Canadian national biomass equations: new parameter estimates that include British Columbia data

Chhun-Huor Ung, Pierre Bernier, and Xiao-Jing Guo

Abstract: National allometric equations covering the most common tree species of Canada's forests were produced based on tree mass data acquired in the early 1980s during the ENergy from the FORest (ENFOR) program. The equations allow us to calculate the mass estimate of four tree components (foliage, branches, stem bark, and stem wood) using either diameter at breast height or a combination of diameter at breast height and height. Missing from that data set, however, were the data from British Columbia. A usable British Columbia data set was finally found and has now been incorporated into the national data set. Here, we present revised allometric equations for six species covered in the previous work and also found in the British Columbia data set as well as for the "hardwoods", "softwoods", and "all species" equations. New equations are also provided for eight species specific to the British Columbia data.

Résumé : Des équations allométriques nationales pour la majorité des essences commerciales de la forêt canadienne ont été produites à partir de données acquises au début des années 1980 par le biais du programme « ÉNergie de la FORêt » (ENFOR). Les équations permettent l'évaluation de la masse de quatre composantes de l'arbre (feuillage, branches, écorce de la tige et bois de la tige) à partir soit du diamètre à hauteur de poitrine, soit du diamètre à hauteur de poitrine et de la hauteur. Malheureusement, il avait été impossible de localiser une version utilisable des données de la Colombie-Britannique. La persévérance a porté ses fruits, et un jeu de données utilisable a été localisé récemment et incorporé à la base de données nationale. Nous présentons un nouveau jeu de paramètres pour six essences couvertes dans les travaux antérieurs et également présentes dans la base de données de la Colombie-Britannique, ainsi que pour les équations des regroupements « feuillus », « résineux » et « toutes essences ». Nous présentons aussi de nouvelles équations pour huit essences qui sont spécifiques à cette base de données.

Introduction

Estimating forest biomass rests on the use of allometric equations that convert the mensuration of trees, either diameter or height, into the mass of tree components or mass of the whole tree. However, most allometric equations are local in application, fail to provide the variance of parameters, or are not internally consistent. In the early 1980s, the ENergy from the FORest (ENFOR) program sponsored a Canadian Forest Service-wide biomass project. Thousands of trees were sampled, and regional allometric equations were produced, relating the mass of foliage, branches, bark, and trunks to the diameter at breast height (DBH) and height of the trees. Appendix A of Lambert et al. (2005) contains a complete list of ENFOR references containing most of the original biomass equations. These equations were helpful, but remained regional and incomplete, prompting Canadian Forest Service researchers to produce national equations using the original ENFOR data (Lambert et al. 2005). However, the British Columbia (BC) ENFOR data (Talisman Land Resource Consultants 1982) were recovered only after the article by Lambert et al. (2005) on the first set of national allometric equations was published. This left an important and well-acknowledged gap in the initial report.

We have now redone the analyses of Lambert et al. (2005) using an ENFOR data set that now contains data from trees that were sampled in BC. This note presents revised parameter values for species covered in Lambert et al. (2005) but also sampled in BC, as well as parameter values for species that were sampled only in BC. New parameter values are also presented for the three species aggregates: "hardwoods", "softwoods", and "all species".

Received 14 September 2007. Accepted 23 November 2007. Published on the NRC Research Press Web site at cjfr.nrc.ca on 23 April 2008.

C.-H. Ung[1] and X.-J. Guo.[2] Natural Resources Canada, Canadian Forest Service, Canadian Wood Fibre Centre, P.O. Box 10380, Stn. Sainte-Foy, QC G1V 4C7, Canada.
P. Bernier. Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, P.O. Box 10380, Stn. Sainte-Foy, QC G1V 4C7, Canada.

[1]Corresponding author (e-mail: cung@nrcan.gc.ca).
[2]Present address: Ministère des Ressources naturelles et de la Faune, Direction de la recherche forestière, 2700, rue Einstein, QC G1P 3W8, Canada.

Material and methods

Details of the original ENFOR sampling and processing methods were recovered from the original reports and are summarized in Lambert et al. (2005). Figure 1 presents the geographical coverage of the newly completed database. The addition of 573 sampled stems from BC (Table 1) pushed the total sample number to 9209 stems for all of Canada. The new BC data cover 14 species, 8 of which are unique to that data set. Descriptive statistics per species, given in Table 2, provide domain bounds beyond which the application of the empirical allometric equations is not recommended.

The analysis was done as in Lambert et al. (2005). Model adjustment involved refitting the national equations for species whose ranges extend into BC (black spruce, lodgepole pine, subalpine fir, trembling aspen, white birch, and white spruce). We also developed new equations for species unique to the BC data set (black cottonwood, Douglas-fir, Engelmann spruce, Pacific silver fir, red alder, Sitka spruce, western hemlock, western redcedar). English and French common names and scientific names are listed in Appendix A. Parameters were also re-estimated for the "all hardwoods", "all softwoods" and "all species" equations. Small sample size forced us to group red alder and black cottonwood together as if they were one species. Coastal Douglas-fir and interior Douglas-fir were also grouped under the heading "Douglas-fir".

Parameters were estimated with either DBH or with DBH and height for all species. The DBH-based equations are as follows:

$$[1] \quad \begin{aligned} y_{\text{wood}} &= \beta_{\text{wood1}} D^{\beta\ \text{wood2}} + e_{\text{wood}} \\ y_{\text{bark}} &= \beta_{\text{bark1}} D^{\beta\ \text{bark2}} + e_{\text{bark}} \\ y_{\text{stem}} &= \widehat{y}_{\text{wood}} + \widehat{y}_{\text{bark}} + e_{\text{stem}} \\ y_{\text{foliage}} &= \beta_{\text{foliage1}} D^{\beta\ \text{foliage2}} + e_{\text{foliage}} \\ y_{\text{branches}} &= \beta_{\text{branches1}} D^{\beta\ \text{branches2}} + e_{\text{branches}} \\ y_{\text{crown}} &= \widehat{y}_{\text{foliage}} + \widehat{y}_{\text{branches}} + e_{\text{crown}} \\ y_{\text{total}} &= \widehat{y}_{\text{wood}} + \widehat{y}_{\text{bark}} + \widehat{y}_{\text{foliage}} + \widehat{y}_{\text{branches}} + e_{\text{total}} \end{aligned}$$

