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End-point diameter and total length coarse woody debris models for the United States

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ABSTRACT

Coarse woody debris (CWD) may be defined as dead and down trees of a certain minimum size that are an important forest ecosystem component (e.g., wildlife habitat, carbon stocks, and fuels). Due to field efficiency concerns, some natural resource inventories only measure the attributes of CWD pieces at their point of intersection with a sampling transect (e.g., transect diameter) although measurements of large-end diameter, small-end diameter, and length are often required by natural resource managers. The goal of this study was to develop a system of empirical models that predict CWD dimensions (e.g., large-end diameter) based on CWD attributes measured at the point of intersection with a sample transect and ancillary data (e.g., ecological province). Results indicated that *R*-squared (R^2) values exceeded 0.60 for most of this study's CWD large-end diameter and small-end diameter with only fair results for the length models. The mean residuals of numerous CWD models were within the measurement tolerance expected of actual field crews. Despite remaining unexplained variation, these CWD models may provide foresters with an alternative to the time-consuming activity of measuring all CWD dimensional attributes of interest during large-scale forest inventories.

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1. Introduction

Coarse woody debris (CWD) is a component of forest detritus typically defined as downed and dead wood of a certain minimum size. Sampling methods and estimates of CWD resources are critical to numerous scientific fields such as carbon accounting (Smith et al., 2004), wildlife habitat assessment (for examples see Maser et al., 1979; Harmon et al., 1986; Bull et al., 1997), and fuel loading estimation (Van Wagner, 1968; Woodall et al., 2004; Lutes et al., 2006). CWD provides a diversity (stages of decay, size classes, and species) of habitat for fauna ranging from large mammals to invertebrates (Maser et al., 1979; Harmon et al., 1986; Bull et al., 1997). Plants use the microclimate of moisture, shade, and nutrients provided by CWD to establish and regenerate (Harmon et al., 1986). Due to the possibility of dwindling CWD habitat for native species and increasing fuel loadings across the United States, comprehensive large-scale inventories of CWD have been established for habitat assessments/wildlife conservation efforts and fire hazard mitigation efforts (for examples see Marshall et al., 2000; Ohmann and Waddell, 2002; Tietje et al., 2002; Rollins et al., 2004; Woodall and Monleon, 2008). Worldwide, there has been increased effort during past years to inventory CWD resources to address greenhouse gas offset accounting and biodiversity concerns (Kukuev et al., 1997; Woldendorp et al., 2004; Woodall et al., in press).

The method generally preferred for inventorying CWD resources during fuel assessments is to record the attributes of CWD at the point of intersection with a sampling transect (Ringvall and Stahl, 1999) (for examples see Van Wagner, 1968; Brown, 1971, 1974; Van Wagner and Wilson, 1976). Transect diameter (D_T), species, and decay class are attributes often recorded at the point of intersection (Brown, 1974). These transects have become so ubiquitous in assessments of fuel loadings that they are often referred to as "Brown's Transects" (for examples see Knapp et al., 2005; McIver and Ottmar, 2007).

The measurements of CWD intersection attributes allow accurate estimation of volume (Van Wagner and Wilson, 1976) and, subsequently, biomass and carbon. However, this widely used fuel sampling protocol does not include measurement of CWD end-point diameters and length. Estimates of coarse woody debris

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diameter distributions (small- or large-end diameter) and pieces per unit area are not possible without these measurements (see Table 1 in Marshall et al., 2000). These estimates are necessary for wildlife habitat assessments (for examples see Ohmann and Waddell, 2002; Tietje et al., 2002) and numerous forest management activities (Marshall and Davis, 2002). Given such wide use of CWD sample protocols that result in estimates of limited use to many wildlife and forest management efforts, development of models to predict CWD dimensions based on CWD transect intersection measurements is warranted. Therefore, the goal of this study was to develop a nationwide system of models, stratified by Bailey's ecological provinces (Bailey, 1995), to predict the small-end (D_S), large-end (D_L), and total length of CWD pieces based on variables measured at the point of intersection with a sampling transect (D_T, softwood/hardwood species classification, and decay class).

2. Methods

2.1. National inventory of coarse woody debris

The FIA program is responsible for inventorying the forests of the United States, including both standing trees and dead wood on permanent sample plots established across the United States using a three phase inventory (Bechtold and Patterson, 2005). During the inventory's first phase, sample plot locations are established at an intensity of approximately 1 plot per 2400 ha. If the plot lies partially or wholly within a forested area, field personnel will visit the site and establish a second phase inventory plot. FIA's second phase inventory plots consist of four 7.32-m fixed radius subplots for a total plot area of approximately 0.07 ha. All standing trees greater than 12.7-cm diameter at breast height (dbh) are inventoried on the plot, while trees less than 12.7-cm dbh are measured on a 2.07-m fixed radius microplot on each subplot.

