Estimating felled-tree stump volumes in the Pacific Northwest

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Introduction

Pacific Northwest forest land managers seek estimates of post-harvest woody residues to meet a variety of land management objectives, including characterizing woody biomass, life cycle analyses, and carbon accounting. Stumps of felled trees can be a significant source of woody biomass remaining in forest stands after timber harvest. Land managers need the ability to accurately estimate stump volumes and biomass with the use of standard inventory variables, such as diameter breast height (DBH).

National biomass component ratio protocols (Woodall et al. 2011) specify the use of the Raile (1983) taper functions to estimate stump diameters and cubic volume (above ground) based on tree DBH and stump height. Woodall et al. (2011) provide species-specific parameters for use with the Raile equations, including Douglas-fir, the most commonly harvested species in the Pacific Northwest. The Raile taper function have been shown to be highly accurate for estimating the volume and diameter of eastern U.S. hardwood and conifer stumps (Barker 2017). However, little is known of the accuracy of the Raile equations for characterizing western U.S. Douglas-fir stump diameters and volumes. Western taper functions may prove superior to Raile for estimating these attributes.

Objective: Identify an existing DBH-based taper function that accurately estimates young-growth Douglas-fir above-ground stump volumes outside bark in the Pacific Northwest.

Methods

Overall approach. We compared above ground stump volumes computed with three different taper functions with "*true*" stump volumes, calculated with Douglas-fir stump diameters and heights and estimated ground-level diameters measured by the University of Montana's Bureau of Business and Economic Research (BBER).

Sampling. The BBER's logging utilization research (see Simmons et al. 2014 and 2016) provided records of 1,481 second and third-growth green Douglas-fir felled trees measured 2011-2013 within 110 commercial logging sites (generally 15 to 29 Douglas-fir trees per site) in Idaho, Montana, Oregon, and Washington. Individual tree measurements included outside bark felled-tree stump height and diameter and tree DBH.

Estimating ground-level stump diameters. Accurate estimates of ground-level stump diameters were needed for all sampled trees to calculate "true" stump volumes. Three DBH-based taper functions were evaluated as ground-level stump diameter estimators against field-measured diameters of 43 Douglas-fir stumps ranging 0.0 to 0.2 feet in height. We assumed if a taper function could accurately predict diameters for these short stumps it could also accurately predict diameters at ground level. Lin's (1989) concordance correlation coefficient was used to gauge taper equation estimation accuracy. The three DBH-based taper functions included Raile and two functions developed for western North America sites:

- **Raile** (1983): $d = \beta DBH + \beta DBH * (4.5-h)/(h+1)$; Douglas-fir coefficient = 0.12667. Developed for northeastern U.S. stump diameter and volume estimation; coefficients provided by Woodall et al. (2011) for all U.S. tree species.
- **Demaerschalk and Omule** (1982): $d = DBH/(1 + \beta * \ln((h + 1)/2.3)))$; Douglas-fir coefficient = 0.275603 for coastal sites, 0.267082 for sites east of the Cascades. This equation was parameterized in metric units to predict DBH using stump diameter and was intended for use with timber trespass applications; we modified the equation to predict stump diameter based on DBH in English units. This function was developed for young-growth Douglas-fir in British Columbia.
- **Wensel and Olson** (1995): $d = DBH * e^{\beta(4.5--h)}$; Douglas-fir coefficient = 0.04302. This is a below DBH taper function developed for Douglas-fir in northern California.
- Note- β = Douglas-fir coefficient; d = stump diameter outside bark; *e* = exponential function; h = stump height of interest; ln = natural logarithm.

Estimating stump volumes from the taper functions. The three taper functions were also used to estimate cubic volumes of stumps by integrating the functions using the standard solid of revolution procedure:

$$\text{Cubic foot volume} = 0.005454 \times \int_0^h t^2 \, dh$$

Note- t^2 above refers to the taper equation squared.

Calculating "true" stump volumes. Volumes were computed with Smalian's formula using field-measured diameters and heights, and ground-level diameters provided by the "best" taper function. These "true" volumes were assumed to be accurate and the standard by which integrated taper function volumes would be judged.