where y_i is the dry mass of compartment i (wood, bark, foliage, or branches, in kg), $\widehat{y}_i$ is the modeled value of y_i, D is tree DBH (cm), β_{ik} are the parameters to be estimated (i is as above, k = 1 or 2), and e_i is the error term for compartment i. The DBH- and height-based equations are as follows:

$$[2] \quad \begin{aligned} y_{\text{wood}} &= \beta_{\text{wood1}} D^{\beta\ \text{wood2}} H^{\beta\ \text{wood3}} + e_{\text{wood}} \\ y_{\text{bark}} &= \beta_{\text{bark1}} D^{\beta\ \text{bark2}} H^{\beta\ \text{bark3}} + e_{\text{bark}} \\ y_{\text{stem}} &= \widehat{y}_{\text{wood}} + \widehat{y}_{\text{bark}} + e_{\text{stem}} \\ y_{\text{foliage}} &= \beta_{\text{foliage1}} D^{\beta\ \text{foliage2}} H^{\beta\ \text{foliage3}} + e_{\text{foliage}} \\ y_{\text{branches}} &= \beta_{\text{branches1}} D^{\beta\ \text{branches2}} H^{\beta\ \text{branches2}} + e_{\text{branches}} \\ y_{\text{crown}} &= \widehat{y}_{\text{foliage}} + \widehat{y}_{\text{branches}} + e_{\text{crown}} \\ y_{\text{total}} &= \widehat{y}_{\text{wood}} + \widehat{y}_{\text{bark}} + \widehat{y}_{\text{foliage}} + \widehat{y}_{\text{branches}} + e_{\text{total}} \end{aligned}$$

where H is total tree height (m) and k = 1, 2, or 3. All other terms are as above.

Parameters estimation was performed using the seemingly unrelated regression (SUR) technique (Gallant 1987) within the MODEL procedure in SAS/ETS (SAS Institute Inc. 1999). This technique minimizes the sum of squared residuals across all equations simultaneously within the equation system. The parameters and predictions made from these SUR-fitted equations are described in Lambert et al. (2005). However, the cardinal is one of additivity: the sum of individual component predictions is equal to the predicted total of the aboveground tree component, a property that is not always assured in tree component allometric equations.

Results and discussion

Parameter estimates and their standard error for the DBH-based equations and for the DBH- and height-based equations are presented in Tables 3 and 4. For black spruce, trembling aspen, white spruce, and white birch, the new parameter values for the DBH-based equations yield total aboveground biomass estimates for a DBH of 30 cm that are within 1% of those obtained using the Lambert et al. (2005) equations. This is to be expected as the new trees added to the BC data make up about 4% of the total tree number for black spruce, trembling aspen, and white birch, and 12% for white spruce. For lodgepole pine, the new data set adds 39% of new trees, and the new parameters of the DBH-based equation yield total aboveground biomass estimates that are 9% lower than those obtained with Lambert et al. (2005).

Fig. 1. Distribution of plot biomass measured by the ENergy from the FORest (ENFOR) program (when location is available).

As in Lambert et al. (2005), analysis of the adjusted R^2 and of the RMSE (Table 5) show that crown equations are associated with higher prediction errors than are stem equations, that DBH is essential for predicting crown biomass compartments, and that height provides little additional predictive power for these compartments. Moreover, Lambert et al. (2005) showed that, for a set of selected species, total biomasses predicted by equations found in Ter-Mikaelian and Korzukhin (1997) were within the 95% prediction interval of the predictions obtained with national equations. These comparisons were not redone, but their results hint at the larger problem of variability over space and of differences among species, a problem that also encompasses the 9% difference in the lodgepole pine biomass estimates mentioned above. Users of allometric equations must for example decide on whether to use local or national equations, or on how to decide what equation to use for species for which allometric equations do not exist. And nationally, we must decide if the collection of additional tree data for regions or species not well covered in the current ENFOR data set is necessary. Answers to these questions can only be given following a rigorous statistical analysis, likely using the mixed model approach, in which the sources of variability are

Table 1. Number of trees per province and territory for each species represented in the new BC data set.

	Province/territory										
Species	AB	BC	MB	NL	NS	NT	ON	QC	SK	YK	Total
Black cottonwood		19									19
Black spruce	20	57	20	300	49	48	73	714	20	290	1591
Douglas-fir (coastal)		14									14
Douglas-fir (interior)		11									11
Engelmann spruce		26									26
Lodgepole pine	60	79								141	280
Pacific silver fir		28									28
Red alder		11									11
Sitka spruce		12									12
Subalpine fir	60	73									133
Trembling aspen	20	26	19	67	46	54	226	133	20	188	799
Western hemlock		48									48
Western redcedar		47									47
White birch	20	23	20	270	44		134	98	20		629
White spruce	20	99	20	164	44	56	76	78	20	354	931
Total	200	573	79	801	183	158	509	1023	80	973	4579

Table 2. Descriptive statistics for DBH, height, and total biomass by tree species.