During FIA's third phase, one of every 16 phase two plots are sampled for down woody materials including CWD. CWD pieces are defined as down woody debris in forested conditions with a diameter greater than 7.60 cm along a length of at least 1.3 m and a lean angle greater than 45° from vertical. Dead woody pieces with a lean angle less than 45° from vertical are considered standing dead trees (i.e., snags) and were not included in this study. CWD are sampled on each of three 7.32-m horizontal distance transects radiating from each FIA subplot center at azimuths of 30°, 150°, and 270°, totaling 87.8 m for a fully forested inventory plot. Data collected for every CWD piece include D_T, D_S, D_L, decay class (DC), length, and species. D_T is the diameter of a CWD piece measured perpendicular to its center longitudinal axis at the point of intersection with a sampling transect using a diameter tape. Length is defined as the total length of the CWD piece between the D_S and D_L measurements. DC is a subjective determination of the amount of decay present in an individual log. A DC of 1 is the least decayed (freshly fallen log), while a DC of 5 is an extremely decayed log (cubicle rot pile) (Sollins, 1982; Waddell, 2002). The species of each fallen log is identified through determination of species-specific bark, branching, bud, and wood composition attributes (excluding DC 5 pieces). CWD pieces with a DC of 5 are not measured for end point diameters in order to gain field efficiency. Based on this data limitation, pieces with a DC of 5 could not be included in the study's calibration or validation data sets. (For further details regarding FIA's inventory, please refer to USDA, 2005; Woodall and Monleon, 2008.)

2.2. Data

CWD data used to develop this study's models were from the Forest Service's FIA program. FIA has been tasked by the U.S. Congress to report on the current status and trends in U.S. Forest Resources (Frayer and Furnival, 1999; Gillespie, 1999). FIA initiated a nationwide inventory of CWD in 2001 (Woodall and Monleon, 2008). The model calibration data set included all of FIA's CWD measurements (excluding decay class 5 pieces) from 2001–2005; this data set exceeded 30,000 observations for 190 individual tree species in 44 states (Table 1a). The data for every CWD piece included D_T, D_S, D_L, length, DC, species, and Bailey's

Table 1a
Calibration data set description, forest inventory and analysis coarse woody debris data for the United States, 2001–2005

Province number(s)[a]	Description	Plots (*n*)	Species group	CWD pieces (*n*)	Mean small-end diameter (cm)	Mean large-end diameter (cm)	Mean total length (m)	Mean piece volume (m^3)
231, 234	Southeastern Mixed/Lower	379	Hwd	1199	9.80	18.20	5.44	0.50014
	Mississippi Riverine	315	Sftwd	1113	10.92	19.04	6.34	0.45631
251, 255	Midwest Prairie Parkland	135	All	530	10.74	19.97	5.04	0.26015
262, 313, 315, 321, 322	Western Dry Steppe/	51	Hwd.	133	9.55	17.78	4.81	0.12747
	Semi-Arid/Desert	111	Sftwd	351	11.49	22.41	4.72	0.2512
331, 334	Southern Rocky Mtn./Black Hills	77	Hwd	509	8.78	16.17	6.19	0.11924
		167	Sftwd	1079	10.34	23.50	8.12	0.36255
341, 342	Intermountain West	37	Hwd	254	9.52	16.60	5.22	0.13731
		131	Sftwd	522	10.71	22.80	5.94	0.30965
212	Northeastern Mixed/	634	Hwd	3476	11.24	18.70	5.21	0.36416
	Laurentian Mixed	435	Sftwd	2806	10.68	19.29	6.03	0.22796
221	Eastern Broadleaf (Oceanic)	442	Hwd	2658	11.12	22.04	6.21	0.86743
		142	Sftwd	513	11.54	21.60	7.34	1.18403
222	Eastern Broadleaf (Continental)	411	Hwd	2014	10.8	20.44	5.95	0.39212
		74	Sftwd	204	12.07	20.44	5.81	0.5161
232	Outer Coastal Plain Mixed	184	Hwd	611	11.46	21.46	5.49	0.50536
		176	Sftwd	503	12.33	21.08	5.49	0.67155
242	Pacific Northwest Coast Ranges	84	Hwd	319	11.36	18.04	5.11	0.21378
		327	Sftwd	4127	16.55	26.59	6.91	0.7122
261	West Coast Chaparral	110	Hwd	346	10.31	18.95	4.46	0.27227
		215	Sftwd	1294	16.51	27.80	6.48	0.81254
263	West Coast Steppe	209	Hwd	1264	10.25	19.09	7.55	0.24736
		125	Sftwd	1111	11.34	20.49	8.73	0.36341
332	Great Plains Steppe	43	Hwd	179	10.27	18.16	5.47	0.16098
		151	Sftwd	1670	11.61	22.16	8.08	0.35086
333	Northern Rocky Mtn. Steppe	113	All	1380	11.50	21.13	8.27	0.35509