Evaluating the accuracy of three taper equations as stump volume estimators. Using the 1,481 sample tree measurements, integrated taper equation volumes were regressed against the calculated "true" volumes using a multilevel linear mixed model (trees nested within logging sites within each of four Pacific Northwest sub-regions) with SAS PROC MIXED (SAS 2013).

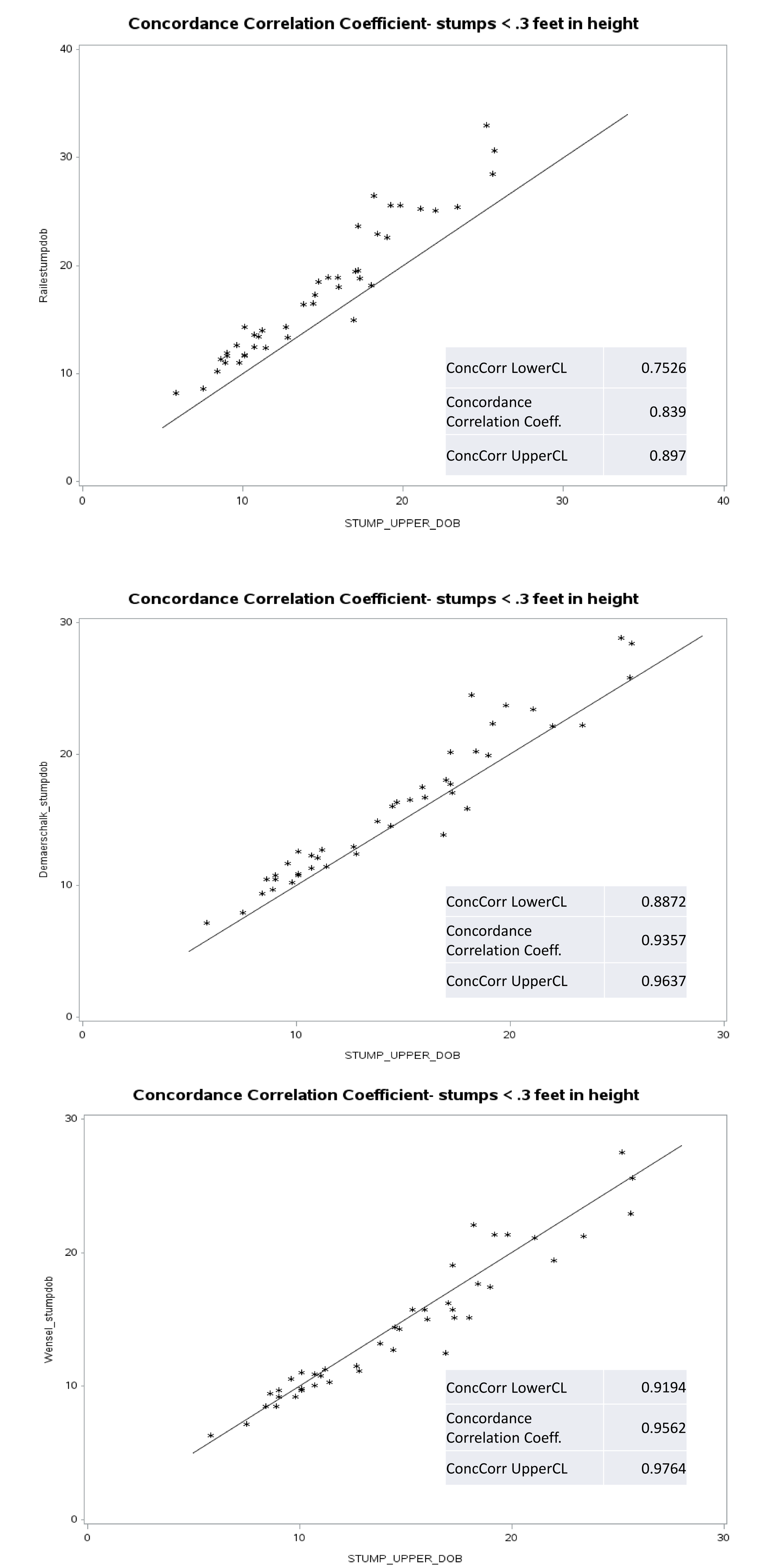

Figure 1. Concordance coefficients and 95 percent confidence limits (see text inserts within the figures) for taper curve predicted diameters vs. measured diameters (in inches) (STUMP_UPPER_DOB) of 43 Douglas-fir stumps 0.0 to 0.2 feet in height. The Wensel and Olson coefficient was highest, 0.9562, and therefor judged to best estimate ground-level diameters.

