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Controlling coarse woody debris inventory quality: taper and relative size methods

C.W. Woodall and J.A. Westfall

Abstract: Accurately measuring the dimensions of coarse woody debris (CWD) is critical for ensuring the quality of CWD estimates and, hence, for accurately estimating forest ecosystem attributes (e.g., CWD carbon stocks). To improve the quality of CWD dimensional measurements, the distribution of taper (ratio of change in diameter and length) and relative size (RS; ratio of length and large-end diameter) of CWD pieces across the US were examined. Additionally, an outlier identification technique was developed by predicting the median and interquartile range of taper and RS as a function of large-end diameter, length, and decay class by major species group. The median CWD taper and RS across the US were 1.268 cm/m and 0.280 m/cm, respectively, with notable outliers. The taper and RS outlier identification protocol rapidly identified nearly 3% of study observations as outliers. Incorporation of CWD taper and RS outlier identification protocols into field data recorders may allow efficient control of measurement errors during field inventories.

Résumé : Il est crucial de mesurer avec précision les dimensions des débris ligneux grossiers (DLG) pour s'assurer de la qualité des estimations des DLG et, par conséquent, estimer avec précision les attributs des écosystèmes forestiers (p. ex. les stocks de carbone emmagasinés dans les DLG). Pour améliorer la mesure des dimensions des DLG, la distribution du défilement (rapport du changement entre le diamètre et la longueur) et la dimension relative des DLG (rapport entre la longueur et le diamètre au gros bout) des pièces de DLG ont été étudiées à travers les États-Unis. De plus, une technique d'identification des observations aberrantes a été développée en prédisant la médiane et l'étendue de l'interquartile du défilement et de la dimension relative en fonction du diamètre au gros bout, de la longueur et de la classe de décomposition par groupe des principales espèces. Les valeurs médianes du défilement et de la dimension relative des DLG à travers les États-Unis étaient respectivement de 1,268 cm/m et 0,280 m/cm et il y avait des observations aberrantes notables. Le protocole d'identification des valeurs aberrantes de défilement et de dimension relative a identifié près de 3 % de valeurs aberrantes parmi les observations qui faisaient partie de l'étude. L'incorporation de protocoles d'identification des valeurs aberrantes de défilement et de dimension relative des DLG dans les enregistreurs de données de terrain peut permettre d'effectuer un contrôle efficace des erreurs de mesure lors des relevés sur le terrain.

[Traduit par la Rédaction]

Introduction

Coarse woody debris (CWD) is a component of forest detritus typically defined as downed and dead woody debris of a certain minimum size. Accurate estimates of CWD resources are critical to numerous scientific fields, such as carbon accounting (Smith et al. 2004), wildlife habitat assessment (Maser et al. 1979; Harmon et al. 1986; Bull et al. 1997), and fuel loading estimation (Woodall et al. 2004). As evidence of such, CWD is now inventoried as a standard component of forest inventories around the world (see Kukuev et al. 1997; Fridman and Walheim 2000; Woldendorp et al. 2002). Thus, accurately measuring the dimensions of CWD pieces and estimating their attributes, such as volume, are essential.

Large-area inventories of CWD resources often require numerous field crews operating in diverse forest conditions. Consequently, minimizing measurement errors and ensuring data quality is a difficult task. If left unchecked, simple data entry errors can turn a relatively small CWD piece (large-end diameter of 10 cm) into a relatively large piece (large-end diameter of 100 cm). These errors can be further propagated during inventory analyses or reporting through application of population estimators such as CWD unit volume or area estimators (for examples of estimation procedures, see Van Wagner 1982; De Vries 1986). Development of efficient data quality control techniques for CWD inventories is crucial for obtaining unbiased estimates of CWD attributes.

Taper for standing trees typically is defined as the change in bole diameter along a defined length of the bole (Martin

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C.W. Woodall.[1] USDA Forest Service, Northern Research Station, St. Paul, MN 55108, USA.
J.A. Westfall. USDA Forest Service, Northern Research Station, Newtown Square, PA 19073, USA.