[a] Inclusive of mountain provinces, "all" species group indicates insufficient sample size such that all species were included in the model fitting.

Table 1b
Validation data set description, forest inventory and analysis coarse woody debris data for the United States, 2006

Province number(s)[a]	Description	Plots (n)	Species Group	CWD Pieces (n)	Mean small-end diameter (cm)	Mean large-end diameter (cm)	Mean total length (m)	Mean piece volume (m^3)
231, 234	Southeastern Mixed/	2	Hwd	9	14.11	23.14	3.83	0.15
	Lower Mississippi Riverine	96	Sftwd	341	9.97	18.21	5.14	0.14
251, 255	Midwest Prairie Parkland	34	All	143	10.73	20.71	5.01	0.23
262, 313, 315, 321, 322	Western Dry Steppe/	–	Hwd.	0	–	–	–	–
	Semi-Arid/Desert	7	Sftwd	99	13.03	24.63	4.96	0.36
331, 334	Southern Rocky Mtn./Black Hills	–	Hwd	0	–	–	–	–
		8	Sftwd	371	9.95	20.27	7.20	0.30
341, 342	Intermountain West	–	Hwd	0	–	–	–	–
		5	Sftwd	47	13.02	20.86	4.04	0.19
212	Northeastern Mixed/	82	Hwd	341	10.37	17.69	5.22	0.14
	Laurentian Mixed	110	Sftwd	794	10.47	18.09	5.55	0.15
221	Eastern Broadleaf (Oceanic)	95	Hwd	525	10.76	19.70	6.24	0.23
		46	Sftwd	163	11.48	18.96	5.67	0.17
222	Eastern Broadleaf (Continental)	95	Hwd	490	10.21	19.88	6.17	0.24
		27	Sftwd	77	10.32	17.15	5.67	0.13
232	Outer Coastal Plain Mixed	48	Hwd	136	10.10	18.12	4.65	0.14
		54	Sftwd	203	10.49	19.11	5.99	0.17
242	Pacific Northwest Coast Ranges	6	Hwd	10	10.92	20.57	4.85	0.11
		27	Sftwd	502	16.21	25.58	7.13	0.73
261	West Coast Chaparral	23	Hwd	114	9.14	19.28	4.68	0.19
		49	Sftwd	515	14.02	25.00	6.15	0.52
263	West Coast Steppe	1	Hwd	4	7.62	12.70	2.51	0.02
		1	Sftwd	4	22.86	33.66	4.04	1.11
332	Great Plains Steppe	3	Hwd	5	7.62	15.24	3.47	0.04
		9	Sftwd	578	10.36	20.92	8.49	0.31
333	Northern Rocky Mtn. Steppe	–	All	0	–	–	–	–

[a] Inclusive of mountain provinces, "–" indicates no observations for a particular ecological province and species combination, "all" species group indicates insufficient sample size such that all species were included in the model fitting.

ecological province. A model validation data set was created from the 2006 field season which included over 5400 observations (excluding pieces with a DC of 5) (Table 1b).

2.3. Analysis and prediction models

To explain the diversity of CWD conditions across the U.S., all models were developed for either softwood or hardwood classes of CWD species and stratified by Bailey's ecological province. The softwood/hardwood classes were used to reflect excurrent/decurrent growth habits. Bailey's ecological provinces were used to stratify observations due to its wide availability, its current use in FIA's national database structure for other applications (e.g., phase three stratified estimation), and its ability to broadly reflect unique climatic/ecological regions across the United States. Even so, insufficient sample sizes of some ecological provinces necessitated collapsing them into groups of the most similar provinces. For example, Provinces 251 and 255 were combined due to sparse forest inventory plots in the Midwestern Prairie/Parkland areas. Additionally, for certain unique provinces the hardwood and softwood species groups were collapsed into one group termed "all." The collapsing of Bailey's provinces and softwood/hardwood/all species groups resulted in 26 unique combinations for subsequent CWD model building (Table 1a).