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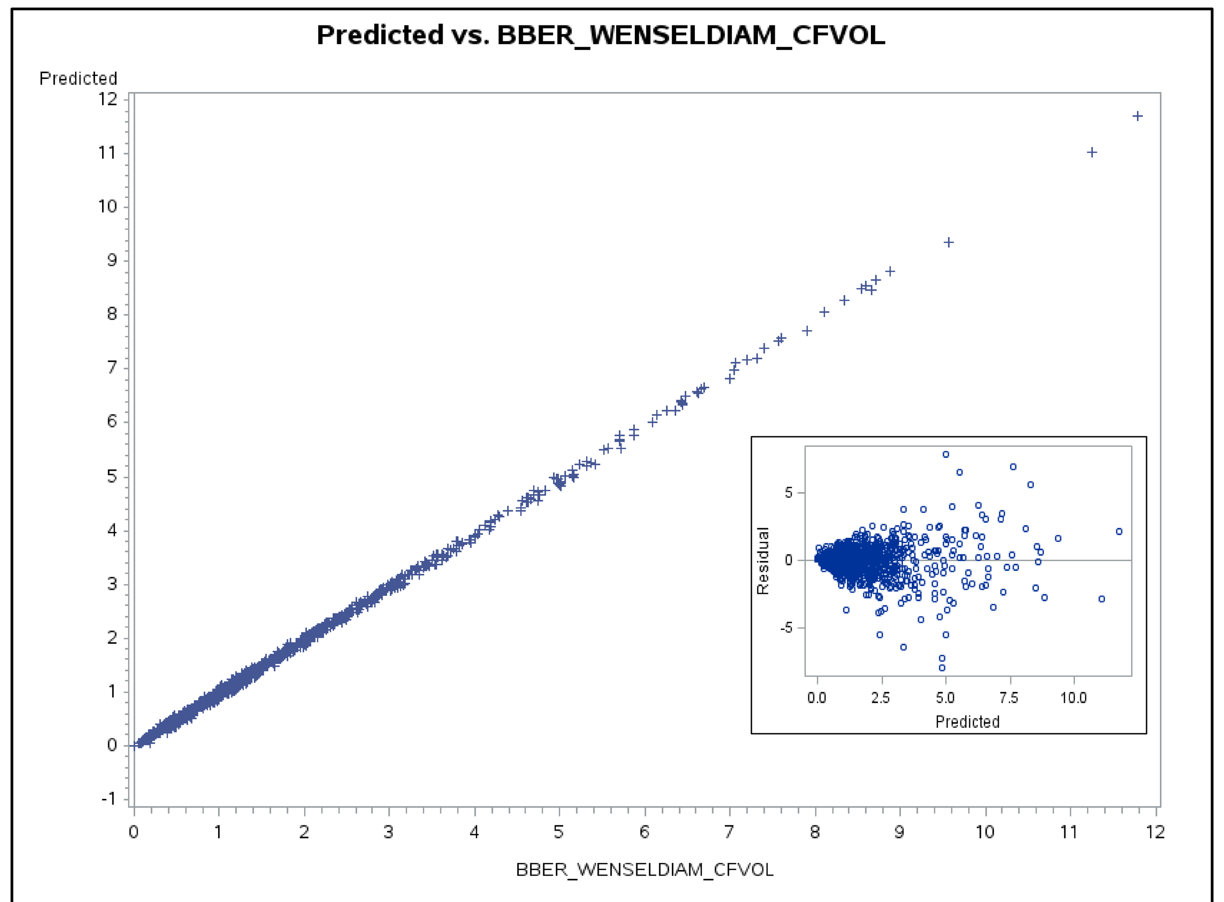

Figure 2. Plot of the PROC MIXED predicted Wensel and Olson cf volumes vs. the "true" volumes (BBER_WENSELDIAM_CFVOL). The residuals plot is provided as an inset.

