Using TLS-measured Tree Attributes to Estimate Above Ground Biomass in Small Black Spruce Trees

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*The zip file also includes a csv file (treedata.csv) with the data frame used as input to the R lm() function.

Table S1. Average values for each predictor of the harvested trees used in this study. Shown as average value ± standard deviation (minimum value in range; maximum value in range). TLS = terrestrial laser scanned, QSM = quantitative structure model, DBH = diameter at breast height, AGB = above ground biomass.

Plot Name	# of Black Spruce Used in Study	TLS Height (m)	QSM DBH (cm)	Crown Area (m^2)	Crown Diameter (m)	Bounding Box Volume (m^3)	QSM Volume (L)	Avg AGB (kg)
V2B006	10	2.50 ± 0.97	2.83 ± 2.48	0.16 ± 0.11	0.42 ± 0.15	1.14 ± 1.19	10.08 ± 13.24	1.55 ± 1.50
		(1.54; 4.86)	(0.27; 6.91)	(0.05; 0.43)	(0.26; 0.74)	(0.19; 3.65)	(0.89; 36.36)	(0.41; 5.42)
V2B009	10	2.67 ± 1.06	4.85 ± 3.16	0.18 ± 0.09	0.46 ± 0.12	1.20 ± 0.98	22.11 ± 29.20	1.93 ± 1.95
		(1.41; 5.01)	(0.39; 11.66)	(0.06; 0.35)	(0.29; 0.66)	(0.18; 3.34)	(2.52; 102.71)	(0.37; 6.78)
V2B011	10	2.66 ± 1.12	5.92 ± 2.99	0.23 ± 0.10	0.53 ± 0.12	1.54 ± 0.88	20.42 ± 11.28	1.85 ± 1.19
		(1.40; 4.59)	(0.64; 10.19)	(0.08; 0.41)	(0.32; 0.72)	(0.49; 3.45)	(3.14; 37.45)	(0.46; 4.14)
V2B012	8	3.19 ± 1.33	4.33 ± 2.77	0.32 ± 0.21	0.61 ± 0.21	3.02 ± 2.64	27.80 ± 31.73	3.80 ± 3.40
		(1.42; 5.38)	(1.37; 9.98)	(0.11; 0.66)	(0.37; 0.92)	(0.34; 8.14)	(4.86; 102.63)	(0.60; 9.31)
V2B015	8	2.16 ± 0.88	3.43 ± 1.93	0.15 ± 0.10	0.41 ± 0.15	0.94 ± 1.11	9.63 ± 13.78	1.02 ± 1.06
		(1.46; 4.37)	(0.92; 7.13)	(0.04; 0.35)	(0.23; 0.67)	(0.14; 3.71)	(1.67; 45.38)	(0.11; 3.68)
V2B016	7	2.69 ± 1.28	4.83 ± 2.49	0.17 ± 0.05	0.47 ± 0.08	1.21 ± 0.67	15.95 ± 12.97	1.72 ± 1.52
		(1.29; 5.12)	(0.87; 8.03)	(0.08; 0.23)	(0.31; 0.54)	(0.23; 2.31)	(2.23; 39.58)	(0.28; 5.07)
V2B019	9	2.24 ± 0.74	2.75 ± 1.51	0.11 ± 0.05	0.37 ± 0.09	0.72 ± 0.52	5.39 ± 6.11	0.93 ± 0.69
		(1.36; 3.75)	(0.38; 4.54)	(0.06; 0.22)	(0.27; 0.53)	(0.31; 1.69)	(0.54; 19.97)	(0.24; 2.48)
V2B022	10	2.30 ± 0.87	4.48 ± 2.15	0.18 ± 0.11	0.46 ± 0.13	1.10 ± 1.30	16.77 ± 23.55	1.50 ± 1.73
		(1.41; 4.58)	(0.66; 8.62)	(0.08; 0.49)	(0.31; 0.79)	(0.30; 4.91)	(2.94; 85.96)	(0.51; 6.58)
V2B023	9	2.40 ± 1.06	3.77 ± 2.63	0.10 ± 0.07	0.34 ± 0.11	0.78 ± 0.86	9.94 ± 12.08	1.10 ± 1.24
		(1.26; 4.73)	(0.54; 8.05)	(0.04; 0.27)	(0.22; 0.59)	(0.12; 3.04)	(1.87; 39.20)	(0.15; 4.28)
V2B026	8	2.04 ± 0.63	4.54 ± 2.46	0.12 ± 0.05	0.38 ± 0.08	0.59 ± 0.41	9.96 ± 8.94	0.95 ± 0.81

