weight-to-volume conversion relationships were established for each harvest area by species and quarter (Table 4). These multipliers were estimated by developing the ratio of the predicted net volume of sample loads to actual net weights. W:V relationships in Table 4 show changes across seasonal quarter. The conversions of western redcedar contained the greatest variation among W:V relationships, and the lodgepole–ponderosa pine sort had the smallest variation. Comparisons of predicted W:V conversions and the observed results showed positive correlation for each species sort (Fig. 5).

Validation

The W:V relationships were further investigated by comparing them with current state conversion multipliers. The current predictors used are annual supervisory district averages of all species. A comparison of predicted values using the current multipliers and predictions from the new model is shown in Table 7. Differences between predictions from the two models were evaluated by calculating absolute and percent differences in prediction error (Fig. 6). The greatest differences were observed for western redcedar, which differed between supervisory areas.

The conversion multipliers show minimal differences among other species sorts when compared with harvest region. Much of the variation in current conversion multipliers used is proportional to the percent volume harvested the prior year for a given species. For example, several of the Southern and drier harvest regions have higher ratios compared with the Northern regions, which harvested a higher percentage of volume of western redcedar on a yearly basis.

Discussion

Evaluation of hypotheses

SED and piece count improved prediction of net truckload volume, based on the relative magnitude of Random Forests MIR values. In support of our initial hypotheses, species, and

Table 6.—Mixed-model analysis of covariance for Scribner net board foot volume using weight, small-end diameter (SED), defect, quarter, piece count (PC), and length as covariates and sale number and load ticket as fixed effects.[a]

	Mean ± SE (t value)[b]			
Coefficient	LPPP	DFL	GFHAF	WRC
Weight	0.185 ± 0.0111 (17.30)	0.157 ± 0.004 (33.21)	0.167 ± 0.288 (32.32)	0.151 ± 0.007 (20.62)
SED	1.035 ± 0.103 (9.99)	1.783 ± 0.062 (28.52)	1.962 ± 0.005 (33.98)	2.511 ± 0.128 (19.53)
Defect	−5.729 ± 0.652 (−8.78)	−5.582 ± 0.246 (−22.66)	−7.113 ± 0.057 (−27.14)	1.166 ± 0.495 (2.35)
Quarter 2	0.016 ± 0.052 (1.31)	0.349 ± 0.029 (12.04)	0.3588 ± 0.262 (14.28)	0.476 ± 0.059 (8.02)
Quarter 3	0.142 ± 0.052 (2.75)	0.493 ± 0.0266 (18.80)	0.493 ± 0.025 (21.37)	0.908 ± 0.057 (15.82)
Quarter 4	−0.055 ± 0.063 (−1.99)	0.162 ± 0.028 (5.73)	0.224 ± 0.025 (8.97)	0.383 ± 0.058 (6.57)
PC	−0.556 ± 0.063 (−8.84)	−0.266 ± 0.032 (−8.13)	−0.007 ± 0.031 (−1.21)	−0.117 ± 0.073 (−2.59)
Length	0.006 ± 0.005 (1.47)	−0.014 ± 0.002 (−5.16)	−0.002 ± 0.002 (−1.96)	0.024 ± 0.005 (4.31)
R^2 (RMSE %)	0.90 (±5.8)	0.93 (±3.7)	0.92 (±4.2)	0.74 (±9.0)

[a] The response of net board foot volume to weight was best fit to a linear model, where each model used Quarter 1 as the base treatment.

[b] Species sorts: LPPP = lodgepole pine and ponderosa pine; DFL = Douglas-fir and western larch; GFHAF = grand fir, western hemlock, and sub-alpine fir; WRC = western redcedar.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