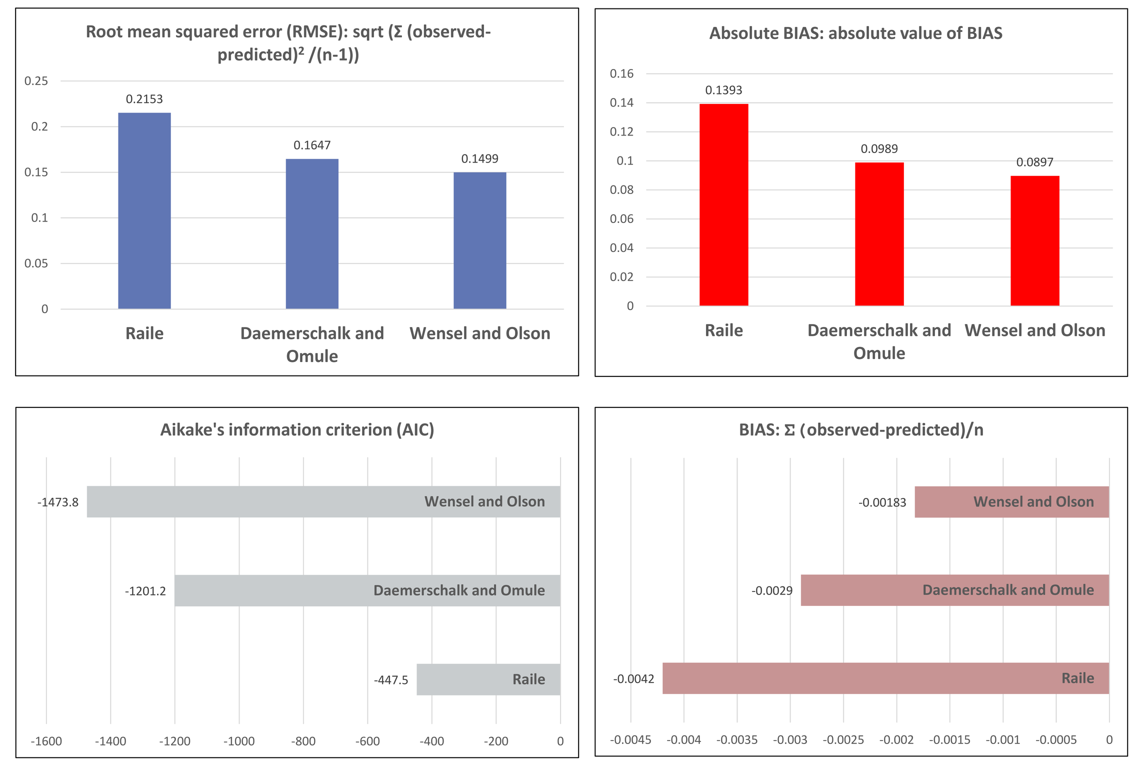

Figure 3. Model validation metrics for integrated taper equation volumes versus "true" volumes; calculated with PROC MIXED regression outputs. Smaller values (to avoid confusion- this refers to further into the negative range for AIC and a smaller bias number) for all metrics indicate superior model accuracy. The Wensel and Olson function rated best for all measures.