		(1.43; 3.56)	(0.54; 8.91)	(0.06; 0.20)	(0.28; 0.50)	(0.25; 1.44)	(1.13; 28.35)	(0.34; 2.95)
Total	89	2.48 ± 1.06	4.18 ± 2.69	0.17 ± 0.12	0.44 ± 0.15	1.21 ± 1.35	14.86 ± 19.55	1.63 ± 1.83
		(1.26; 5.38)	(0.27; 11.66)	(0.04; 0.66)	(0.22; 0.92)	(0.12; 8.14)	(0.54; 102.71)	(0.11; 9.31)

Appendix S1. Original Orthogonal Measurement Method for Estimating Crown Diameter

Our initial estimates of crown diameter came from two perpendicular measurements done on a 2-dimensional overhead image of the individual tree point cloud. Using a script in R, we then located the tallest point of the tree by determining the centre point that had the greatest z value (P_c). The script then located the point that was farthest away from the centre point (P_1) and determined the equation of a line that ran between P_c and P_1. The slope of this line is given by

$$m = (y_1 - y_c)/(x_1 - x_c), \tag{S1}$$

and the intercept is given by

$$b = y_1 - mx_1. \tag{S2}$$

From these two equations the equation of a line

$$y = mx + b, \tag{S3}$$

can be used to determine which points in the point cloud lie along that line. Because the points generated in the point clouds are discrete, we allowed for points to be up to 0.05 m horizontally off this line to make sure that the crown diameter measurements covered the distance from one side of the crown to the other. Points considered followed the equation:

$$|(mx_2 + b) - y_2| \leq 0.05, \tag{S4}$$

Once the line points were determined, the script located the point that was the farthest away from P_1 (P_2) and visually confirmed that both points were on opposite edges of the tree crown with a line between them that ran through P_c. The distance between P_1 and P_2 gave the first crown diameter measurement.

Next, the script determined the equation of a line perpendicular to the first and using the new slope (equation 1) and intercept (equation 2) found the point farthest away from P_c on the new perpendicular line (P_3) (equation 4). Then, just like in the previous step (equation 4), the script found the point farthest away from P_3 that was also on the perpendicular line (P_4), which was visually inspected to make sure it was on the edge of the tree crown and used the distance between P_3 and P_4 as the second crown diameter measurement. The mean of the two measurements was then taken, and uncertainty was calculated using the following formula:

$$\delta x = (x_{max} - x_{min}) / 2\sqrt{N}, \tag{S5}$$

where x is the measurements, and N is the number of measurements made ($N = 2$).

While this method is a plausible estimation of crown diameter, we had some reservations about using it. Tree crowns are generally irregular, so using only two measurements to measure the crown diameter is likely insufficient, which is why we switched to the raster method outlined in the main manuscript.

Table S2. TreeQSM input parameters used to build quantitative structure models (QSMs) of the individual trees.

Input	Value
inputs.PatchDiam1	1
inputs.PatchDiam2Min	0.001
inputs.PatchDIam2Max	0.008
inputs.lcyl	1
inputs.FilRad	4
inputs.BallRad1	inputs.PatchDiam1 + 0.075
inputs.BallRad2	inputs.PatchDiam2Max + 0.02
inputs.nmin1	3
inputs.nmin2	1
inputs.OnlyTree	1
inputs.Tria	1
inputs.Dist	1
inputs.MinCylRad	0.001
inputs.ParentCor	1
inputs.TaperCor	1
inputs.GrowthVolCor	0
inputs.GrowthVolFac	2.5