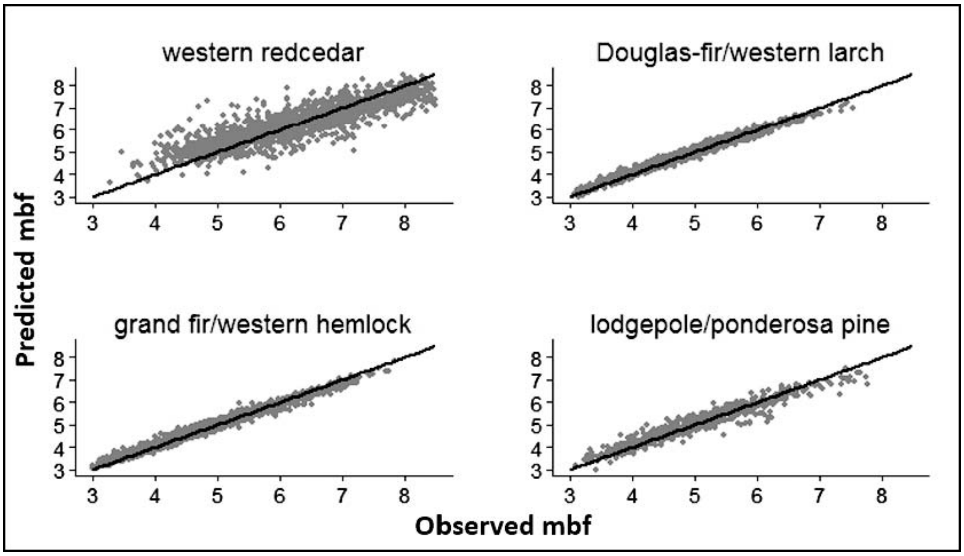

Figure 5.—The model predicted truckload volume of delivered sawlogs compared with observed truckload volumes during the study duration, over the net weight of each load separated by species sort.

seasonal quarter improved the prediction of W:V relationships. However, supervisory district did not reduce regression model prediction error. Net weight, SED, and species explained most of the variability in net truck volume. Seasonal quarter also proved to be highly correlated with temperature, precipitation, latitude and longitude. Therefore, while climate and topography affect W:V, quarter is a suitable surrogate. This empirical model provides a foundation to build future weight scaling practices upon. Although accounted through seasonal quarter, previous research has not investigated the impact of short or long-term weather effects on W:V relationships.

Additional factors

Bark.—Beyond environmental and scaling factors measured in each harvest load, several notable variables including bark and stem density were not accounted for in this study. Conventional scaling procedures require inside bark diameter for determining the scaling diameter. However, delivered sawlogs may contain bark in varying surface percentages, adding to the net weight of each load, while being unaccounted for in the scaling process. Therefore, potential error in the model may arise from variability in bark coverage percentage. Accurate determination of the percentage of bark in each load is difficult to assess. Bark makes up 10 to 25 percent of the over-bark volume and weight of a tree as reported in prior studies (Meyer 1946, Philip 1994). Depending on harvest location, season, and processing method, operational bark loss can vary (Murphy and Pilkerton 2011).

Table 7.—Comparisons of weight–volume relationships showing variation between currently employed weight-to-volume conversions and updated model predictions.

		Model conversion (% change from current)[a]			
Supervisory area	Current conversion	LPPP, 5.80	DFL, 5.74	GFHAF, 5.71	CED, 4.55
Cataldo	5.57	4.1	3.0	2.5	−18.3
Clearwater	5.07	14.4	13.2	12.6	−10.3
Craig Mountain	5.38	7.8	6.7	6.1	−15.4
Maggie Creek	5.51	5.2	4.2	3.6	−17.4
Mica	5.80	−0.1	−1.1	−1.6	−21.6
Payette Lake	5.65	2.7	1.7	1.1	−19.4
Ponderosa	5.17	12.1	10.9	10.4	−12.1
Priest Lake	5.82	−0.3	−1.3	−1.8	−21.8
Southwest	5.75	0.8	−0.2	−0.7	−20.9
St. Joe	5.54	4.6	3.5	3.0	−17.9
Pend Oreille Lake/ Kootenai Valley	5.78	−0.7	−1.7	−2.2	−22.1

[a] LPPP = lodgepole pine and ponderosa pine; DFL = Douglas-fir and western larch; GFHAF = grand fir, western hemlock, and sub-alpine fir; WRC = western redcedar.