To conform to the objectives of the study and observed relationships in the data, we specified the regression model for D_L as

$$\hat{D}_L = \beta_0 + \beta_1 D_T + \beta_2 \mathrm{DC} + \beta_3 D_T \mathrm{DC} + \varepsilon \quad (1)$$

where $\hat{D}_L$: large-end diameter (cm); D_T: transect diameter (cm).

$$\mathrm{DC} = \text{decay class}\begin{cases} 1 = \text{sound; no decay} \\ 2 = \text{sound; sapwood beginning to decay} \\ 3 = \text{sound heartwood; decayed sapwood} \\ 4 = \text{decayed heartwood} \end{cases}$$

ε: residual error; β_i: estimated coefficients (i = 0–3).

The small-end diameter (D_S) model formulation is

$$\hat{D}_S = \beta_0 + \beta_1 D_T + \beta_2 \mathrm{DC} + \beta_3 D_T \mathrm{DC} + \varepsilon \quad (2)$$

where $\hat{D}_S$: small-end diameter (cm).

We utilized the end diameters estimated from Eqs. (1) and (2) along with decay class to model CWD length:

$$\hat{L} = \beta_0 + \beta_1 \hat{D}_S + \beta_2 \hat{D}_L + \beta_3 \mathrm{DC} + \varepsilon \quad (3)$$

where L: length (m).

The employed methodology results in a system of equations for predicting CWD size and length attributes. A specific characteristic of this system is that predicted values from Eqs. (1) and (2) are needed to implement the length prediction model (3). These simultaneous equations must be handled with appropriate regression analysis techniques to obtain unbiased results (Hasenauer et al., 1998). We used the 3-stage least squares (3SLS) method, which accounts for the endogenous variables and cross-equation error correlations (Jorgenson and Laffont, 1974).

2.4. Model validation

The D_L, D_S, and length models were applied to 2006 field season observations, which were unavailable at the time of model development. To avoid potential correlations between observations that might be introduced (some plots were measured in both 2001 and 2006), these data were not used to re-calibrate the models upon completion of the validation exercise. Additionally, CWD piece volumes (Smalian's volume equation, Woodall and Monleon, 2008) were determined using actual and estimated dimensional measurements and compared. Finally, validation results were compared with FIA field crew measurement tolerances to discuss study results in the context of a large-scale inventory. Tolerance defines the acceptable range of differences between independent measurements by FIA field crews (±5.1 cm for D_L and D_S, ±20% for length) (Westfall and Woodall, 2007).

Table 2
Large-end diameter (D_L) model (Eq. (1)) coefficients and fit statistics for 26 ecological provinces/species group combinations, United States

Province number(s)[a]	Species group	r^2	RMSE (cm)	β_0	β_1	β_2	β_3
231, 234	Hwd	0.89	6.64	−3.69337	1.658456	2.399251	−0.20525
	Sftwd	0.89	6.03	1.850483	1.165082	*0.00706*	−0.01987
251, 255	All	0.48	9.66	*2.56695*	1.131675	*1.57656*	−0.10553
262, 313, 315, 321, 322	Hwd.	0.82	4.80	10.59167	0.546193	−2.90857	0.193144
	Sftwd	0.65	7.90	5.053361	1.039224	–	–
331, 334	Hwd	0.63	3.94	6.308868	1.057759	−1.0301	–
	Sftwd	0.63	7.62	8.009243	1.035468	−0.62605	–
341, 342	Hwd	0.80	4.13	−7.25262	1.635434	2.961388	−0.1658
	Sftwd	0.34	13.54	*−0.2073*	1.424592	2.75928	−0.17247
212	Hwd	0.65	9.91	*0.62354*	1.386844	0.769562	−0.11114
	Sftwd	0.65	8.85	9.316273	0.767369	−1.44584	0.05762
221	Hwd	0.77	14.34	5.58013	0.982297	−1.29878	0.081545
	Sftwd	0.91	7.39	−8.28239	1.85613	4.04301	−0.27559
222	Hwd	0.70	9.77	15.35261	0.350272	−4.06644	0.246346
	Sftwd	0.94	5.50	8.831406	0.603953	−1.82365	0.131462
232	Hwd	0.75	13.01	3.562082	1.0766	–	–
	Sftwd	0.80	12.53	−4.90228	1.531362	2.613917	−0.16497
242	Hwd	0.18	16.26	17.1895	*−0.4964*	*−2.5937*	0.382727
	Sftwd	0.75	11.99	13.98465	0.505707	−3.42489	0.168162
261	Hwd	0.84	5.65	2.898361	1.099612	–	–
	Sftwd	0.58	14.42	9.975538	0.63736	*−1.0449*	0.099899
263	Hwd	0.49	7.45	18.89486	0.197879	−3.93162	0.191344
	Sftwd	0.87	6.06	1.279455	1.144238	–	–
332	Hwd	0.72	6.59	18.86758	*0.04548*	−4.53069	0.258974
	Sftwd	0.71	6.40	2.981522	1.270299	*0.37162*	−0.06636
333	All	0.69	6.80	2.436994	1.232931	*0.37899*	−0.05677