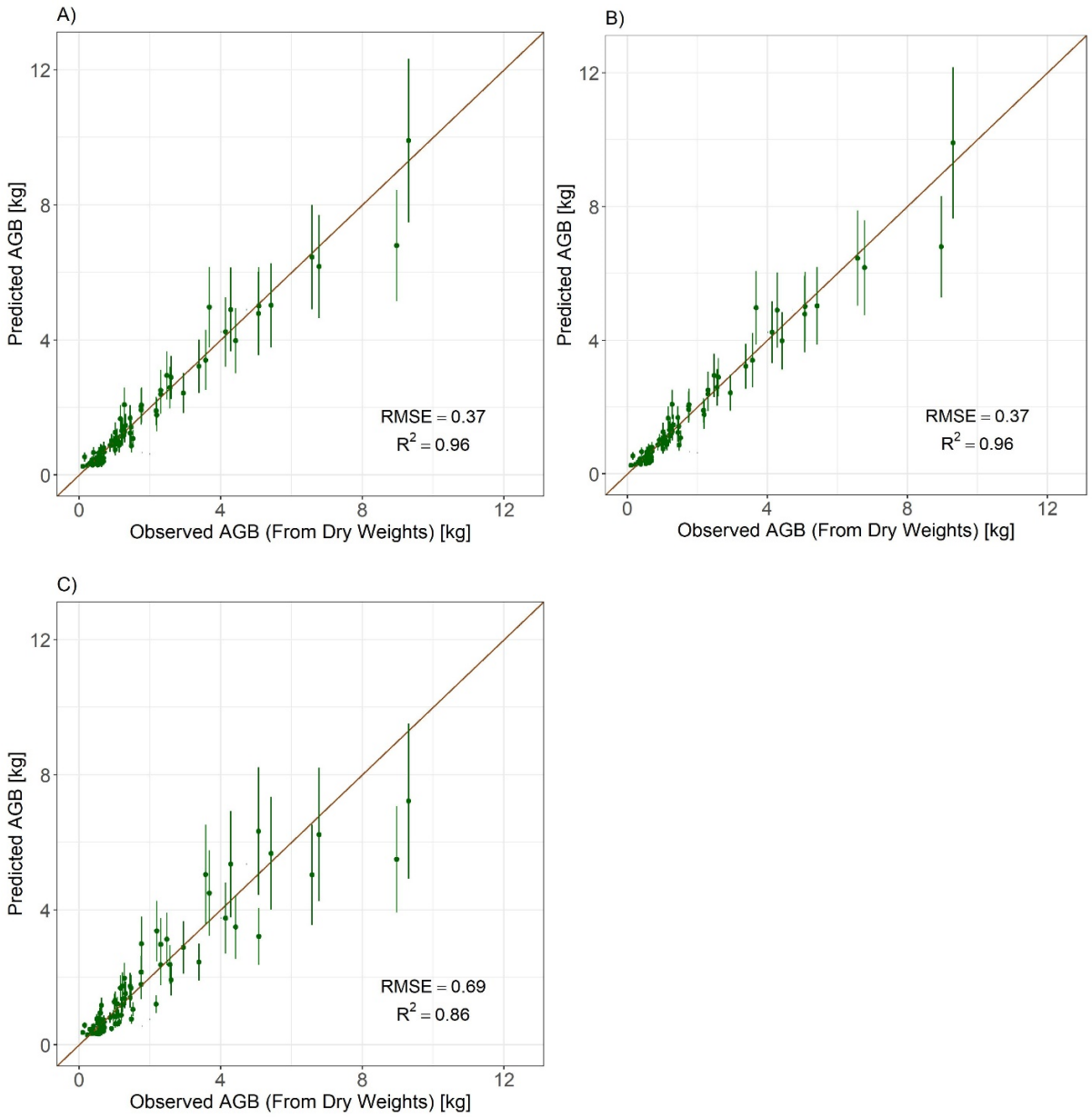

Figure S1. Scatterplots of predicted versus observed AGB for multiple regression weighted least squares (WLS) models using A) crown area and height, B) crown diameter and height and C) DBH (QSM-derived) and height as predictors when fitted using the whole sample. The brown line represents a 1:1 line, and models are shown with their root mean square error (RMSE) and coefficient of determination (R^2). Error bars represent the combination of model uncertainties and measurement uncertainties as outlined in Appendix A.