Moisture.—Bark cover percentage on stems is fixed after mechanical processing, while stem moisture loss continues through the time of log delivery, varying with the season. Long-term studies on seasonal effects of moisture changes within standing timber have found seasonal changes associated with extended lag periods (Marden et al. 1975). Additional studies have explored both the rates and quantities of stem moisture loss after harvest (Yerkes 1967). Disease-free sawlogs lose moisture after felling in summertime. The addition of disease such as beetle-killed timber in British Columbia, Canada, may only accelerate the process (Yerkes 1967, Saralecos et al. 2014). Wood contains hygroscopic tendencies, with internal moisture content tending to equilibrate with surrounding atmospheric conditions (Siau 1984). Relative humidity, temperature, and precipitation can all affect moisture loss rates (Siau 1984). Studies have identified seasonal patterns of bole moisture reduction during summer months (Beedlow et al. 2007). These long-term seasonal changes correspond with relative humidity. However, there are delayed lag times associated with wood and the surrounding environmental conditions (Marden et al. 1975). The rate of equilibration increases with the difference between relative humidity and stem moisture content at the time of harvesting.

Variability in the heartwood to sapwood ratio can cause different densities at points along the stem profile (Patterson and Wiant 1993). These ratios are characteristic of stem

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

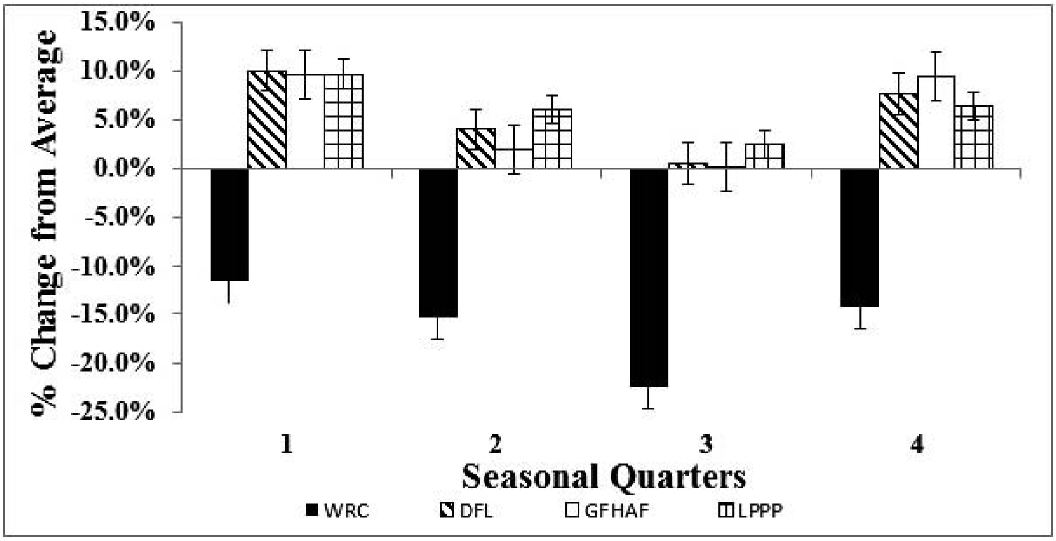

Figure 6.—Seasonal variation among species sorts showing percent change from the current Idaho Department of Lands quarterly weight–volume conversion factors (baseline) and the updated species-dependent conversion factors. WRC = western redcedar; DFL = Douglas-fir and western larch; GFHAF = grand fir, western hemlock, and sub-alpine fir; LPPP = lodgepole pine and ponderosa pine.

taper, which varies regionally by species (Garber and Maguire 2003). The potential for regional changes in stem form are accounted for in the previous model using scaled log length. Scaled log volume corresponds highly with log length through the taper rules built into the Scribner Short Log scaling rule. Additionally, changes in specific density also occur regionally (Schumacher 1946, Bowyer et al. 2007). Regional variability of factors like specific gravity of wood affects log weight. For example, specific gravity of coastal Douglas-fir varies from 0.36 to 0.54 and that of western hemlock varies from 0.34 to 0.50 (Hoadley 1990, Bowyer et al. 2007).

Economic impact of conversions.—Current organization and infrastructure of weight scaling in the western North America is firmly established. Weigh stations and conversion relationships are present at most sawmills. Sample weight scaling is used to continuously update conversion relationships used to predict volume. Research on weight scaling accuracy has shown efficiency and economic benefits (Donnelly and Barger 1977, Amateis et al. 1984). However, many landowners, owners of sawmills, and contractors use proprietary relationships, rarely sharing production and efficiency numbers (Via and Shupe 2005). Improvements in the understanding of W:V relationships in the Intermountain West associated with this study will benefit landowners and mills in log inventory and sale and help expand regional knowledge among foresters and contractors. These improvements are increasingly important as catastrophic wildfires, beetle outbreaks, and climate shifts alter the W:V relationships of various commercial softwood species.