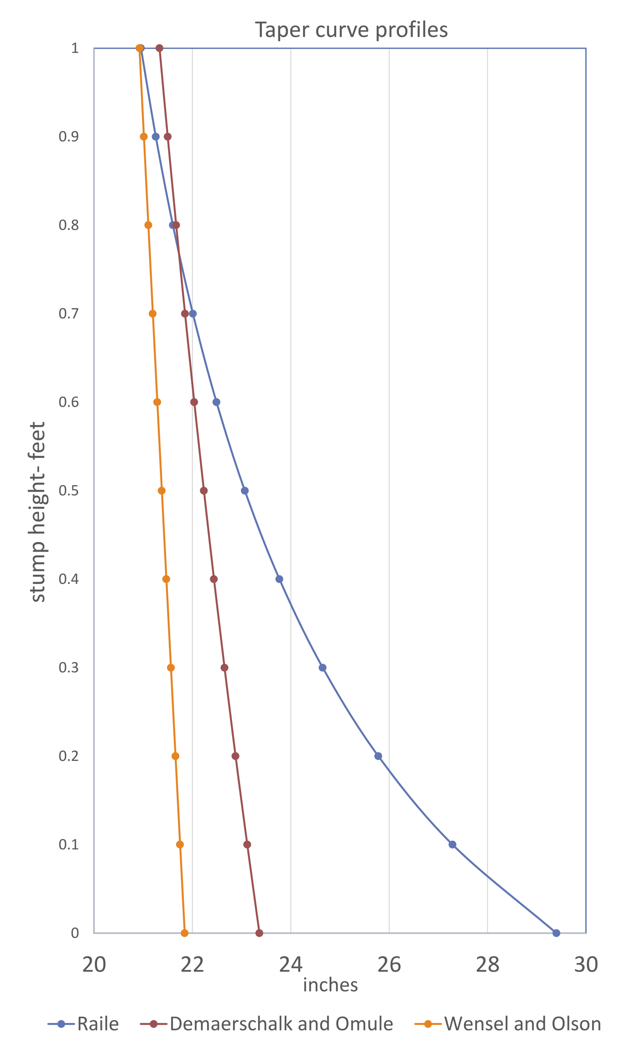

Figure 4. Taper curve profiles for an 18.0 inch DBH Douglas-fir tree section below 1.0 foot in height.

Stump height- feet	Integrand	10.0 inch DBH Doug-fir stump cf volume
0.0	0.000	0.00
0.1	0.147	0.08
0.2	0.292	0.16
0.3	0.436	0.24
0.4	0.579	0.32
0.5	0.721	0.39
0.6	0.861	0.47
0.7	1.001	0.55
0.8	1.139	0.62
0.9	1.276	0.70
1.0	1.411	0.77

Table 1. Examples of outside bark stump volume calculations using integrands derived from the Wensel and Olson taper function. Users can multiply basal area at DBH by the integrands to obtain cubic foot volume at desired stump heights. Example values are provided for a 10.0 inch DBH Douglas-fir.

Results and Discussion

Ground-level stump diameter estimates. The Wensel and Olson equation provided superior estimates of ground-level diameters with the highest concordance correlation coefficient of 0.9562 (figure 1). These estimated ground-level diameters were used with measured stump attributes to calculate "true" stump volumes.

Stump volume estimates. All integrated taper function stump volumes were strongly related to the measured "true" volumes in PROC MIXED multilevel regressions (figure 2, the Wensel and Olson function serving as an example, all functions displayed similar plots).

All accuracy measures - Aikake's Information Criteria, (AIC), root mean squared error (RMSE), bias, and absolute bias - demonstrated that the integrated Wensel and Olson equation was the most accurate estimator of Douglas-fir above ground stump volumes among the three taper functions (figure 3).

The residuals plot for the predicted Wensel and Olson vs. "true" volumes regression displayed moderate heteroscedasticity (figure 2 inset). Variables were not transformed to account for this.

Estimated volume differences among the three equations are directly related to taper function curve profiles (figure 4). The Raile function's profile flares strongly towards ground-level, so stump volumes increase substantially as stump height drops. For example, the Raile calculated volume of a 0.5 foot tall stump for an 18.0 inch DBH Douglas-fir is 1.83 cf, Demaerschalk and Omule is 1.42 cf and Wensel and Olson calculated volume is 1.27 cf.

This analysis did not account for irregular stump shapes or stump volume downhill below ground level on steep slopes.

Application

Recommended taper function. The Wensel and Olson function can be used to accurately predict outside bark volumes of young-growth Douglas-fir stumps in the Pacific Northwest.

Calculating stump volumes. Above ground cubic foot volume of stumps can be calculated by multiplying the Wensel and Olson integrands (table 1) by basal area at tree DBH. Example volumes have been calculated for stumps varying from 0.0 to 1.0 feet in height for a 10.0 inch DBH Douglas-fir tree (table 1). Basal areas of Douglas-fir trees of any DBH can be used with these same integrands to calculate stump volume. The authors can provide integrands for any stump height of interest.

Estimating stump biomass and carbon content. Land managers can apply models and coefficients found in Woodall et al. (2011) to the Wensel and Olson volumes to estimate biomass and carbon content of the stump's bark and wood components.

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