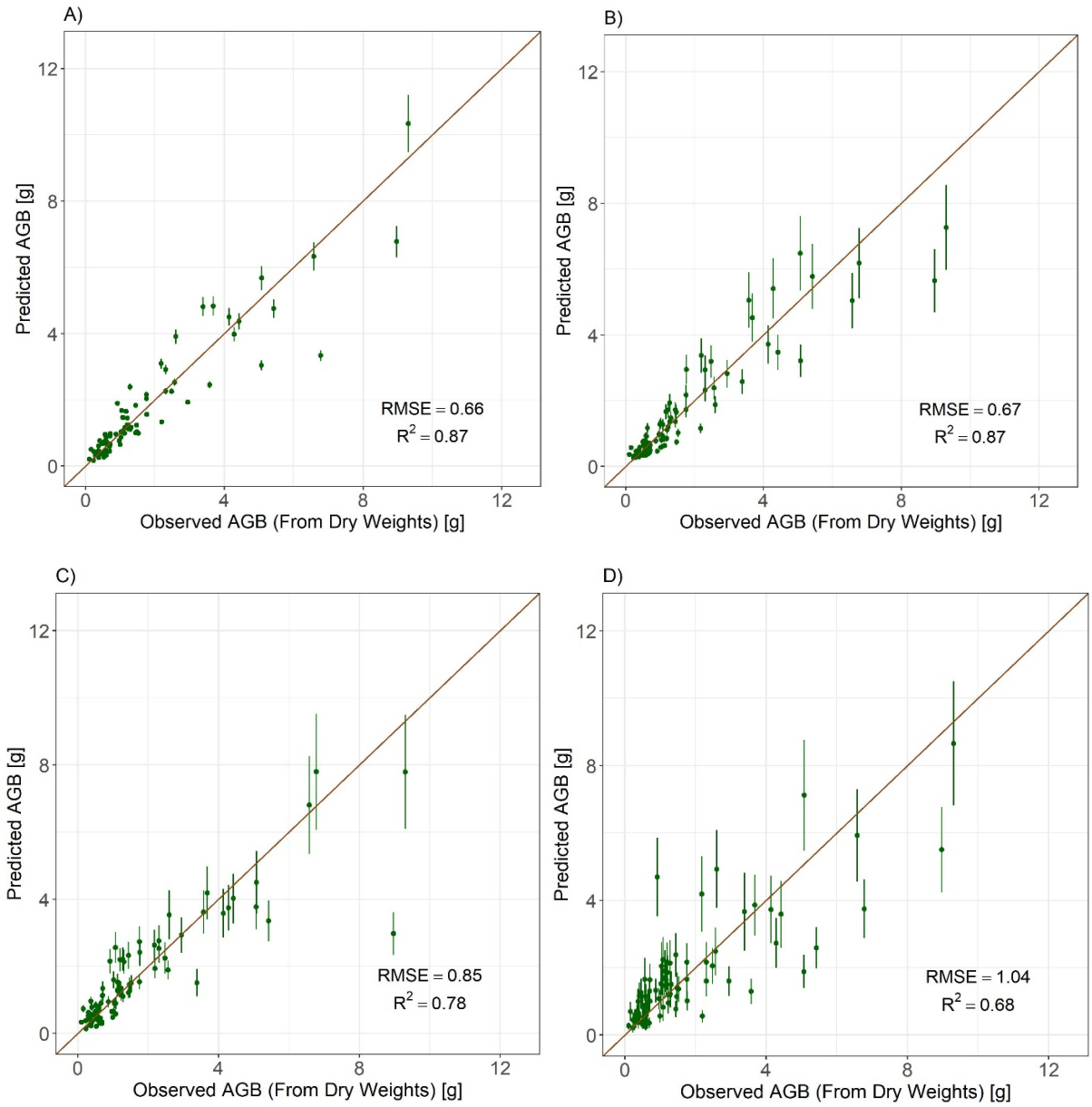

Figure S2. Predicted versus observed AGB plots for power weighted least squares (WLS) models using A) bounding box volume, B) height, C) QSM volume and D) crown area as predictors when fitted using the whole sample. The brown line represents a 1:1 line, and models are shown with their root mean square error (RMSE) and coefficient of determination (R^2). Error bars represent the combination of model uncertainties and measurement uncertainties as outlined in Appendix A.