[a] All coefficients significant at the 0.05 level except where '–' indicate a dropped term and italics indicate a nonsignificant estimate kept for intercept and/or main effects, "all" species group indicates insufficient sample size such that all species were included in the model fitting. Model specified as $\hat{D}_L = \beta_0 + \beta_1 D_T + \beta_2 DC + \beta_3 D_T DC + \varepsilon$ where D_T is transect diameter and DC is decay class.

3. Results

The performance of the D_L model varied considerably across the 26 groups (Table 2). R^2 values ranged from 0.18 to 0.94 and root mean squared error (RMSE) statistics ranged from 3.94 to 16.26 cm. No apparent trends were evident in either of these measures by hardwood/softwood group or spatial location (ecological provinces). Interactions between D_T and DC were significant ($p < 0.05$) for 20 of the 26 groups. The main effect D_T was significant ($p < 0.05$) for 24 of the 26 groups, while the DC main effect was significant ($p < 0.05$) for 16 of 26 groups. Nonsignificant decay class effects were retained when the $D_T \times$ DC

Table 3
Small-end diameter (D_S) model (Eq. (2)) coefficients and fit statistics for 26 ecological provinces/species group combinations, United States

Province number(s)[a]	Species group	r^2	RMSE (cm)	β_0	β_1	β_2	β_3
231, 234	Hwd	0.57	4.85	4.070835	0.295126	0.534479	–
	Sftwd	0.74	4.84	4.153441	0.369479	−0.84971	0.07838
251, 255	All	0.45	5.47	7.353968	0.047648	−0.96345	0.118174
262, 313, 315, 321, 322	Hwd.	0.51	4.63	2.050184	0.523678	–	–
	Sftwd	0.48	4.88	6.158396	0.14449	−0.82768	0.099826
331, 334	Hwd	0.25	2.26	8.218852	*−0.0839*	−0.81658	0.103664
	Sftwd	0.40	4.75	1.149844	0.397441	0.758509	–
341, 342	Hwd	0.71	2.79	11.45194	−0.22333	−2.786	0.231142
	Sftwd	0.38	5.21	4.032534	0.372983	–	–
212	Hwd	0.66	5.28	1.156473	0.549057	0.468735	0.012438
	Sftwd	0.56	5.74	9.48667	−0.0951	−1.81356	0.174653
221	Hwd	0.71	6.38	6.998718	0.134679	−1.22727	0.112648
	Sftwd	0.82	5.10	−8.93487	1.293096	3.677651	−0.24512
222	Hwd	0.64	6.19	11.03344	−0.18543	−3.33795	0.271853
	Sftwd	0.91	4.30	9.144141	*−0.0629*	−2.36044	0.20825
232	Hwd	0.64	6.91	−3.85303	0.982192	3.177143	−0.21279
	Sftwd	0.76	7.24	*0.50505*	0.702893	*0.71679*	−0.05094
242	Hwd	0.56	4.05	13.47571	−0.41524	−2.9607	0.285164
	Sftwd	0.69	7.78	11.59001	−0.14572	−2.51648	0.228159
261	Hwd	0.49	5.15	8.506253	*−0.0789*	−1.54807	0.171001
	Sftwd	0.52	9.64	*2.48888*	0.435196	*0.59543*	0.036479
263	Hwd	0.44	3.97	11.79881	−0.27755	−2.28636	0.212973
	Sftwd	0.80	5.17	2.091376	0.431102	−0.98323	0.099007
332	Hwd	0.66	4.97	11.49059	−0.24516	−2.87949	0.250315
	Sftwd	0.54	4.73	4.316684	0.284341	−0.62802	0.090506
333	All	0.57	4.49	6.73571	*0.06219*	−1.08715	0.140426

[a] All coefficients significant at the 0.05 level except where italics indicate a nonsignificant estimate kept for intercept and/or main effects, "all" species group indicates insufficient sample size such that all species were included in the model fitting. Model specified as $\hat{D}_L = \beta_0 + \beta_1 D_T + \beta_2 DC + \beta_3 D_T DC + \varepsilon$ where D_T is transect diameter and DC is decay class.