Species	Trees	DBH (cm)	Height (m)	Total biomass (kg)
Black cottonwood	19	16.7±1.7 (7.4; 30.6)	13.6±1.1 (6.9; 23.5)	102.5±26.2 (13.4; 366.3)
Black spruce	1591	14.0±0.2 (1.6; 38.4)	11.7±0.1 (1.8; 30.1)	74.5±1.9 (0.6; 685.1)
Douglas-fir (coastal)	14	15.6±3.5 (4.5; 50.8)	10.8±2.3 (4.1; 31.2)	166.6±98.9 (4.9; 1394.5)
Douglas-fir (interior)	11	17.6±4.0 (5.6; 39.5)	10.8±2.1 (3.6; 21.7)	193.0±81.9 (5.6; 803.8)
Engelmann spruce	26	24.2±2.6 (5.7; 57.6)	17.5±1.7 (4.4; 40.8)	319.7±82.7 (5.8; 1923.5)
Lodgepole pine	280	16.1±0.5 (2.5; 48.9)	13.5±0.4 (2.3; 39.6)	128.4±10.0 (0.8; 1180.9)
Pacific silver fir	28	14.3±1.1 (4.5; 30.4)	10.3±0.7 (3.1; 18.4)	64.2±11.9 (4.2; 313.3)
Red alder	11	12.2±0.9 (9.3; 19.5)	11.8±0.6 (7.4; 14.5)	36.7±9.3 (12.4; 123.8)
Sitka spruce	12	14.5±2.2 (7.2; 27.3)	10.5±1.4 (4.6; 17.7)	73.6±24.4 (8.7; 233.8)
Subalpine fir	133	17.9±0.9 (2.1; 44.4)	12.5±0.6 (2.2; 27.9)	149.2±16.0 (1.7; 1085.2)
Trembling aspen	799	17.7±0.3 (0.7; 47.2)	15.8±0.2 (1.8; 28.3)	161.1±7.0 (0.1; 1081.5)
Western hemlock	48	16.3±1.2 (3.1; 42.4)	12.3±1.0 (3.5; 28.3)	113.8±22.9 (2.5; 796.8)
Western redcedar	47	19.0±1.6 (5.6; 54.2)	12.4±0.9 (3.8; 32.4)	130.1±29.0 (5.8; 1153.9)
White birch	629	16.4±0.3 (1.5; 43.6)	13.3±0.2 (2.6; 23.9)	149.9±6.9 (0.4; 1020.8)
White spruce	931	16.8±0.3 (1.8; 57.6)	12.9±0.2 (1.1; 37.5)	133.1±6.3 (0.4; 1577.7)

Note: Each mean (±SE) has been calculated from the number of trees. Values in parentheses indicate the range.

Table 3. Model parameter estimates and their standard error for the DBH-based set of equations for each species, for all hardwoods, for all softwoods, and for all species combined.

Species	Parameter	Estimate	SE
Black spruce	β_{wood1}	0.0494	0.0012
	β_{wood2}	2.5025	0.0083
	β_{bark1}	0.0148	0.0004
	β_{bark2}	2.2494	0.0100
	$\beta_{\mathrm{branches1}}$	0.0291	0.0019
	$\beta_{\mathrm{branches2}}$	2.0751	0.0238
	$\beta_{\mathrm{foliage1}}$	0.1631	0.0083
	$\beta_{\mathrm{foliage2}}$	1.4222	0.0200
Douglas-fir	β_{wood1}	0.0204	0.0079
	β_{wood2}	2.6974	0.1066
	β_{bark1}	0.0069	0.0016
	β_{bark2}	2.5462	0.0698
	$\beta_{\mathrm{branches1}}$	0.0404	0.0181
	$\beta_{\mathrm{branches2}}$	2.1388	0.1334
	$\beta_{\mathrm{foliage1}}$	0.1233	0.0717
	$\beta_{\mathrm{foliage2}}$	1.6636	0.1806
Engelmann spruce	β_{wood1}	0.0223	0.0033
	β_{wood2}	2.7169	0.0455
	β_{bark1}	0.0118	0.0016
	β_{bark2}	2.2733	0.0391
	$\beta_{\mathrm{branches1}}$	0.0336	0.0125
	$\beta_{\mathrm{branches2}}$	2.2123	0.1085
	$\beta_{\mathrm{foliage1}}$	0.0683	0.0170
	$\beta_{\mathrm{foliage2}}$	1.8022	0.0827
Lodgepole pine	β_{wood1}	0.0323	0.0021
	β_{wood2}	2.6825	0.0209
	β_{bark1}	0.0144	0.0010
	β_{bark2}	2.1768	0.0225
	$\beta_{\mathrm{branches1}}$	0.0209	0.0029
	$\beta_{\mathrm{branches2}}$	2.1772	0.0485
	$\beta_{\mathrm{foliage1}}$	0.0584	0.0059
	$\beta_{\mathrm{foliage2}}$	1.6432	0.0357
Pacific silver fir	β_{wood1}	0.0424	0.0096
	β_{wood2}	2.4289	0.0794
	β_{bark1}	0.0057	0.0015
	β_{bark2}	2.4786	0.0922
	$\beta_{\mathrm{branches1}}$	0.0322	0.0098
	$\beta_{\mathrm{branches2}}$	2.1313	0.0944
	$\beta_{\mathrm{foliage1}}$	0.0645	0.0105
	$\beta_{\mathrm{foliage2}}$	1.9400	0.0611
Red alder and Black cottonwood	β_{wood1}	0.0460	0.0137
	β_{wood2}	2.4312	0.1056
	β_{bark1}	0.0074	0.0024
	β_{bark2}	2.4442	0.1119
	$\beta_{\mathrm{branches1}}$	0.0086	0.0039
	$\beta_{\mathrm{branches2}}$	2.7326	0.1424
	$\beta_{\mathrm{foliage1}}$	0.0114	0.0061
	$\beta_{\mathrm{foliage2}}$	2.0860	0.1819
Sitka spruce	β_{wood1}	0.0302	0.0048
	β_{wood2}	2.5776	0.0493
	β_{bark1}	0.0066	0.0043
	β_{bark2}	2.4433	0.2000
	$\beta_{\mathrm{branches1}}$	0.0739	0.0267
	$\beta_{\mathrm{branches2}}$	1.8342	0.1319
	$\beta_{\mathrm{foliage1}}$	0.0157	0.0048

Table 3 (*continued*).