[1]Corresponding author (e-mail: cwoodall@fs.fed.us).

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Table 1. Order statistics for coarse woody debris taper and relative size (RS) across the US, 2001–2005.

Percentile	Taper	RS
100 (maximum)	102.778	6.720
99	10.417	1.008
95	4.545	0.700
90	3.333	0.600
75 (Q3)	2.083	0.429
50 (median)	1.268	0.280
25 (Q1)	0.758	0.160
10	0.000	0.100
5	0.000	0.074
1	0.000	0.040
0 (minimum)	0.000	0.004
IQR (Q3 – Q1)*	1.325	0.269

*IQR, interquartile range; Q1, quartile 1; Q3, quartile 3.

1981; Newnham 1991). Taper models for standing trees have been used primarily for improving volume estimation accuracy. Because taper is based on the three CWD dimensions often measured during resource inventories (small- and large-end diameters, total length), developing appropriate thresholds for reasonable CWD taper may be one method to control CWD inventory data quality. Few studies have explicitly examined CWD taper. Recently, Fraver et al. (2007) examined the suitability of numerous volume models for CWD application but did not examine taper across decay classes. Although establishing taper criteria may identify most suspect CWD diameter measurements, instances may arise where both small- and large-end diameters are valid, but length may be in error (too long). In such instances taper will be small but most likely within acceptable thresholds. Another metric for identifying CWD length measurement errors in particular, relative size (RS), is proposed as the ratio of total length and large-end diameter. Large values of RS may indicate a value for CWD length that is suspect. Given the possibility of using CWD dimensional metrics to improve the quality of CWD inventories, the goal of this study was to assess CWD taper and RS attributes for US' downed and dead tree species. Specific objectives were (*i*) to determine summary statistics for CWD taper and RS for CWD pieces both by individual observations and by CWD large-end diameter class, length class, decay class, and species group; (*ii*) to develop taper and RS outlier identification protocols by developing taper and RS median and interquartile range (IQR) models as a function of large-end diameter, length, and decay class by species group; and (*iii*) to suggest opportunities to apply study results to field data collection techniques.

Methods

A national inventory of coarse woody debris

As defined by the USDA Forest Service's Forest Inventory and Analysis (FIA) program, CWD are down logs with a transect diameter ≥7.62 cm and a length ≥0.91 m (Woodall and Monleon 2008). CWD is sampled during the third phase of FIA's multiscale inventory program (USDA Forest Service 2005; Woodall and Monleon 2008) using transects radiating from each FIA subplot center (four subplots on each inventory plot). Each subplot has three 7.32 m transects, totaling 87.8 m for a fully forested inventory plot. The following information is collected for every CWD piece intersected by transects: transect diameter, total length (L, m), small-end diameter (D_s, cm), large-end diameter (D_l, cm), decay class (DC), species, and presence of cavities. Transect diameter is the diameter of a down woody piece at the point of intersection with a sampling transect. Decay class is determined by visual estimate of the amount of decay present in an individual log (Maser et al. 1979; Sollins 1982). Decay class one is the least decayed (freshly fallen log), and decay class five is an extremely decayed log (cubicle rot pile). The species of each fallen log is identified through determination of species-specific bark, branching, bud, and wood composition attributes (excluding decay class five).

The study data set consisted of individual CWD piece measurements collected by the FIA program across the US from 2001 to 2005 with 34 386 observations and 190 individual tree species (because species is not recorded for decay class five CWD pieces, the study dataset had less observations for species-specific analyses).