Table 4
Total CWD length model (Eq. (3)) coefficients and fit statistics for 26 ecological provinces/species group combinations, United States

Province number(s)[a]	Species group	r^2	RMSE (m)	β_0	β_1	β_2	β_3
231, 234	Hwd	0.10	4.59	2.34403	0.977831	−0.20818	−1.00645
	Sftwd	0.10	4.76	6.085437	0.168162	–	−0.60971
251, 255	All	0.29	2.76	3.295282	−0.2224	0.276492	−0.59721
262, 313, 315, 321, 322	Hwd.	0.12	3.60	2.028194	–	0.130487	–
	Sftwd	0.29	3.85	*0.05057*	−0.54778	0.450939	–
331, 334	Hwd	0.20	3.99	−3.36625	0.621958	0.245559	–
	Sftwd	0.21	5.15	3.123761	−0.99068	0.624973	–
341, 342	Hwd	0.36	2.55	4.421321	−0.43603	0.385204	−0.54365
	Sftwd	0.21	4.33	4.965278	−0.16623	0.252386	−1.45838
212	Hwd	0.14	4.34	6.153223	0.425029	−0.11485	−1.27061
	Sftwd	0.16	3.11	6.447497	−0.31879	0.237188	−0.55554
221	Hwd	0.10	4.33	6.488924	0.209616	−0.02654	−0.74833
	Sftwd	0.30	4.62	6.466396	–	0.127461	−0.66202
222	Hwd	0.16	3.97	5.881855	0.108085	0.0524	−0.81528
	Sftwd	0.10	4.22	4.253012	−0.35535	0.277997	–
232	Hwd	0.09	4.24	5.646359	–	0.053631	−0.53395
	Sftwd	0.07	3.83	4.469137	–	0.041732	–
242	Hwd	0.07	4.40	3.630143	–	0.197421	−0.87477
	Sftwd	0.15	5.21	8.309371	−0.0902	0.141544	−1.35649
261	Hwd	0.43	2.87	2.766795	–	0.188721	−0.74281
	Sftwd	0.14	6.50	6.246346	0.718538	−0.26131	−1.57501
263	Hwd	0.26	4.65	4.035758	−0.99455	0.712651	–
	Sftwd	0.17	4.15	8.741094	−0.47462	0.394877	−1.02347
332	Hwd	0.22	2.78	4.115727	−0.21115	0.188839	–
	Sftwd	0.30	4.18	4.590929	−0.65537	0.549881	−0.49693
333	All	0.35	4.35	4.04228	−0.64788	0.59282	−0.36982

[a] All coefficients significant at the 0.05 level except where '–' indicate a dropped term and italics indicate a nonsignificant estimate kept for intercept and/or main effects, "all" species group indicates insufficient sample size such that all species were included in the model fitting. Model specified as $\hat{L} = \beta_0 + \beta_1 \hat{D}_S + \beta_2 \hat{D}_L + \beta_3 DC + \varepsilon$ where $\hat{D}_S$ is small-end diameter from (Eq. (2)), $\hat{D}_L$ is large-end diameter from (Eq. (1)), and DC is decay class.

Table 5
Means and standard deviations of residuals (observed-predicted) for modeled CWD large-end, small-end, length, and total volume (Smalian's volume equation) using validation data set