Species	Parameter	Estimate	SE
	$\beta_{\mathrm{foliage2}}$	2.3113	0.1136
Subalpine fir	β_{wood1}	0.0250	0.0026
	β_{wood2}	2.6378	0.0319
	β_{bark1}	0.0061	0.0007
	β_{bark2}	2.5375	0.0336
	$\beta_{\mathrm{branches1}}$	0.0178	0.0044
	$\beta_{\mathrm{branches2}}$	2.4255	0.0759
	$\beta_{\mathrm{foliage1}}$	0.0416	0.0081
	$\beta_{\mathrm{foliage2}}$	2.0130	0.0610
Trembling aspen	β_{wood1}	0.0608	0.0029
	β_{wood2}	2.4735	0.0153
	β_{bark1}	0.0159	0.0006
	β_{bark2}	2.4123	0.0131
	$\beta_{\mathrm{branches1}}$	0.0082	0.0008
	$\beta_{\mathrm{branches2}}$	2.5139	0.0327
	$\beta_{\mathrm{foliage1}}$	0.0235	0.0032
	$\beta_{\mathrm{foliage2}}$	1.6656	0.0440
Western hemlock	β_{wood1}	0.0141	0.0028
	β_{wood2}	2.8668	0.0696
	β_{bark1}	0.0025	0.0004
	β_{bark2}	2.8062	0.0555
	$\beta_{\mathrm{branches1}}$	0.0703	0.0115
	$\beta_{\mathrm{branches2}}$	1.9547	0.0653
	$\beta_{\mathrm{foliage1}}$	0.1676	0.0298
	$\beta_{\mathrm{foliage2}}$	1.4339	0.0572
Western redcedar	β_{wood1}	0.0111	0.0016
	β_{wood2}	2.8027	0.0438
	β_{bark1}	0.0003	0.0001
	β_{bark2}	3.2721	0.0770
	$\beta_{\mathrm{branches1}}$	0.1158	0.0329
	$\beta_{\mathrm{branches2}}$	1.7196	0.0863
	$\beta_{\mathrm{foliage1}}$	0.1233	0.0524
	$\beta_{\mathrm{foliage2}}$	1.5152	0.1346
White birch	β_{wood1}	0.0604	0.0016
	β_{wood2}	2.4959	0.0090
	β_{bark1}	0.0140	0.0008
	β_{bark2}	2.3923	0.0195
	$\beta_{\mathrm{branches1}}$	0.0147	0.0009
	$\beta_{\mathrm{branches2}}$	2.5227	0.0217
	$\beta_{\mathrm{foliage1}}$	0.0591	0.0026
	$\beta_{\mathrm{foliage2}}$	1.6036	0.0167
White spruce	β_{wood1}	0.0334	0.0008
	β_{wood2}	2.5980	0.0086
	β_{bark1}	0.0114	0.0004
	β_{bark2}	2.3057	0.0115
	$\beta_{\mathrm{branches1}}$	0.0302	0.0019
	$\beta_{\mathrm{branches2}}$	2.0927	0.0227
	$\beta_{\mathrm{foliage1}}$	0.1515	0.0079
	$\beta_{\mathrm{foliage2}}$	1.5012	0.0182
All hardwoods	β_{wood1}	0.0864	0.0015
	β_{wood2}	2.3715	0.0053
	β_{bark1}	0.0226	0.0008
	β_{bark2}	2.2151	0.0112
	$\beta_{\mathrm{branches1}}$	0.0186	0.0007
	$\beta_{\mathrm{branches2}}$	2.4462	0.0127
	$\beta_{\mathrm{foliage1}}$	0.0385	0.0010
	$\beta_{\mathrm{foliage2}}$	1.6255	0.0089

Table 3 (*concluded*).

Species	Parameter	Estimate	SE
All softwoods	β_{wood1}	0.0564	0.0010
	β_{wood2}	2.4347	0.0059
	β_{bark1}	0.0153	0.0002
	β_{bark2}	2.2110	0.0055
	$\beta_{branches1}$	0.0194	0.0006
	$\beta_{branches2}$	2.2408	0.0097
	$\beta_{foliage1}$	0.0935	0.0025
	$\beta_{foliage2}$	1.6106	0.0094
All species	β_{wood1}	0.0741	0.0012
	β_{wood2}	2.3875	0.0051
	β_{bark1}	0.0182	0.0002
	β_{bark2}	2.2181	0.0041
	$\beta_{branches1}$	0.0227	0.0006
	$\beta_{branches2}$	2.2797	0.0093
	$\beta_{foliage1}$	0.0764	0.0021
	$\beta_{foliage2}$	1.5861	0.0096

Table 4. Model parameter estimates and their standard error for the DBH- and height-based set of equations for each species, for all hardwoods, for all softwoods, and for all species combined.

Species	Parameter	Estimate	SE
Black spruce	β_{wood1}	0.0335	0.0005
	β_{wood2}	1.7389	0.0120
	β_{wood3}	0.9835	0.0142
	β_{bark1}	0.0132	0.0005
	β_{bark2}	1.7657	0.0276
	β_{bark3}	0.5775	0.0310
	$\beta_{branches1}$	0.0405	0.0026
	$\beta_{branches2}$	3.1917	0.0550
	$\beta_{branches3}$	–1.3674	0.0610
	$\beta_{foliage1}$	0.2078	0.0085
	$\beta_{foliage2}$	2.5517	0.0497
	$\beta_{foliage3}$	–1.3453	0.0561
Douglas-fir	β_{wood1}	0.0191	0.0014
	β_{wood2}	1.5365	0.0640
	β_{wood3}	1.3634	0.0676
	β_{bark1}	0.0083	0.0014
	β_{bark2}	2.4811	0.0512
	β_{bark3}	—	—
	$\beta_{branches1}$	0.0351	0.0070
	$\beta_{branches2}$	2.2421	0.0662
	$\beta_{branches3}$	—	—
	$\beta_{foliage1}$	0.0718	0.0121
	$\beta_{foliage2}$	2.2935	0.1839
	$\beta_{foliage3}$	–0.4744	0.2061
Engelmann spruce	β_{wood1}	0.0133	0.0011
	β_{wood2}	1.3303	0.0876
	β_{wood3}	1.6877	0.1022
	β_{bark1}	0.0086	0.0015
	β_{bark2}	1.6216	0.1587
	β_{bark3}	0.8192	0.1849
	$\beta_{branches1}$	0.0428	0.0071
	$\beta_{branches2}$	2.7965	0.1789
	$\beta_{branches3}$	–0.7328	0.1880
	$\beta_{foliage1}$	0.0854	0.0180

Table 4 (*continued*).