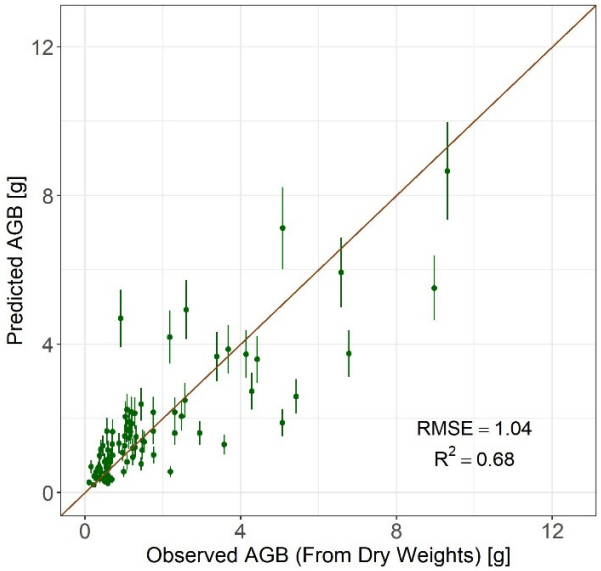

Figure S3. Scatterplot of predicted versus observed AGB for power weighted least squares (WLS) model using crown diameter as a predictor when fitted using the whole sample. The brown line represents a 1:1 line, and models are shown with their root mean square error (RMSE) and coefficient of determination (R^2). Error bars represent the combination of model uncertainties and measurement uncertainties as outlined in Appendix A.

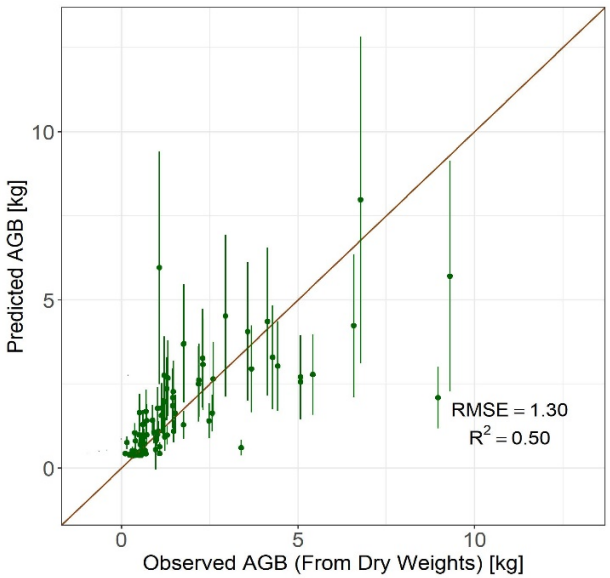

Figure S4. Scatterplot of predicted versus observed AGB for quadratic weighted least squares (WLS) model using QSM-derived DBH as a predictor when fitted using the whole sample. The brown line represents a 1:1 line, and models are shown with their root mean square error (RMSE) and coefficient of determination (R^2). Error bars represent the combination of model uncertainties and measurement uncertainties as outlined in Appendix A.

Table S3. Trees removed from this study after being scanned and harvested, and the reason for discarding them. DBH = diameter at breast height.

Tree Reflector Number	Plot	Height (m)	DBH (cm)	Reason for Removal
1	V2B012	1.6	0.6	Missing bags for ground truth measurements.
7	V2B012	2.3	2.0	Overly occluded point cloud of tree.
7	V2B015	1.6	2.8	Missing bags for ground truth measurements.
8	V2B015	1.4	0.6	Overly occluded point cloud of tree.
3	V2B016	4.8	3.9	Tree in tight clump, could not accurately segment.
6	V2B016	1.8	1.6	Tree in tight clump, could not accurately segment.
7	V2B016	3.5	4.5	Overly occluded point cloud of tree.
5	V2B019	2.2	1.6	Could not find tree in plot-level point cloud.
7	V2B023	2.6	2.4	Could not find tree in plot-level point cloud.
5	V2B026	1.7	1.0	Could not find tree in plot-level point cloud.
7	V2B026	1.8	1.1	Overly occluded point cloud of tree.

Table S4. Estimated value (val), lower (CL95-) and upper (CL95+) 95% confidence intervals and standard errors (SE) of model parameters for multiple regression power models ($AGB = \beta \cdot x_1^{\alpha} \cdot x_2^{\omega} \cdot \varepsilon$ where ε is the bias correction term used during back transformation). For the purposes of this table x_2 is always the height variable. CA = crown area, H = height, CD = crown diameter, DBH (QSM) = diameter at breast height derived from quantitative structure models, OLS = the model parameters were estimated using ordinary least squares, WLS = the model parameters were estimated using weighted least squares.