Province number(s)[a]	Species group	Large-end diameter (cm)			Small end diameter (cm)			Length (m)			Volume (m^3)	
		Mean	S.D.	WMQO (%)	Mean	S.D.	WMQO (%)	Mean	S.D.	WMQO (%)	Mean	S.D.
231, 234	Hwd	1.13	5.44	89	2.44	3.67	89	−1.54	1.83	11	0.01	0.14
	Sftwd	0.66	4.40	87	−0.23	3.10	91	−0.84	3.60	20	0.02	0.19
251, 255	All	0.16	6.96	64	−0.30	5.52	83	0.13	3.36	27	0.07	0.45
262, 313, 315, 321, 322	Hwd.	–	–	–	–	–	–	–	–	–	–	–
	Sftwd	−0.02	7.52	56	1.18	6.66	79	0.29	5.11	16	0.05	0.80
331, 334	Hwd	8.84	5.18	0	2.96	4.94	50	−0.65	2.29	50	0.10	0.05
	Sftwd	−0.94	6.81	57	0.62	3.91	87	0.06	4.68	25	0.07	0.44
341, 342	Hwd	–	–	–	–	–	–	–	–	–	–	–
	Sftwd	−3.03	5.39	57	2.34	7.04	77	−1.11	3.40	17	−0.04	0.28
212	Hwd	−0.37	4.73	86	−0.40	3.51	89	0.08	3.90	20	0.02	0.17
	Sftwd	−0.59	4.77	82	0.36	3.43	90	−0.58	3.54	21	0.02	0.23
221	Hwd	−1.10	8.23	76	0.07	5.39	87	0.29	4.49	15	0.02	0.62
	Sftwd	−0.18	5.88	82	1.13	3.89	83	−1.36	4.15	14	>0.00	0.24
222	Hwd	0.11	6.92	73	−0.17	3.46	90	0.36	4.74	19	0.09	0.45
	Sftwd	−0.39	4.40	86	0.28	3.08	88	0.12	4.04	22	0.02	0.16
232	Hwd	−0.56	5.02	89	−0.32	3.58	87	−0.40	3.22	26	0.03	0.20
	Sftwd	0.73	5.30	87	−0.38	3.95	85	0.75	4.46	23	0.06	0.20
242	Hwd	1.91	7.62	50	−0.27	3.39	90	−0.19	3.25	20	−0.01	0.16
	Sftwd	0.40	9.27	73	0.54	6.01	78	0.50	6.86	19	0.32	2.25
261	Hwd	1.06	8.94	82	−0.55	3.47	88	0.44	3.20	24	0.07	0.36
	Sftwd	−1.33	16.53	60	−1.42	10.45	76	0.13	5.51	17	−0.73	19.78
263	Hwd	−2.97	0.43	100	−1.69	1.05	100	−3.43	2.34	25	−0.06	0.04
	Sftwd	3.31	8.55	75	3.69	1.51	75	−3.75	3.41	25	0.30	0.81
332	Hwd	1.57	4.15	80	−0.56	2.23	100	−1.49	0.65	20	−0.01	0.03
	Sftwd	0.32	6.86	73	−0.43	3.97	86	0.97	4.84	21	0.07	0.40
333	All	–	–	–	–	–	–	–	–	–	–	–
All softwoods	−0.13	9.25	73	−0.02	6.04	83	0.29	5.09	21	−0.04	8.28	
All hardwoods	−0.45	6.55	77	−0.05	4.06	89	−0.20	4.08	19	0.03	0.39	
All species	−0.27	8.13	75	−0.04	5.23	86	0.07	4.66	20	>0.00	6.12	

[a] "–" indicates no observations for a particular ecological province and species combination, "all" species group indicates insufficient sample size such that all species were included in the model fitting. WMQO is the percent within minimum quality objectives ... a measurement quality tolerance subjectively set by the FIA program for field crews.

DC interaction was significant to maintain the complete model (Harrell, 2001). Similarly, estimates of the intercept term were preserved regardless of statistical significance to allow better fit to the data.

Results for the D_S model differed from the D_L model in several ways. First, the R^2 values had a narrower range (0.25–0.91) (Table 3). Compared to the D_L model, the range of RMSE statistics was smaller (2.26–9.64 cm). The $D_T \times$ DC interaction term was significant for all 26 groups. Therefore, all coefficients for main-effects D_T and DC (and intercept terms) were retained, regardless of significance.

The CWD length model fit statistics were indicative of a relatively weak model compared to the end-point diameter models. Across the 26 groups, R^2 statistics varied from 0.07 to 0.43 and RMSE values ranged from 2.55 to 6.50 m (Table 4). Softwood species tended to have larger RMSE's than hardwood species. The coefficients for both the D_S and D_L predictor variables were statistically significant ($p < 0.05$) across 20 and 25 of the 26 groups, respectively. DC was a significant predictor ($p < 0.05$) for 18 of the 26 groups.

Validation results indicated that the system of CWD dimension models were largely unbiased (Table 5). Of the 78 sets of model coefficients, all but four mean residuals were not statistically different from zero at the 95% confidence level. The majority of the D_L model's residual means by ecological province and species group were below 1.50 cm. Similarly, the majority of the D_S model's residual means by ecological province and species group were below 1.00 cm. Although most length model residual means by ecological province and species group were below 1 m, the standard deviations were substantial, typically exceeding 3 m. To further evaluate the validation results, residuals were compared to the measurement tolerances expected of actual field crews ($\pm$5.1 cm for D_L and D_S, $\pm$20% for length). The percentage of residuals for all models within tolerance was 75, 86, and 20% for D_L, D_S, and length, respectively. An evaluation of actual field crew measurements within tolerance found ranges of 72.7–90.5% for D_L, 80.0–94.9 for D_S, and 72.2 for length (Westfall and Woodall, 2007). Finally, in order to evaluate the model's ability to predict overall CWD piece volume (predicted D_L, D_S, and length variables used in Smalian's log rule), the residuals between actual and predicted log volume were examined. Mean volume residuals ranged from -0.73 to $0.32\ m^3$ with substantial standard deviations. Additionally, there appeared to be a tendency for CWD piece volume to be slightly underestimated using this study's system of equations.