Although past studies have examined weight scaling for multiple products (Guttenberg and Fasick 1973, Amateis et al. 1984), accuracy (Yerkes 1966), and effects of moisture (Yerkes 1967, Lothner et al. 1974), and have been completed in varying forest regions across the United States, little work has evaluated influences of bark and species-specific gravity (Sollins et al. 1987, Harmon and Sexton 1995). Regional weight scaling could improve through an increased understanding of bark characteristics and specific gravity for weight scaled species.

Large differences between cubic foot scaling and Scribner log rule volume estimates suggest shifting towards cubic scaling practices would significantly improve W:V conversion relationships. Cubic scaling accounts for the entirety of the log volume, opposed to diagram-based methods such as Scribner, which only measure the scaling cylinder board feet within each log segment. Through accounting for more volume within each log, cubic scaling volumes are more closely correlated with weight and the error associated with weight–to–cubic volume relationships is greatly reduced (Markstrom and King 1993).

Conclusions

Consistent with the shifting trend toward sample weight scaling in the Intermountain West, we showed that regression modeling can accurately predict sawlog volume. Additionally, we failed to reject our H_o that tons, SED, piece count, seasonal quarter, and defect are significant predictors of net sawlog truckload volume. Furthermore, this study showed that seasonal quarter was autocorrelated and can be used as a surrogate for precipitation and temperature. We then constructed and evaluated four linear mixed-effects models predicting net sawlog volume that can be applied across the region. The models developed for the Douglas-fir–larch, lodgepole–ponderosa pine, and grand fir–hemlock regional sorts proved highly efficient at explaining the error within each model, whereas the western redcedar model accounts for much less model error.

Surprisingly, we rejected our H_o that harvest area would significantly improve the regression models as it is currently applied to structure regional W:V conversion factors. For the remaining uncertainty of influences affecting weight and volume relationships, several factors such as wood moisture content and sawlog bark coverage percentage were discussed. It is apparent that while coefficients improve the short-term model accuracy, increases in data through sample weight scaling procedures provide the best long-

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

term improvement to W:V relationships and subsequent scaling conversions factors.

Literature Cited

Ahmed, O. S., S. E. Franklin, M. A. Wulder, and J. C. White. Characterizing stand-level forest structure using landsat time series, samples of airborne lidar, and machine learning. (Submitted for publication.)

Akaike, H. 1974. A new look at the statistical model identification. *IEEE Trans. Automat. Control* 19(6):716–23.

Alden, H. A. 1997. Softwoods of North America. General Technical Report FPL-GTR-102. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 151 pp.

Amateis, R. L., H. E. Burkhart, B. J. Greber, and E. E. Watson. 1984. A comparison of approaches for predicting multiple-products yields from weight-scaling data. *Forest Sci*. 30(4):991–998.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2013. Lme4: Linear mixed-effect models using Eigen and S4. R package version 1.0-5.

Bauer, E. and R. Hogan. 2006. Log scaling in Idaho, scaling and marketing private timber. University of Idaho Cooperative Extension, Moscow.

Beedlow, P. A., D. T. Tingey, E. H. Lee, D. L. Phillips, C. P. Andersen, R. S. Waschmann, and M. G. Johnson. 2007. Sapwood moisture in Douglas-fir boles and seasonal changes in soil water. *Can. J. Forest Res*. 37:1263–1271.

Benson, R. E., A. W. Green, and D. D. Van Hooser. 1987. Idaho's forest resources. Resource Bulletin INT-39. USDA Forest Service, Intermountain Research Station, Fort Collins, Colorado. 122 pp.

Bowyer, J. L., R. Shmulsky, and J. G. Haygreen. 2007. Forest Products and Wood Science: An Introduction. Blackwell, Ames, Iowa. 558 pp.

Breck, S. W., K. R. Wilson, and D. C. Andersen. 2003. Beaver herbivory and its effect on cottonwood trees: Influence of flooding along matched regulated and unregulated rivers. *River Res. Appl*. 19:43–58.

Breiman, L. 2001. Random Forests. *Machine Learning* 45:5–32.

Briggs, D. 1994. Measurements of Logs: Forest Products Measurements and Conversion Factors. University of Washington Press, Seattle. 154 pp.