Species	Parameter	Estimate	SE
	$\beta_{foliage2}$	2.4388	0.1770
	$\beta_{foliage3}$	–0.7630	0.1990
Lodgepole pine	β_{wood1}	0.0239	0.0016
	β_{wood2}	1.6827	0.0385
	β_{wood3}	1.1878	0.0467
	β_{bark1}	0.0117	0.0007
	β_{bark2}	1.6398	0.0556
	β_{bark3}	0.6524	0.0646
	$\beta_{branches1}$	0.0285	0.0025
	$\beta_{branches2}$	3.3764	0.1032
	$\beta_{branches3}$	–1.4395	0.1081
	$\beta_{foliage1}$	0.0769	0.0057
	$\beta_{foliage2}$	2.6834	0.0949
	$\beta_{foliage3}$	–1.2484	0.1009
Pacific silver fir	β_{wood1}	0.0315	0.0045
	β_{wood2}	1.8297	0.1083
	β_{wood3}	0.8056	0.1233
	β_{bark1}	0.0067	0.0014
	β_{bark2}	2.6970	0.1843
	β_{bark3}	–0.3105	0.2149
	$\beta_{branches1}$	0.0420	0.0151
	$\beta_{branches2}$	2.0313	0.1375
	$\beta_{branches3}$	—	—
	$\beta_{foliage1}$	0.0453	0.0099
	$\beta_{foliage2}$	2.4867	0.2372
	$\beta_{foliage3}$	–0.4982	0.2499
Red alder	β_{wood1}	0.0051	0.0008
Black cottonwood	β_{wood2}	1.0697	0.0696
	β_{wood3}	2.2748	0.1011
	β_{bark1}	0.0009	0.0002
	β_{bark2}	1.3061	0.0922
	β_{bark3}	2.0109	0.1212
	$\beta_{branches1}$	0.0131	0.0053
	$\beta_{branches2}$	2.5760	0.1363
	$\beta_{branches3}$	—	—
	$\beta_{foliage1}$	0.0224	0.0159
	$\beta_{foliage2}$	1.8368	0.2825
	$\beta_{foliage3}$	—	—
Sitka spruce	β_{wood1}	0.0237	0.0037
	β_{wood2}	2.5813	0.1090
	β_{wood3}	0.0822	0.1336
	β_{bark1}	0.0045	0.0019
	β_{bark2}	1.2275	0.2742
	β_{bark3}	1.5190	0.3787
	$\beta_{branches1}$	0.0498	0.0157
	$\beta_{branches2}$	1.9671	0.1242
	$\beta_{branches3}$	—	—
	$\beta_{foliage1}$	0.0140	0.0037
	$\beta_{foliage2}$	3.1305	0.2663
	$\beta_{foliage3}$	–0.9070	0.2778
Subalpine fir	β_{wood1}	0.0220	0.0016
	β_{wood2}	1.6469	0.0516
	β_{wood3}	1.1714	0.0576
	β_{bark1}	0.0061	0.0005
	β_{bark2}	1.8603	0.0893
	β_{bark3}	0.7693	0.0959
	$\beta_{branches1}$	0.0265	0.0051

Table 4 (*concluded*).

Species	Parameter	Estimate	SE
	$\beta_{branches2}$	3.6747	0.2086
	$\beta_{branches3}$	–1.5958	0.1984
	$\beta_{foliage1}$	0.0509	0.0087
	$\beta_{foliage2}$	2.9909	0.1908
	$\beta_{foliage3}$	–1.2271	0.1860
Trembling aspen	β_{wood1}	0.0143	0.0005
	β_{wood2}	1.9369	0.0169
	β_{wood3}	1.0579	0.0259
	β_{bark1}	0.0063	0.0005
	β_{bark2}	2.0744	0.0343
	β_{bark3}	0.6691	0.0511
	$\beta_{branches1}$	0.0150	0.0012
	$\beta_{branches2}$	2.9068	0.0436
	$\beta_{branches3}$	–0.6306	0.0620
	$\beta_{foliage1}$	0.0284	0.0017
	$\beta_{foliage2}$	1.6020	0.0213
	$\beta_{foliage3}$	—	—
Western hemlock	β_{wood1}	0.0113	0.0010
	β_{wood2}	1.9332	0.0451
	β_{wood3}	1.1125	0.0445
	β_{bark1}	0.0019	0.0003
	β_{bark2}	2.3356	0.0840
	β_{bark3}	0.6371	0.0810
	$\beta_{branches1}$	0.0609	0.0148
	$\beta_{branches2}$	2.0021	0.0906
	$\beta_{branches3}$	—	—
	$\beta_{foliage1}$	0.2656	0.0469
	$\beta_{foliage2}$	2.0107	0.1379
	$\beta_{foliage3}$	–0.7963	0.1587
Western redcedar	β_{wood1}	0.0188	0.0012
	β_{wood2}	1.3376	0.0562
	β_{wood3}	1.5293	0.0647
	β_{bark1}	0.0002	0.0000
	β_{bark2}	2.4369	0.1197
	β_{bark3}	1.1315	0.1254
	$\beta_{branches1}$	0.0611	0.0167
	$\beta_{branches2}$	1.9208	0.0838
	$\beta_{branches3}$	—	—
	$\beta_{foliage1}$	0.1097	0.0411
	$\beta_{foliage2}$	1.5530	0.1221
	$\beta_{foliage3}$	—	—
White birch	β_{wood1}	0.0333	0.0011
	β_{wood2}	2.0794	0.0157
	β_{wood3}	0.6811	0.0234
	β_{bark1}	0.0079	0.0005
	β_{bark2}	1.9905	0.0307
	β_{bark3}	0.6553	0.0451
	$\beta_{branches1}$	0.0253	0.0020
	$\beta_{branches2}$	3.1518	0.0492
	$\beta_{branches3}$	–0.9083	0.0682
	$\beta_{foliage1}$	0.1361	0.0088
	$\beta_{foliage2}$	2.2978	0.0525
	$\beta_{foliage3}$	–1.0934	0.0733
White spruce	β_{wood1}	0.0252	0.0006
	β_{wood2}	1.7819	0.0174
	β_{wood3}	1.0022	0.0199
	β_{bark1}	0.0096	0.0004

Table 4 (*concluded*).