Analysis

For this study, the taper of CWD pieces (T_{cwd}) was defined as

$$[1] \qquad T_{cwd} = \frac{D_l - D_s}{L}$$

and the RS of CWD pieces (RS_{cwd}) was defined as

$$[2] \qquad RS_{cwd} = \frac{L}{D_l}$$

CWD pieces were assigned to species groups based on individual species: spruce–fir–cedar (*Abies* spp., *Picea* spp., *Thuja* spp.), pine (*Pinus* spp.), birch (*Betula* spp.), oak–hickory (*Quercus* spp., *Carya* spp.), and other hardwoods or softwoods (remaining hardwood and softwood species). Taper and RS distributions were also summarized via the median and IQR by classes of D_l, L, and DC. Statistical tests of differences in medians (Dwass, Steel, Critchlow, and Fligner method; for example see Hollander and Wolfe 1999) for CWD T and RS were conducted among classes of species, D_l, L, and DC. These tests indicated that a large proportion of the pairwise comparisons exhibited significant differences at the 95% confidence level. This provided evidence of correlations for D_l, L, and DC with the variables of interest: T and RS.

Based on these initial results, a modeling process was used to determine T and RS outliers. Because of the presence of outliers, least absolute value regression (SAS Institute Inc. 2003) was used to fit the median response. Observed relationships in the data resulted in the following model specification:

$$[3] \qquad \widehat{T}_{cwd} = \widehat{\beta}_0 + \widehat{\beta}_1 D_l + \frac{\widehat{\beta}_2}{L} + \widehat{\beta}_3 \mathrm{DC} + \widehat{\beta}_4 D_l \mathrm{DC} + \widehat{\beta}_5 \frac{D}{L}$$

where $\widehat{T}_{cwd}$ is the predicted median taper (cm/m) for CWD with DC, $\widehat{\beta}_0 - \widehat{\beta}_5$ are estimated from the data, and the other variables are as previously defined.

Fig. 1. Histogram of taper for coarse woody debris pieces across the US, 2001–2005.

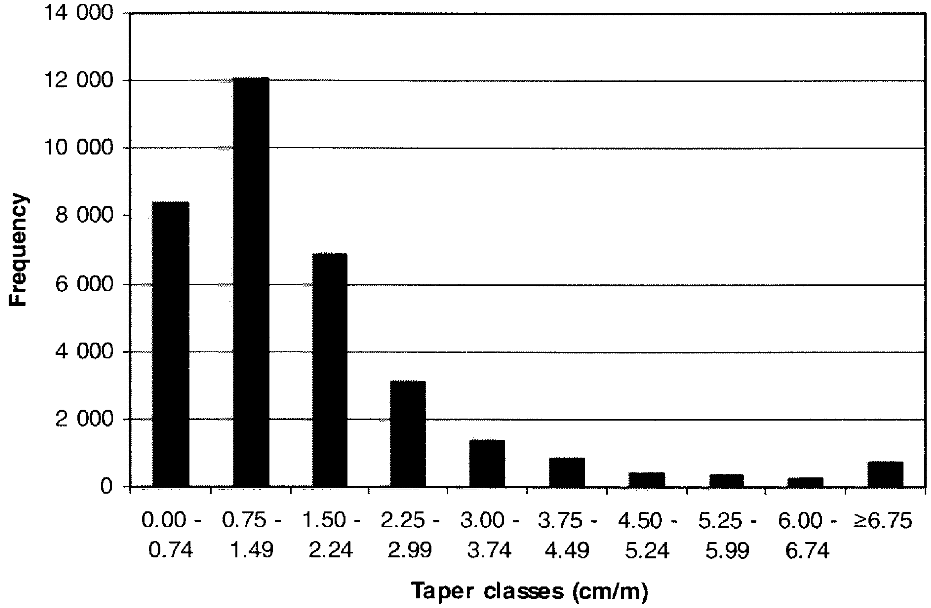


Table 2. Median and interquartile range (IQR) for coarse woody debris taper and RS by large-end diameter, length, decay class, and species group across the US, 2001–2005.