	β				α				ω				
Model	**Val**	**CL95-**	**CL95+**	**SE**	**Val**	**CL95-**	**CL95+**	**SE**	**Val**	**CL95-**	**CL95+**	**SE**	**ε**
CAxH OLS	0.75	0.53	1.08	0.14	0.53	0.41	0.64	0.06	1.63	1.44	1.82	0.10	1.04
CAxH WLS	0.73	0.52	1.03	0.13	0.54	0.43	0.65	0.06	1.68	1.50	1.85	0.09	1.00
CDxH OLS	0.66	0.48	0.92	0.11	1.06	0.82	1.29	0.12	1.63	1.44	1.82	0.10	1.04
CDxH WLS	0.64	0.47	0.88	0.10	1.07	0.86	1.29	0.11	1.68	1.50	1.85	0.09	1.00
DBH(QSM)xH OLS	0.17	0.14	0.21	0.02	0.07	-0.06	0.19	0.06	2.08	1.79	2.37	0.15	1.07
DBH(QSM)xH WLS	0.16	0.13	0.19	0.02	0.06	-0.07	0.20	0.07	2.19	1.91	2.46	0.14	1.00

Table S5. Estimated value (val), lower (CL95-) and upper (CL95+) 95% confidence intervals and standard errors (SE) of model parameters for power models ($AGB = \beta \cdot x^{\alpha} \cdot \varepsilon$ where ε is the bias correction term used during back transformation). CA = crown area, H = height, CD = crown diameter, DBH (QSM) = diameter at breast height derived from quantitative structure models, V (Bounding Box) = bounding box volume, V (QSM) = volume derived from quantitative structure models, OLS = the model parameters were estimated using ordinary least squares, WLS = the model parameters were estimated using weighted least squares.

	β				α				
Model	**Val**	**CL95-**	**CL95+**	**SE**	**Val**	**CL95-**	**CL95+**	**SE**	**ε**
CA OLS	10.34	7.09	15.09	1.97	1.17	0.99	1.36	0.09	1.16
CA WLS	14.64	10.56	20.28	2.40	1.29	1.11	1.46	0.09	1.00
CAxH OLS	2.92	2.60	3.28	0.17	0.92	0.84	1.00	0.04	1.06
CAxH WLS	3.14	2.87	3.42	0.14	0.96	0.89	1.02	0.03	1.00
CD OLS	7.79	5.57	10.90	1.32	2.35	1.98	2.71	0.18	1.16
CD WLS	10.73	8.05	14.30	1.55	2.57	2.22	2.92	0.18	1.00
CDxH OLS	1.08	1.02	1.14	0.03	1.38	1.29	1.47	0.05	1.04
CDxH WLS	1.08	1.02	1.15	0.03	1.42	1.34	1.49	0.04	1.00
DBH (QSM) OLS	0.47	0.37	0.59	0.05	0.70	0.54	0.86	0.08	1.25
DBH (QSM) WLS	0.45	0.34	0.60	0.06	0.90	0.73	1.08	0.09	1.00
DBH (QSM)xH OLS	5.31	4.01	7.03	0.75	0.614	0.518	0.710	0.048	1.16
DBH (QSM)xH WLS	7.97	6.27	10.12	0.96	0.729	0.635	0.822	0.047	1.00
H OLS	0.17	0.14	0.20	0.02	2.193	1.992	2.394	0.101	1.07
H WLS	0.16	0.13	0.19	0.02	2.287	2.111	2.463	0.089	1.00
V (Bounding Box) OLS	1.31	1.21	1.41	0.05	0.932	0.852	1.011	0.040	1.06
V (Bounding Box) WLS	1.35	1.26	1.46	0.50	0.969	0.899	1.040	0.036	1.00
V (QSM) OLS	0.25	0.21	0.31	0.03	0.689	0.607	0.772	0.042	1.11
V (QSM) WLS	0.23	0.19	0.28	0.03	0.761	0.685	0.837	0.038	1.00

Table S6. Estimated value (val), lower (CL95-) and upper (CL95+) 95% confidence intervals and standard errors (SE) of model parameters for quadratic models ($AGB = exp(\beta + \alpha x^2 + \omega x) \cdot \varepsilon$ where ε is the bias correction term used during back transformation). CA = crown area, H = height, CD = crown diameter, DBH (QSM) = diameter at breast height derived from quantitative structure models, V (Bounding Box) = bounding box volume, V (QSM) = volume derived from quantitative structure models, OLS = the model parameters were estimated using ordinary least squares, WLS = the model parameters were estimated using weighted least squares.