Brown, M. J. and D. C. Chojnacky. 1996. Idaho's forests, 1991. Resource Bulletin INT-RB-88. USDA Forest Service, Intermountain Research Station, Fort Collins, Colorado.

Daniels, R. A. 2005. Marketing your timber: The basics of weight scaling. Publication 2005. Cooperative Extension Service, Mississippi State University, Starkville. 4 pp.

Dicke, S. and R. Parker. 1999. Pine timber volume-to-weight conversions. Publication 2244. Cooperative Extension Service, Mississippi State University, Starkville. 4 pp.

Donnelly, D. M. and R. L. Barger. 1977. Weight scaling for southwestern ponderosa pine. Technical Report M-181. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 10 pp.

Finklin, A. I. 1983. Climate of Priest River Experimental Forest, northern Idaho. General Technical Report INT-159. USDA Forest Service, Intermountain Forest and Range Experiment Station, Fort Collins, Colorado. 58 pp.

Fonseca, M. A. 2005. The Measurement of 1 Roundwood: Methodologies and Conversion Ratios. CABI Publishers, Wallingford, UK. 269 pp.

Freese, F. 1973. A collection of log rules. General Technical Report. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 65 pp.

Garber, S. M. and D. A. Maguire. 2003. Modeling stem taper of three central Oregon species using nonlinear mixed effects model and autoregressive error structures. *Forest Ecol. Manag*. 179(1):507–522.

Goode, J. R., C. H. Luce, and J. M. Buffington. 2012. Enhanced sediment delivery in a changing climate in semi-arid mountain basins: Implications for water resource management and aquatic habitat in the northern Rocky Mountains. *Geomorphology* 139–140:1–15.

Guttenberg, S. and C. A. Fasick. 1973. Scaling multiple products by weight. *J. Forest Prod*. 23:34–37.

Guttenberg, S., D. Fassnacht., and W. C. Siegel. 1960. Weight-scaling southern pine sawlogs. Occasional Paper 177. USDA Forest Service, Southern Forest Experiment Station, Ashville, North Carolina. 6 pp.

Harmon, M. E. and J. Sexton. 1995. Water balance of conifer logs in early stages of decomposition. *Plant Soil Sci*. 172:141–152.

Hoadley, B. R. 1990. Identifying Wood: Accurate Results with Simple Tools. Tauton Press, Inc., Newtown, Connecticut. 223 pp.

Lau, M. K. 2013. DTK: Dunnett-Tukey-Kramer Pairwise Multiple Comparison Test Adjusted for Unequal Variances and Unequal Sample Sizes. R package version 3.5. http://CRAN.R-project.org/package=DTK. Accessed January 12, 2014.

Lothner, D. C., R. M. Marden, and E. Kallio. 1974. Weight-volume relationships of aspen and winter-cut black spruce pulpwood in Northern Minnesota. Research Note NC-174. USDA Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota. 5 pp.

Marden, R. M., D. C. Lothner, and E. Kallio. 1975. Wood and bark percentages and moisture contents of Minnesota pulpwood species. Research Paper. NC-114. USDA Forest Service, North Central Forest Experiment Station, Saint Paul, Minnesota. 9 pp.

Markstrom, D. C. and R. M. King. 1993. Cubic foot/weight scaling of Rocky Mountain area sawtimber. Technical Report RM-311. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 9 pp.

Meyer, H. A. 1946. Bark volume determination in trees. *J. Forestry* 44(12):1067–1070.

Morgan, T. A., C. E. Keegan III, T. P. Spoelma, T. Dillon, A. L. Hearst, F. G. Wagner, and L. T. DeBlander. 2001. Idaho's forest products industry: A descriptive analysis. Resource Bulletin. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. 31 pp.

Murphy, G. E. and S. J. Pilkerton. 2011. Seasonal impacts of bark loss on simulated payloads, bark delivery, and transport costs for freshly harvested logs. *Forest Prod. J*. 61(1):71–76.

Murphy, M. A., J. S. Evans, and A. S. Storfer. 2009. Quantifying Bufoboreas connectivity in Yellowstone National Park with landscape genetics. *Ecology* 91:252–261.

Nakagawa, S. and H. Schielzeth. 2013. A general and simple method for obtaining R^2 from generalized linear mixed-effects models. *Methods Ecol. Evol*. 4:133–142.