Species	Parameter	Estimate	SE
	β_{bark2}	1.6901	0.0393
	β_{bark3}	0.7393	0.0441
	$\beta_{branches1}$	0.0322	0.0019
	$\beta_{branches2}$	2.8961	0.0592
	$\beta_{branches3}$	–0.9203	0.0641
	$\beta_{foliage1}$	0.1832	0.0080
	$\beta_{foliage2}$	2.4144	0.0518
	$\beta_{foliage3}$	–1.0948	0.0573
All hardwoods	β_{wood1}	0.0353	0.0009
	β_{wood2}	2.0249	0.0100
	β_{wood3}	0.7048	0.0167
	β_{bark1}	0.0090	0.0005
	β_{bark2}	1.8677	0.0205
	β_{bark3}	0.7144	0.0332
	$\beta_{branches1}$	0.0448	0.0024
	$\beta_{branches2}$	2.6855	0.0306
	$\beta_{branches3}$	–0.5911	0.0456
	$\beta_{foliage1}$	0.0869	0.0038
	$\beta_{foliage2}$	1.8541	0.0262
	$\beta_{foliage3}$	–0.5491	0.0407
All softwoods	β_{wood1}	0.0276	0.0003
	β_{wood2}	1.6868	0.0068
	β_{wood3}	1.0953	0.0087
	β_{bark1}	0.0101	0.0002
	β_{bark2}	1.8486	0.0167
	β_{bark3}	0.5525	0.0204
	$\beta_{branches1}$	0.0313	0.0008
	$\beta_{branches2}$	2.9974	0.0200
	$\beta_{branches3}$	–1.0383	0.0245
	$\beta_{foliage1}$	0.1379	0.0034
	$\beta_{foliage2}$	2.3981	0.0224
	$\beta_{foliage3}$	–1.0418	0.0271
All species	β_{wood1}	0.0283	0.0004
	β_{wood2}	1.8298	0.0075
	β_{wood3}	0.9546	0.0101
	β_{bark1}	0.012	0.0003
	β_{bark2}	1.6378	0.017
	β_{bark3}	0.7746	0.0233
	$\beta_{branches1}$	0.0338	0.0008
	$\beta_{branches2}$	2.6624	0.0182
	$\beta_{branches3}$	–0.5743	0.0233
	$\beta_{foliage1}$	0.1699	0.0036
	$\beta_{foliage2}$	2.3289	0.0184
	$\beta_{foliage3}$	–1.1316	0.0235

Note: Missing values (—) correspond to parameter estimates not significantly different from zero (α = 0.05).

clearly attributed to different degrees of geographic aggregation (e.g., within plot, region, and ecozone) or of species aggregation.

Conclusion

The equations presented in this report and in Lambert et al. (2005) provide an important national-level tool for estimating tree biomass. We have discussed above how the question of choosing between local versus national equations could be tackled on theoretical grounds. From a more pragmatic point of view, however, we recommend the use of

Table 5. Nonlinear seemingly unrelated regression fit statistics with weight function.

		DBH-based system of equations					DBH- and height-based system of equations				
Species	Model	$\widehat{\sigma}^2_{\mathrm{SUR}}$	$\widehat{\sigma}$	R^2_{adj}	RMSE	c	$\widehat{\sigma}^2_{\mathrm{SUR}}$	$\widehat{\sigma}$	R^2_{adj}	RMSE	c
Black spruce	Wood	1.0002	0.0132	0.92	14.8	3.26	1.0004	0.0007	0.98	7.9	3.90
	Bark		0.0003	0.90	2.2	3.32		0.0000	0.93	1.8	3.91
	Stem		0.0168	0.93	16.1	3.24		0.0008	0.98	8.5	3.93
	Branches		0.0014	0.61	7.6	3.53		0.0008	0.69	6.8	3.62
	Foliage		0.0106	0.52	5.2	2.79		0.0076	0.59	4.8	2.81
	Crown		0.0137	0.61	11.7	3.15		0.0067	0.69	10.4	3.30
	Total		0.0069	0.96	15.4	3.67		0.0092	0.97	12.7	3.39
Douglas-fir	Wood	1.0123	0.1739	0.97	33.3	2.58	1.0336	0.0038	0.99	16.0	3.27
	Bark		0.0002	0.97	6.4	3.80		0.0001	0.97	6.2	4.15
	Stem		0.2238	0.97	36.3	2.58		0.0053	0.99	22.0	3.36
	Branches		0.0003	0.81	29.2	3.73		0.0065	0.90	21.2	3.12
	Foliage		0.0365	0.82	13.7	1.90		0.2423	0.93	8.3	1.60
	Crown		42.3713	0.81	42.9	—		0.0000	0.91	29.4	8.71
	Total		0.1816	0.97	58.1	2.75		0.0000	0.98	43.5	8.20
Engelmann spruce	Wood	1.0979	0.0031	0.94	82.9	4.03	1.0386	0.0045	0.99	27.6	3.41
	Bark		0.0040	0.98	4.4	2.41		0.0000	0.99	3.0	3.94
	Stem		0.0001	0.94	87.8	5.21		0.0004	0.99	30.0	4.19
	Branches		0.0233	0.78	28.2	2.82		0.0000	0.85	23.6	4.79
	Foliage		0.0024	0.64	13.5	3.28		0.0029	0.68	12.9	2.95
	Crown		0.0453	0.75	40.6	2.89		0.0005	0.82	34.7	4.19
	Total		0.1443	0.96	79.2	2.98		0.0004	0.98	55.5	4.65
Lodgepole pine	Wood	1.0065	0.0283	0.94	35.2	3.31	1.0007	0.0485	0.97	25.6	2.73
	Bark		0.0006	0.92	2.8	2.96		0.0000	0.94	2.5	4.08
	Stem		0.0381	0.94	36.8	3.25		0.0505	0.97	26.6	2.75
	Branches		0.0005	0.62	10.9	3.96		0.0009	0.65	10.4	3.63
	Foliage		0.0062	0.56	4.9	2.64		0.0074	0.60	4.7	2.51
	Crown		0.0030	0.65	14.2	3.57		0.0075	0.69	13.5	3.12
	Total		0.0219	0.95	39.2	3.41		0.0972	0.96	33.0	2.71
Pacific silver fir	Wood	1.0203	0.0014	0.95	8.1	3.93	1.6130	0.0027	0.95	7.9	3.47
	Bark		0.0003	0.93	1.6	3.20		0.0007	0.93	1.6	2.88
	Stem		0.0014	0.95	9.4	4.05		0.0049	0.95	9.4	3.40
	Branches		23.5756	0.80	4.9	—		0.0005	0.79	4.9	4.05
	Foliage		0.0088	0.90	3.7	2.47		0.0273	0.92	3.3	2.04
	Crown		0.0987	0.90	6.8	2.19		0.0000	0.91	6.7	7.56
	Total		0.0015	0.96	12.4	3.96		0.0000	0.96	12.7	7.66
Red alder and Black cottonwood	Wood	1.0164	0.0003	0.83	24.5	4.84	1.0651	0.0014	0.99	6.7	3.72
	Bark		0.0001	0.85	4.2	3.86		0.0022	0.98	1.5	2.54
	Stem		0.0001	0.83	28.7	5.22		0.0032	0.99	7.5	3.52
	Branches		0.2338	0.83	11.1	2.05		0.0067	0.84	10.9	3.33
	Foliage		0.0021	0.51	4.3	2.57		0.0000	0.47	4.4	4.85
	Crown		0.6705	0.83	13.1	1.79		0.0000	0.83	13.2	6.98