	β				α				ω				
Model	**Val**	**CL95-**	**CL95+**	**SE**	**Val**	**CL95-**	**CL95+**	**SE**	**Val**	**CL95-**	**CL95+**	**SE**	**ε**
CA OLS	2.94	2.10	3.78	0.42	0.19	-0.05	0.42	0.12	1.88	-0.98	2.79	0.46	1.16
CA WLS	2.72	2.02	3.42	0.35	0.01	-0.21	0.24	0.11	1.33	-0.50	2.16	0.42	1.00
CAxH OLS	1.07	0.96	1.19	0.06	0.06	-0.02	0.13	0.04	1.02	-0.87	1.18	0.08	1.06
CAxH WLS	1.14	1.05	1.23	0.05	0.01	-0.06	0.07	0.03	0.97	-0.84	1.09	0.06	1.00
CD OLS	2.49	1.85	3.14	0.32	0.74	-0.19	1.67	0.47	3.59	-2.00	5.18	0.80	1.16
CD WLS	2.40	1.88	2.92	0.26	0.05	-0.86	0.96	0.46	2.65	-1.21	4.10	0.73	1.00
CDxH OLS	0.05	-0.04	0.13	0.04	0.07	-0.06	0.20	0.07	1.36	-1.27	1.46	0.05	1.04
CDxH WLS	0.07	-0.01	0.15	0.04	0.02	-0.10	0.13	0.06	1.41	-1.32	1.50	0.05	1.00
DBH (QSM) OLS	-0.98	-1.19	-0.78	0.10	0.41	0.28	0.54	0.07	0.14	0.08	0.37	0.11	1.17
DBH (QSM) WLS	-0.97	-1.22	-0.71	0.13	0.40	0.25	0.56	0.08	0.25	0.04	0.54	0.15	1.00
DBH(QSM)xH OLS	3.15	2.68	3.63	0.24	0.21	0.15	0.26	0.03	1.83	-1.48	2.18	0.18	1.10
DBH(QSM)xH WLS	3.14	2.73	3.56	0.21	0.18	0.12	0.24	0.03	1.74	-1.39	2.09	0.18	1.00
H OLS	-1.59	-2.01	-1.18	0.21	0.28	-0.24	0.81	0.27	1.67	-0.66	2.67	0.50	1.07
H WLS	-1.79	-2.22	-1.36	0.22	0.10	-0.40	0.59	0.25	2.09	-1.11	3.08	0.50	1.00
V (Bounding Box) OLS	0.23	0.13	0.33	0.05	0.05	-0.03	0.12	0.04	0.94	-0.86	1.02	0.04	1.06
V (Bounding Box) WLS	0.30	0.20	0.41	0.05	0.00	-0.07	0.07	0.04	0.97	-0.90	1.04	0.04	1.00
V (QSM) OLS	-1.06	-1.32	-0.80	0.13	0.10	0.04	0.16	0.03	0.27	0.00	0.53	0.13	1.10
V (QSM) WLS	-1.25	-1.55	-0.96	0.15	0.06	0.00	0.12	0.03	0.49	-0.22	0.76	0.14	1.00

Table S7. Model rankings based on accuracy and goodness of fit statistics (average mean absolute error (Avg MAE), average root mean square error (Avg RMSE), and average adjusted R^2 (Avg Adj R^2)) from the leave-one-plot-out cross validation. The coefficient of variation in the RMSE (CV RMSE) is an indication of the model's robustness. The final column shows the sum of the three rankings and was used to select the best models appearing in Table 3 of the main manuscript. Multi Pwr = multiple regression power, Pwr = power, Quad = quadratic, CA = crown area, CD = crown diameter, H = height, V (Bounding Box) = bounding box volume, DBH = diameter at breast height, V (QSM) = volume derived from quantitative structure models, WLS = model fitted using weighted least squares, OLS = model fitted using ordinary least squares.