Variable and class	*n*	Median taper (cm/m)	IQR	Median RS (m/cm)	IQR
Large-end diameter (cm)					
<10.0	1 967	0.000	0.000	0.240	0.200
10.0–19.9	18 484	1.111	0.972	0.280	0.264
20.0–29.9	8 285	1.449	1.212	0.312	0.287
30.0–39.9	3 188	1.802	1.528	0.280	0.270
40.0–49.9	1 087	1.970	1.510	0.240	0.249
≥50.0	1 375	2.724	3.750	0.152	0.212
Length (m)					
<3.0	10 423	1.667	2.778	0.140	0.084
3.0–5.9	9 989	1.316	1.326	0.270	0.160
6.0–8.9	9 486	1.190	0.928	0.410	0.411
9.0–11.9	3 478	1.111	0.885	0.467	0.240
12.0–14.9	2 057	1.111	0.803	0.533	0.275
≥15.0	2 431	1.144	0.796	0.567	0.303
Decay class					
1	2 519	1.250	1.045	0.360	0.304
2	8 010	1.190	1.094	0.320	0.280
3	14 543	1.250	1.326	0.280	0.259
4	9 314	1.389	1.590	0.216	0.240
Species groups					
Spruce–fir–cedar	2 857	1.149	0.952	0.355	0.281
Pine	6 127	1.190	1.236	0.312	0.329
Oak–hickory	3 211	1.515	1.418	0.264	0.214
Birch	1 076	1.087	1.071	0.249	0.234
Other softwoods	8 628	1.389	1.459	0.240	0.261
Other hardwoods	12 290	1.226	1.245	0.277	0.249

Similarly, the relationship between RS and the predictor variables was described by:

$$[4] \qquad \widehat{\mathrm{RS}}_{\mathrm{cwd}} = \widehat{\beta}_0 + \frac{\widehat{\beta}_1}{D_1} + \widehat{\beta}_2 L + \widehat{\beta}_3 \mathrm{DC} + \widehat{\beta}_4 \frac{\mathrm{DC}}{D_1} + \widehat{\beta}_5 \mathrm{DC}L$$

where $\widehat{\mathrm{RS}}_{\mathrm{cwd}}$ is the predicted median RS (m/cm) for CWD and the other variables are as previously defined.

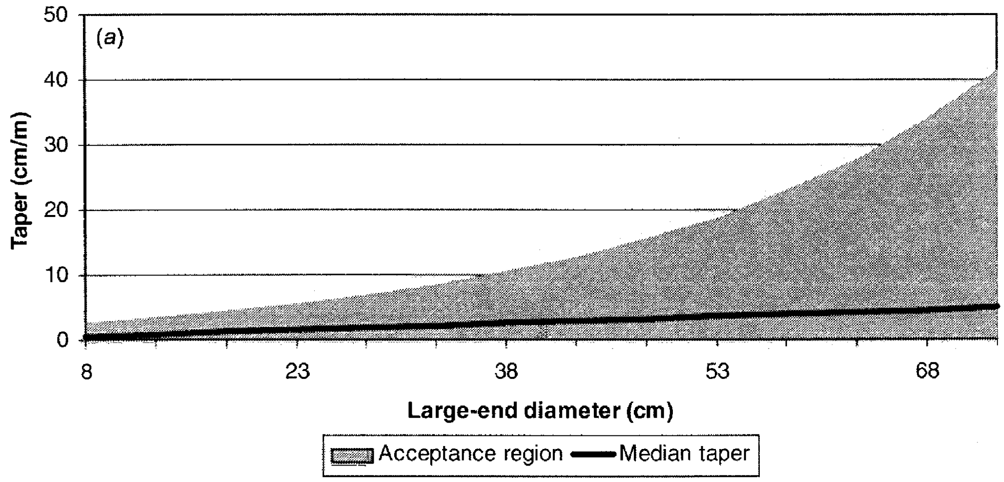
To account for heterogeneous IQR (i.e., variability), the residuals (observed – predicted) from eqs. 3 and 4 were sorted by their predicted values ($\widehat{T}_{\mathrm{cwd}}$ and $\widehat{\mathrm{RS}}_{\mathrm{cwd}}$, respectively) and placed into classes of 100 observations each. For each class, we computed the IQR of the residuals and

Table 3. Parameter estimates for eqs. 3–6.