O'Hara, K. L., P. A. Latham, P. Hessburg, and B. G. Smith. 1996. A structural classification for inland Northwest forest vegetation. *West. J. Appl. Forestry* 11:97–102.

O'Laughlin, J. 2012. Idaho forests by the numbers. www.cnrhome.uidaho.edu/pag/. Accessed May 8, 2014.

Page, R. H. and P. J. Bois. 1961. Buying and selling Southern yellow pine sawlogs by weight. Report no. 7. Georgia Forest Research Council, Macon. 8 pp.

Patterson, D. W. and P. F. Doruska. 2005. Effect of seasonality on bulk density, moisture content, and specific gravity of loblolly pine tree-length pulpwood logs in southern Arkansas. *Forest Prod. J*. 55(12):205–209.

Patterson, D. W. and H. V. Wiant, Jr. 1993. Relationship of position in tree to bulk density of logs whose volumes were measured by weighting while immersed. *Forest Prod. J*. 43(4):75–77.

Philip, M. S. 1994. Measuring Trees and Forests. 2nd ed. CAB International, Wallingford, Oxfordshire, UK. 310 pp.

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. ISBN 3-900051-07-0. www.R-project.org/. Accessed February 3, 2013

Row, C. and S. Guttenberg. 1966. Determining weight-volume relationships for sawlogs. *J. Forest Prod*. 16(5):39–47.

Royston, P. 1982. An extension of Shapiro and Wilk's W test for normality to large samples. *Appl. Stat*. 31:115–124.

Saralecos, J. D., R. F. Keefe, R. H. Brooks, W. T. Tinkham, A.M. S. Smith, and L. R. Johnson. 2014. Effects of harvesting systems and bole moisture loss on weight scaling of Douglas-fir sawlogs (*Pseudotsuga menziesii*). *Forests* 5:2289–2306.

Schumacher, F. X. 1946. Volume-weight ratios of pine logs in the Virginia-North Carolina coastal plain. *J. Forestry* 44:583–586.

Siau, J. F. 1984. Transport Processes in Wood. Springer, Berlin. 245 pp.

Sollins, P., S. P. Cline, T. Verhoeven, D. Sachs, and G. Spycher. 1987. Patterns of log decay in old-growth Douglas-fir forests. *Can. J. Forest Res*. 17:1585–1595.

Taras, M. A. 1956. Buying pulpwood by weight as compared with

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

volume measure. OSP-074. USDA Forest Service, Southeastern Forest Experiment Station, Ashville, North Carolina. 11 pp.

Tinkham, W. T., C. Hoffman, M. J. Falkowski, A. M. S. Smith, T. E. Link, and H. P. Marshall. 2013. A methodology to spatially characterize vertical accuracies in LiDAR-derived products. *Photogramm. Eng. Remote Sens*. 79(8):709–716.

Tinkham, W. T., A. M. S. Smith, T. E. Link, H. P. Marshall, M. J. Falkowski, and A. Winstral. 2014. Quantifying spatial distribution of snow depth errors from LiDAR using Random Forests. *Remote Sens. Environ*. 141:105–115.

US Department of Agriculture–National Resources Conservation Service (USDA-NRCS). 2013. SNOTEL and snow survey & water supply forecasting. USDA-NRCS. 2 pp. www.wcc.nrcs.usda.gov/snotel/SNOTEL-brochure.pdf. Accessed May 7, 2014.

Van Deusen, P., W. F. Watson, and J. Evans. 1981. Predicting board foot volume from the weight of a load of logs. Technical Bulletin 108. Mississippi Agricultural and Forestry Experiment Station. 14 pp.

Via, B. K. and T. F. Shupe. 2005. Relationship of species and season to sawmill by-product production: A case study. *Forest Prod. J*. 55(7/8):35–41.

Whitlock, C. and P. J. Bartlein. 1993. Spatial variations of Holocene climate change in the Yellowstone region. *Quaternary Res*. 39:231–238.

Yerkes, V. P. 1966. Weight and cubic-foot relationships for Black Hills ponderosa pine sawlogs. Research Note RM-78. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 4 pp.

Yerkes, V. P. 1967. Effect of seasonal stem moisture variation and log storage on weight of Black Hills ponderosa pine. Research Note RM-96. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 8 pp.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26