Model Type	Model	Avg MAE	Ranking 1	Avg RMSE	Ranking 2	Avg Adj R^2	Ranking 3	CV RMSE	Total Sum of Rankings
Multi Pwr	CAxH WLS	0.22	1	0.34	1	0.94	1	0.60	3
Multi Pwr	CDxH WLS	0.22	1	0.34	1	0.94	1	0.60	3
Multi Pwr	CAxH OLS	0.22	1	0.34	1	0.92	5	0.60	7
Multi Pwr	CDxH OLS	0.22	1	0.34	1	0.92	5	0.60	7
Pwr	CDxH WLS	0.25	5	0.38	5	0.94	1	0.52	11
Quad	CDxH WLS	0.26	7	0.39	7	0.94	1	0.52	15
Pwr	CDxH OLS	0.25	5	0.38	5	0.91	7	0.53	17
Quad	CDxH OLS	0.28	8	0.43	8	0.91	7	0.71	23
Pwr	CAxH WLS	0.37	10	0.53	9	0.90	9	0.55	28
Quad	CAxH WLS	0.38	11	0.56	11	0.90	9	0.60	31
Pwr	CAxH OLS	0.36	9	0.53	9	0.86	16	0.53	34
Pwr	V (Bounding Box) WLS	0.40	12	0.59	13	0.89	11	0.60	36
Quad	V (Bounding Box) WLS	0.41	14	0.60	14	0.89	11	0.60	39
Pwr	V (Bounding Box) OLS	0.40	12	0.58	12	0.86	16	0.58	40
Pwr	H WLS	0.45	16	0.63	15	0.88	13	0.74	44
Multi Pwr	DBHxH WLS	0.46	20	0.64	18	0.88	13	0.80	51
Multi Pwr	DBHxH OLS	0.45	16	0.63	15	0.84	20	0.96	51
Pwr	H OLS	0.45	16	0.63	15	0.84	20	0.73	51
Quad	CAxH OLS	0.44	15	0.70	22	0.86	16	0.80	53
Quad	H WLS	0.47	21	0.65	19	0.88	13	0.75	53
Quad	V (Bounding Box) OLS	0.45	16	0.69	21	0.86	16	0.78	53
Quad	H OLS	0.47	21	0.68	20	0.84	20	0.64	61

Pwr	V (QSM) WLS	0.50	23	0.70	22	0.82	24	0.94	69
Quad	V (QSM)WLS	0.50	23	0.78	25	0.83	23	0.83	71
Pwr	V (QSM) OLS	0.53	25	0.72	24	0.76	28	1.00	77
Quad	DBHxH WLS	0.56	26	0.79	26	0.81	25	0.86	77
Quad	DBHxH OLS	0.58	28	0.86	27	0.78	26	0.87	81
Pwr	DBHxH WLS	0.67	29	0.90	28	0.73	29	0.87	86
Quad	V (QSM) OLS	0.57	27	0.97	33	0.78	26	0.89	86
Pwr	CA WLS	0.67	29	0.95	29	0.71	30	0.55	88
Pwr	CD WLS	0.67	29	0.95	29	0.71	30	0.55	88
Quad	CA WLS	0.67	29	0.95	29	0.70	32	0.55	90
Quad	CD WLS	0.67	29	0.95	29	0.70	32	0.55	90
Pwr	CA OLS	0.69	34	0.99	35	0.65	35	0.54	104
Pwr	CD OLS	0.69	34	0.99	35	0.65	35	0.54	104
Quad	CA OLS	0.69	34	1.03	37	0.65	35	0.62	106
Quad	CD OLS	0.69	34	1.03	37	0.65	35	0.62	106
Pwr	DBHxH OLS	0.71	38	0.98	34	0.65	35	0.87	107
Quad	DBH WLS	0.83	40	1.18	39	0.66	34	0.69	113
Quad	DBH OLS	0.82	39	1.22	40	0.63	40	0.72	119
Pwr	DBH WLS	0.92	41	1.24	41	0.56	41	0.69	123
Pwr	DBH OLS	0.92	41	1.29	42	0.47	42	0.71	125