4. Discussion

These models may explain as much variation in CWD dimensional attributes as can be expected given the wide range of CWD conditions found in a diversity of site and stand conditions across the country. As indicated by both fit statistics and validation, the D_L and D_S models were the most robust, followed by the length model. Most modeled D_L and D_S estimates achieved nearly the same measurement quality expected of actual field crews. Many CWD wildlife habitat assessments depend on CWD D_L and D_S distribution assessments. We suggest that because most D_L and D_S models had R^2 values exceeding 0.60, along with satisfactory validation results, these models may be used in lieu of measuring CWD end-point diameters if field efficiency concerns preclude their measurement. However, if modeled variables were to be included in population estimation procedures, then necessary steps to incorporate model error into estimator variance would be expected. Additionally, it should be noted that the standard deviations of residual means were in many cases substantial, possibly exceeding what might be tolerated in small-scale inventories.

The length models were less statistically robust with fair validation results. Only 20% of length model residuals were within the tolerance expected of field crews while most models had an R^2 values under 0.30. Unfortunately, length may be more difficult to model due to natural variability in mortality and disturbance events. Large-scale blowdown events on lower quality sites might result in numerous short CWD pieces while small-scale mortality events on higher quality sites might result in long CWD pieces. Stand dynamics such as these are difficult to quantify and model. Therefore, the CWD length model should be used only when there are no other measurement alternatives with results couched in the model's weak strength and validation results.

When considering all three CWD models as a system, the CWD piece volume results might be the most telling of model performance. Numerous groups had mean volume residuals $0.02\ m^3$ or less. Models for softwood species in west coast forest ecosystems (Provinces 242 and 261) had the poorest validation results. These ecosystems have a high likelihood of containing large-sized CWD pieces (e.g., redwoods, *Sequoia sempervirens*). Therefore, it is not recommended that these models replace detailed CWD inventories in ecosystems with atypical, large-sized CWD pieces. Although this study's models may not be appropriate for prediction of individual CWD piece attributes in certain situations, they represent an average response across a population and may be appropriate for obtaining unbiased population estimates.

Although this study's models may provide an alternative to more time-consuming inventory work, forest inventory specialists still need to choose between measuring and modeling CWD dimensions. For most natural resource inventories (e.g., FIA), population estimation procedures do not explicitly incorporate forest attribute model error into the overall variance estimate (e.g., standing tree volumes, Bechtold and Patterson, 2005). In such cases, this study's models would offer time savings but with underestimated error. In other cases, such as assessing CWD habitat requirements at relatively small-scales (e.g., National Forests), the reductions in accuracy may not be permissible or acceptable. Time is the factor that might be the major determinant in whether model-based or field measurements of CWD dimensions are chosen. There is a lack of information regarding the time it takes to measure CWD end-point diameters and length. However, Jordan et al. (2004) report an average time per CWD piece of 1.5 min to locate and record end-diameters, length, species, and decay. In a study of 104 logs, Van Wagner and Wilson (1976) found that measuring the diameter at both ends took 2.5 times longer than measuring just the intercept diameter. Using 45 s as a conservative estimate of time required to measure end-point diameters and length of one CWD piece (it might be considerably higher in mature/old-growth stands), this study's models might save the FIA inventory program only 8 min per fully forested plot (average 10 CWD pieces/plot). However, on some FIA plots where disturbance events have created large volumes of CWD, this study's models may save up to an hour per plot (60 CWD pieces/plot). Overall, modeling CWD dimensions may be preferred over field measurements only when field efficiency is of the highest priority or post hoc analysis of a CWD inventory (i.e., fuel inventory lacking CWD dimension measurement) is being conducted.

5. Conclusions

CWD dimensional attributes may be modeled adequately for numerous inventory applications, sometimes to the level of measurement precision expected of actual field crews. Ultimately, it is up to forest resource managers to decide if the loss in individual CWD piece dimensional accuracy is worth gains in inventory efficiency, especially for CWD lengths and especially in forest ecosystems containing extremely large CWD. Given that transects are such a widely used field protocol for dead and downed wood assessment nationally (e.g., fuel inventories), this study's models allow further utilization of these inventories for purposes beyond their original intention (e.g., wildlife habitat assessment).

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