Model and species group	β_0	β_1	β_2	β_3	β_4	β_5	θ_0	θ_1
Taper model (eqs. 3 and 5)								
Spruce–fir–cedar	–0.3634*	0.0614*	2.3422*	0.0252	–0.0024*	–0.1204*	–0.6344*	0.3372*
Pine	–0.0498	0.0383*	1.9807*	–0.1110*	0.0060*	0.0977*	—	0.2826*
Oak–hickory	–0.4203*	0.0712*	2.1701*	–0.0112	0.0011*	—	—	0.1397*
Birch	–0.3278*	0.0590*	1.8740*	–0.0700*	0.0040*	—	–0.7068*	0.6545*
Other softwoods	0.0862*	0.0455*	1.7045*	–0.0666*	—	0.1015*	—	0.2681*
Other hardwoods	–0.7028*	0.0793*	2.4209*	0.0628*	–0.0032*	–0.0906*	–0.1584*	0.2036*
RS model (eqs. 4 and 6)								
Spruce–fir–cedar	–0.2510*	6.1428*	0.0384*	0.0079	–0.5578*	0.0034*	–2.9032*	1.9406*
Pine	–0.2796*	5.0398*	0.0531*	0.0357*	–0.4706*	–0.0028*	–2.5313*	1.4589*
Oak–hickory	–0.1489*	3.3918*	0.0439*	0.0055	–0.1454*	—	–2.5371*	1.3322*
Birch	–0.2418*	3.9959*	0.0570*	0.0221*	–0.3531*	—	–3.4454*	2.3960*
Other softwoods	–0.1748*	4.2206*	0.0441*	0.0203*	–0.3802*	–0.0027*	–2.6875*	1.7280*
Other hardwoods	–0.1860*	4.1127*	0.0420*	0.0076*	–0.3158*	0.00257*	–2.9097*	1.7353*

Note: Values with asterisks are significant at 95% confidence level. Values without asterisks were the retained intercept or main effect in a significant interaction.

Fig. 2. Predicted medians and acceptance regions for CWD taper (A) and RS (B) by large-end diameter (length, 4 m; decay class, 2; species group, birch) derived from eqs. 3–6 (Table 3). Note that taper cannot be less than zero; therefore, the lower bound is set to zero when computed value is less than zero.



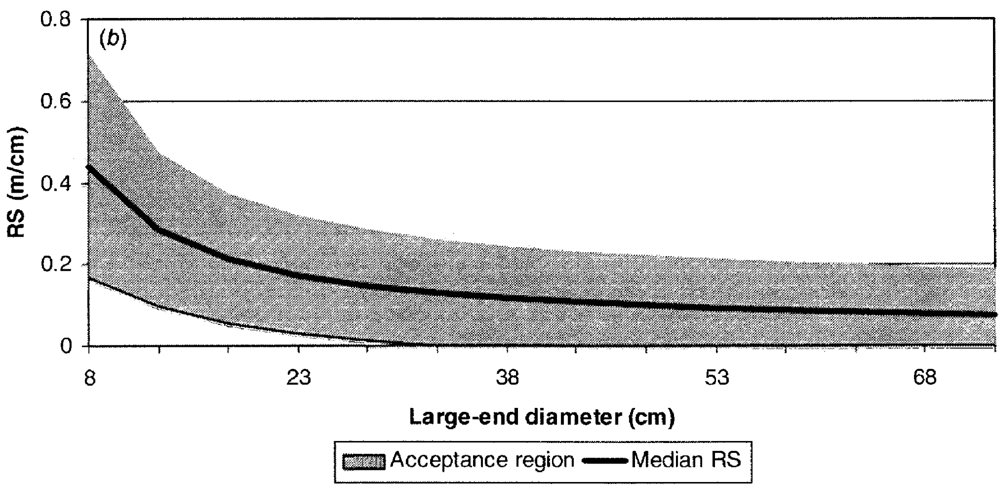


Table 4. Summary of potential CWD outliers by species group and detection source.