Table 5 (*continued*).

Species	Model	DBH-based system of equations $\widehat{\sigma}^2_{SUR}$	$\widehat{\sigma}$	R^2_{adj}	RMSE	c	DBH- and height-based system of equations $\widehat{\sigma}^2_{SUR}$	$\widehat{\sigma}$	R^2_{adj}	RMSE	c
	Total		0.0071	0.93	26.0	3.78		0.0000	0.98	13.8	7.00
Sitka spruce	Wood	1.0045	14.5921	1.00	3.8	—	0.8959	15.1335	1.00	3.9	—
	Bark		1.8009	0.97	1.3	—		1.1523	0.98	1.1	—
	Stem		12.6182	1.00	3.6	—		11.0847	1.00	3.3	—
	Branches		0.0016	0.80	5.0	3.30		0.0018	0.79	5.2	3.28
	Foliage		0.0000	0.96	2.2	4.06		3.7984	0.97	1.9	—
	Crown		0.0011	0.90	6.9	3.65		0.0000	0.90	7.2	5.87
	Total		0.0284	0.99	9.8	2.89		0.0000	0.98	10.7	5.87
Subalpine fir	Wood	1.0012	0.0180	0.96	22.5	3.15	1.0032	0.0015	0.99	11.1	3.49
	Bark		0.0002	0.94	4.8	3.56		0.0001	0.95	4.3	4.00
	Stem		0.0313	0.96	25.5	3.06		0.0018	0.99	13.3	3.57
	Branches		0.0052	0.60	29.3	3.50		0.0004	0.64	27.8	4.41
	Foliage		0.0053	0.53	14.7	3.15		0.0412	0.61	13.3	2.37
	Crown		0.0259	0.59	42.6	3.24		0.0129	0.65	39.7	3.34
	Total		0.0196	0.95	40.7	3.39		0.0057	0.95	41.1	3.81
Trembling aspen	Wood	1.0000	0.0107	0.95	31.6	3.57	1.0000	0.0001	0.98	20.7	4.82
	Bark		0.0002	0.91	9.2	4.13		0.0000	0.93	8.3	4.60
	Stem		0.0136	0.95	37.4	3.60		0.0004	0.98	25.1	4.61
	Branches		0.0001	0.76	12.4	4.49		0.0003	0.76	12.3	4.07
	Foliage		0.0176	0.42	2.7	1.95		0.0241	0.43	2.6	1.84
	Crown		0.0018	0.75	14.1	3.66		0.0039	0.75	13.9	3.37
	Total		0.0234	0.95	42.3	3.48		0.0007	0.97	33.6	4.49
Western hemlock	Wood	1.0378	0.0032	0.87	39.9	4.02	1.0056	0.0054	0.98	15.2	3.21
	Bark		0.0000	0.95	3.8	5.28		0.0004	0.96	3.3	3.16
	Stem		0.0031	0.89	42.8	4.09		0.0030	0.98	17.8	3.50
	Branches		0.0006	0.71	16.4	4.12		0.0005	0.72	16.2	4.09
	Foliage		19.4252	0.74	4.4	—		13.7706	0.82	3.7	—
	Crown		0.0120	0.76	18.8	3.24		0.0000	0.79	17.6	9.00
	Total		0.0033	0.95	33.8	4.11		0.0000	0.98	22.0	8.51
Western redcedar	Wood	1.0047	0.0001	0.95	32.5	4.97	1.0041	0.0023	0.99	13.4	3.34
	Bark		0.0031	0.96	5.6	2.66		0.0450	0.99	3.3	1.64
	Stem		0.0007	0.95	37.5	4.49		0.0457	0.99	16.3	2.52
	Branches		0.1622	0.80	11.5	2.00		0.2604	0.77	12.3	1.83
	Foliage		0.1082	0.54	8.4	1.94		0.0218	0.54	8.4	2.45
	Crown		5.2876	0.88	12.1	0.98		0.0000	0.85	13.4	5.78
	Total		0.0074	0.96	40.7	3.73		0.0000	0.99	20.3	5.81
White birch	Wood	1.0001	0.0048	0.94	27.5	3.80	1.0002	0.0004	0.97	20.6	4.46
	Bark		0.0001	0.90	6.1	4.05		0.0001	0.91	5.6	4.05
	Stem		0.0046	0.94	31.6	3.93		0.0010	0.97	23.8	4.23
	Branches		0.0001	0.78	17.9	4.86		0.0001	0.80	16.9	4.66
	Foliage		0.0090	0.58	3.7	2.44		0.0119	0.61	3.6	2.31

Table 5 (*concluded*).