Species group and model	Observed (n)	Outliers (n)	Outliers (% of species group)
Spruce–fir–cedar			
RS	2 857	65	2.28
Taper	2 857	67	2.35
Taper and RS*	2 857	27	0.95
Pine			
RS	6 127	74	1.21
Taper	6 127	23	0.38
Taper and RS	6 127	5	0.08
Oak–hickory			
RS	3 211	37	1.15
Taper	3 211	8	0.25
Taper and RS	3 211	5	0.16
Birch			
RS	1 076	22	2.04
Taper	1 076	74	6.88
Taper and RS	1 076	10	0.93
Other softwoods			
RS	8 628	129	1.50
Taper	8 628	55	0.64
Taper and RS	8 628	8	0.09
Other hardwoods			
RS	12 290	235	1.91
Taper	12 290	76	0.62
Taper and RS	12 290	29	0.24

*Observation was identified as being an outlier by both RS and taper models.

the mean predicted value. This data set was used to predict IQR as a function of the mean prediction using a nonlinear regression model:

$$[5]\quad \widehat{\mathrm{IQR}}_T = \exp(\widehat{\theta}_0 + \widehat{\theta}_1 \overline{\overline{T}}_{\mathrm{cwd}})$$

$$[6]\quad \widehat{\mathrm{IQR}}_{\mathrm{RS}} = \exp(\widehat{\theta}_0 + \widehat{\theta}_1 \overline{\overline{\mathrm{RS}}}_{\mathrm{cwd}})$$

where $\widehat{\theta}_0$ and $\widehat{\theta}_1$ are parameters estimated from the data.

Finally, the two models for each metric (eqs. 3 and 5 for T and eqs. 4 and 6 for RS) were used to identify outliers by defining an acceptance region for values of T_{cwd} and $\mathrm{RS}_{\mathrm{cwd}}$:

$$[7]\quad \widehat{T}_{\mathrm{upper}} = \widehat{T}_{\mathrm{cwd}} + 3 \times \widehat{\mathrm{IQR}}_T$$

$$[8]\quad \widehat{T}_{\mathrm{lower}} = \widehat{T}_{\mathrm{cwd}} - 3 \times \widehat{\mathrm{IQR}}_T$$

$$[9]\quad \widehat{\mathrm{RS}}_{\mathrm{upper}} = \widehat{\mathrm{RS}}_{\mathrm{cwd}} + 3 \times \widehat{\mathrm{IQR}}_{\mathrm{RS}}$$

$$[10]\quad \widehat{\mathrm{RS}}_{\mathrm{lower}} = \widehat{\mathrm{RS}}_{\mathrm{cwd}} - 3 \times \widehat{\mathrm{IQR}}_{\mathrm{RS}}$$

where $\widehat{T}_{\mathrm{upper}}$ and $\widehat{T}_{\mathrm{lower}}$ and $\widehat{\mathrm{RS}}_{\mathrm{upper}}$ and $\widehat{\mathrm{RS}}_{\mathrm{lower}}$ are upper and lower limits for the range of T_{cwd} and $\mathrm{RS}_{\mathrm{cwd}}$, respectively.

Results and discussion

For all CWD pieces, the mean and median T values were 1.733 and 1.268 cm/m, which indicated a positive skewing of the CWD taper distribution. Although T_{cwd} was found to be typically below 2 cm/m, there were large outliers as indicated by order statistics (Table 1) and a histogram of taper frequencies (Fig. 1). For all CWD pieces, the mean and median RSs were 0.327 and 0.280 m/cm, which indicated less skewing as compared with T. Order statistics indicated that both T and RS had notable outliers beyond the 99th percentile.

To build the T and RS outlier identification models, trends in T and RS median and IQR by D_{l}, L, species group, and DC were observed and tested for significant difference using pairwise tests. The median and IQR of T_{cwd} appeared to vary substantially by D_{l}. CWD pieces with a D_{l} >50.0 cm had a median T of 2.724 cm/m and a median RS of 0.152 m/cm (Table 2). It should be noted that the median and IQR of the smallest sized trees ($D_{\mathrm{l}} < 10.0$ cm) were 0.00 because the majority of these very small CWD pieces havd an identical D_{s} and D_{l}. Over 96% of the pairwise tests indicated that T and RS varied significantly among D_{l} classes. Both taper and RS varied by classes of length with the shortest pieces having the highest taper but lowest RS (90% of pairwise tests indicating significant difference). Median T and RS did not vary as strongly by DC (over 66% of pairwise tests significant), although freshly fallen CWD pieces (decay class one) had a median RS of 0.360 m/cm and highly decayed CWD pieces (decay class four) a median of 0.216 m/cm. Similar to DC results, median values of T and RS did not vary as substantially by species group (over 80% of pairwise tests significant), although oak–hickory had the highest median T (1.515 cm/m), and birch had the lowest mean T (1.087 cm/m).

Because of the significant differences in T and RS among classes of D_{l}, L, DC, and species, models were constructed for each species group to predict RS and T using models that utilized L, DC, and D_{l} as independent variables (Table 3). To develop a range of acceptable measurement values about model estimates of T and RS, IQR models were developed by species group (Table 3). Taper and RS field measurements outside these "acceptable" regions would be considered outliers (Figs. 2A and 2B). Using these outlier identification metrics individually, the taper model flagged 387 (1.14%) of study observations, and the RS criteria flagged 713 (2.08%) observations (Table 4). Additionally, 151 (0.44%) study observations were flagged by both the taper and RS outlier identification metrics. In a field-application scenario, if both the taper and RS metrics were used, then 2.78% of this study's observations would have been flagged as being outliers.

Although most CWD Ts and RSs appeared to be within reason, there were still a substantial number of improbable values in the study data set that were flagged by the outlier identification techniques (949 observations). It is unlikely that a CWD piece with a taper of 100 exists in reality. If such a CWD piece was 30 m long, it could have a D_{l} of approximately 2990 cm and a D_{s} of 10 cm. The presence of such outliers in a national data set demonstrates the need to rapidly "correct" these measurements in the field. Although the models to estimate bounds of reasonable CWD measurements are too cumbersome for hand calculation in the field, they may be programmed into commonly used digital field data recorders to enable rapid identification of data entry or measurement errors in the field.

Whereas the T and RS techniques are inherently better able to identify larger than expected measurements of CWD D_l and L, can this study's results detect D_s measurement errors or smaller than expected measurements for D_l and L? Firstly, data collection edit checks will not allow D_s measurements that exceed D_l, thus limiting the scale of measurement error. Indeed, if both D_s and D_l were incorrectly measured with an additional decimal place, the taper technique would most likely identify this mistake. Secondly, measurement errors resulting in a smaller measurement are most often caught by edit checks. A D_l cannot be smaller than a D_s. Furthermore, given that there are minimum thresholds in most CWD inventories for end-point diameters and length, the effect on population estimates is thought to be minimal.

Given that accurate estimates of CWD resources are essential to estimate forest ecosystem attributes, development of CWD inventory quality control techniques is paramount. Utilizing metrics of CWD dimensions, such as T and RS, may provide a rapid and efficient method for identifying CWD measurement or data entry errors during plot sampling. The economic costs of field crews verifying their measurements on <3% of inventoried CWD pieces are possibly less than the loss in inventory data utility resulting from incorrectly measured CWD pieces.

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