Species	Model	DBH-based system of equations					DBH- and height-based system of equations				
		$\widehat{\sigma}^2_{\mathrm{SUR}}$	$\widehat{\sigma}$	R^2_{adj}	RMSE	c	$\widehat{\sigma}^2_{\mathrm{SUR}}$	$\widehat{\sigma}$	R^2_{adj}	RMSE	c
	Crown		0.0011	0.78	20.1	4.13		0.0021	0.80	19.0	3.83
	Total		0.0053	0.96	34.9	3.89		0.0029	0.97	31.9	4.01
White spruce	Wood	1.0000	0.0001	0.94	35.3	5.05	1.0001	0.0003	0.98	19.6	4.31
	Bark		0.0001	0.92	4.6	3.94		0.0000	0.94	4.1	4.02
	Stem		0.0003	0.95	37.3	4.82		0.0004	0.98	20.2	4.25
	Branches		0.0005	0.66	14.9	4.01		0.0008	0.69	14.3	3.79
	Foliage		0.0476	0.61	8.3	2.33		0.0348	0.60	8.3	2.36
	Crown		0.0094	0.68	21.3	3.40		0.0087	0.70	20.5	3.32
	Total		0.0033	0.96	39.3	4.02		0.0040	0.98	29.4	3.82
Hardwoods	Wood	1.0000	0.0440	0.88	74.5	3.36	1.0000	0.0018	0.92	60.1	4.29
	Bark		0.0021	0.77	14.8	3.33		0.0001	0.82	13.4	4.25
	Stem		0.0905	0.89	80.8	3.18		0.0028	0.93	63.2	4.20
	Branches		0.0001	0.71	48.6	4.96		0.0002	0.69	49.6	4.92
	Foliage		0.0063	0.56	4.4	2.49		0.0086	0.55	4.4	2.38
	Crown		0.0006	0.71	50.8	4.51		0.0006	0.70	51.9	4.52
	Total		0.0368	0.90	103.6	3.63		0.0030	0.92	95.3	4.44
Softwoods	Wood	1.0000	0.0079	0.88	48.2	3.72	1.0000	0.0002	0.97	25.8	4.55
	Bark		0.0000	0.85	7.3	4.40		0.0000	0.85	7.2	4.11
	Stem		0.0067	0.90	50.3	3.82		0.0004	0.97	27.4	4.40
	Branches		0.0005	0.72	16.5	3.98		0.0003	0.75	15.5	4.08
	Foliage		0.0062	0.66	7.6	2.98		0.0071	0.66	7.7	2.85
	Crown		0.0061	0.74	22.0	3.48		0.0052	0.76	21.0	3.43
	Total		0.0053	0.93	50.6	3.92		0.0035	0.96	37.3	3.90
All species	Wood	1.0000	0.0143	0.87	62.8	3.66	1.0000	0.0004	0.91	51.5	4.64
	Bark		0.0001	0.79	11.4	4.32		0.0000	0.77	12.0	4.84
	Stem		0.0160	0.88	68.0	3.69		0.0005	0.92	56.8	4.66
	Branches		0.0002	0.58	40.3	4.77		0.0001	0.61	38.6	4.88
	Foliage		0.0056	0.48	8.2	2.98		0.0093	0.42	8.6	2.73
	Crown		0.0021	0.65	40.8	4.03		0.0022	0.68	38.8	3.94
	Total		0.0119	0.89	85.4	3.91		0.0019	0.90	83.7	4.47

Note: $\widehat{\sigma}^2_{\mathrm{SUR}}$, seemingly unrelated regression system variance.

the national equations for both regional and national applications, for two reasons. First, the national equations offer an interesting alternative for regions not well covered by regional equations, especially since the notion of "region of application'' often remains ill-defined for local equations. Second, the national equations are provided with a set of interesting properties, more particularly a known adjustment error and the respect of additivity. We recognize however that more work is needed to determine the trade-off when using national-level equations for local applications.

Acknowledgements

The extension of the Canadian national biomass equations to British Columbia was carried out with the support of the National Forest Inventory of the Canadian Forest Service. The authors extend their gratitude to Mr. Jean-Pierre Bérubé, whose perseverance led to the recovery of the ENFOR data for British Columbia. We also thank the two anonymous reviewers whose comments have helped to improve the manuscript significantly.

References

Gallant, A.R. 1987. Nonlinear statistical models. John Wiley & Sons, New York.

Lambert, M.-C., Ung, C.-H., and Raulier, F. 2005. Canadian national tree aboveground biomass equations. Can. J. For. Res. **35**: 1996–2018. doi:10.1139/x05-112.

SAS Institute Inc. 1999. SAS/ETS user's guide, version 8. SAS Institute Inc., Cary, N.C.

Talisman Land Resource Consultants. 1982. Estimation of the quantity of biomass following logging in B.C. forests to specified recovery criteria. Project 7952. Interim Report for Canadian Forestry Service, Environment Canada.

Ter-Mikaelian, M.T., and Korzukhin, M.D. 1997. Biomass equations for sixty-five North American tree species. For. Ecol. Manage. **97**: 1–24. doi:10.1016/S0378-1127(97)00019-4.

Appendix A. List of species

Black cottonwood, peuplier de l'Ouest, *Populus trichocarpa* Torr. & A. Gray; black spruce, épinette noire, *Picea mariana* (Mill.) BSP; Douglas-fir, Douglas vert, *Pseudotsuga menziesii* (Mirb.) Franco; Engelmann spruce, épinette d'Engelmann, *Picea engelmannii* Parry ex. Engelm.; lodgepole pine, pin tordu latifolié, *Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.; Pacific silver fir, sapin gracieux, *Abies amabilis* (Dougl. ex Loud.) Dougl. ex J. Forbes; red alder, aulne rouge, *Alnus rubra* Bong.; Sitka spruce, épinette de Sitka, *Picea sitchensis* (Bong.) Carrière; subalpine fir, sapin subalpin, *Abies lasiocarpa* (Hook.) Nutt.; trembling aspen, peuplier faux-tremble, *Populus tremuloides* Michx.; western hemlock, pruche de l'Ouest, *Tsuga heterophylla* (Raf.) Sarg.; western redcedar, thuya géant, *Thuja plicata* Donn ex D. Don; white birch, bouleau à papier, *Betula papyrifera* Marsh.; white spruce, épinette blanche, *Picea glauca* (Moench) Voss.