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Allometric models for aboveground biomass of ten tree species in northeast China

S. Cai, X. Kang, L. Zhang

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Abstract. China contains 119 million hectares of natural forest, much of which is secondary forest. An accurate estimation of the biomass of these forests is imperative because many studies conducted in northeast China have only used primary forest and this may have resulted in biased estimates. This study analyzed secondary forest in the area using information from a forest inventory to develop allometric models of the aboveground biomass (*AGB*). The parameter values of the diameter at breast height (*DBH*), tree height (*H*), and crown length (*CL*) were derived from a forest inventory of 2,733 trees in a 3.5 ha plot. The wood-specific gravity (*WSG*) was determined for 109 trees belonging to ten species. A partial sampling method was also used to determine the biomass of branches (including stem, bark and foliage) in 120 trees, which substantially ease the field works. The mean *AGB* was 110,729 kg ha^{-1}. We developed four allometric models from the investigation and evaluated the utility of other 19 published ones for *AGB* in the ten tree species. Incorporation of full range of variables with *WSG-DBH-H-CL*, significantly improved the precision of the models. Some of models were chosen that best fitted each tree species with high precision ($R^2 \geq 0.939$, $SEE \leq 0.167$). At the latitude level, the estimated *AGB* of secondary forest was lower than that in mature primary forests, but higher than that in primary broadleaf forest and the average level in other types of forest likewise.

Keywords wood-specific gravity, allometric models, biomass estimation, northeast China, secondary forest.

Authors. Shuo Cai, Xingang Kang (55443777@qq.com) - Key Laboratory for Silviculture and Conservation, Ministry of Education, Beijing Forestry University, Qinghua East Road 35, Haidian District, Beijing 100083, China; - Lixin Zhang, Ecological Engineering Laboratory, Yunnan Forest Institute, Kunming, Yunnan 650204, China.

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Introduction

The world's temperate forests play crucial role as one of the carbon sinks for atmospheric carbon dioxide (Schimel et al. 2001, Goodale et al. 2002). It is generally necessary to quantitatively assess their carbon content in order to calculate the global carbon balance. Initially, this demands an estimate of the biomass of trees (UNFCCC 1997, IPCC 2000,2007; Canadell & Raupach 2008, Le Quere et al. 2009, Lewis et al. 2009, Genet et al. 2011). The earliest study of biomass estimation in forests occurred in 1873 (Kunze 1873), but its frequency of evaluation has increased recently due to its importance for evaluating energy usage, productivity, and ecosystem services.

A 2009 survey conducted in China reported that 193 million hectares were covered with forests, from which natural forests comprised 119 million hectares. However, some of undesirable influences, like frequent anthropogenic disturbance, large scale deforestation, and subsequent reforestation in natural forest areas during the last century, explain why the strictly defined primary forests are only found as remnants in some areas of northeast and southwest China (Jia et al. 2009). In regard to 20.36% forest coverage in China's territory, the secondary forests comprise major part of it and have an important role in the national carbon budget. Nevertheless, the accuracy of estimating biomass based on the inventory of actual primary forests may be problematic and further investigation is prospective. Moreover, since northeastern area of China hosts about one third of Chinese forests, both in area and stocking volume (Wang 2006), and its biomass was estimated about 40% of national total amount (Fang et al. 2001), we carried out experiment in a long term forest research plot from area during 2008-2010.

The methods for the estimation of forest biomass are determined by the investigated scale. Large scale assessment of biomass variation is modeled, e.g. using a normalized difference vegetation index (NDVI) based on data obtained from satellites, remote sensing, aerial photographs (Anaya et al. 2009), or environmental data altitude, longitude, and latitude (Wang et al. 2006, Zhu et al. 2010) done with regression models, where allometric equations are fitted to specific plant sample traits (Wang 2006, Djomo et al. 2010).

Generally accurate estimation of forest biomass at fine scale is obtained through the method of allometric regressions. A variety of allometric equations have been developed to meet the applications in different forest types and geographies, in which early allometric equations employed diameter at breast height (*DBH*) as the sole parameter (Gower et al. 1999). Later on, tree height (*H*) was incorporated as the second variable to improve the precision of biomass estimates (Ketterings et al. 2001).

On the aboveground biomass components, the measurement of trunk and bark biomass involves calculation of volume and wood-specific gravity (*WSG*)(Espinoza 2004, Henry et al. 2010), and the determination of branch and foliage biomass is based destructive sampling (Djomo et al. 2010). In most cases this method gives rise to reasonable accuracy, yet is time-consuming, physically demanding and therefore restricts the use in case of large sampling sizes.

WSG reflects the growth rate, life history, and succession characteristics of trees and its value may vary for different tree species (Ketterings et al. 2001), within the same tree species, and in different tree parts (the trunk, bark, branches, and roots). Previous studies (Amorim 1991, De Castro et al. 1993) indicated that *WSG* at breast height dropped drastically from pith to bark in some tropical trees. It is thus necessary to determine *WSG* using a fan shaped disc and to separate the parameter of bark as an independent variable in the models. Henry et al. (2010) showed that the *WSG* at breast height increased drastically from the pith to the bark in some pioneer tree species, whereas the opposite was found in shade the tolerant species (Espinoza 2004). In general, shade tolerant trees have higher *WSG* than pioneer species. On the same tree, it has been (Espinoza 2004) that the *WSG* at breast height is higher than on upper portions. Several researchers (Chave et al. 2004, Henry et al. 2010) have also suggested that the omission of *WSG* from allometric models might lead to less precise estimates. Therefore, it is necessary to further investigate *WSG* to improve the precision of biomass estimation of individual tree or trees in stands.

The objectives of this paper were: (i) investigate *WSG* variation within and among tree species, (ii) to develop accessible allometric equations to estimate aboveground biomass (*AGB*) components of individual tree and to examine *AGB* of individual tree and on the components of a tree.

Materials and methods

Study area

This study was conducted at the Wangqing Long-Term Ecological Research Station (LTER)(Xing et al. 2010) in the eastern Jilin Province of China (43°05′–43°40′ N, 129°56′–131°04′ E). The altitude ranges from 300 to 1,200 m and slope from 0° to 35°. The annual temperature averages 4°C, with the mean temperatures of –32°C (the coldest month) is recorded in January and 32°C (the warmest month) in July. The mean annual rainfall is between 600-700 mm. The total area of Wangqing LTER is 16,286 ha, including 13,347 ha of natural stands and 2,577 ha of plantations. The dominant forest type is *Pinus koraiensis* broadleaf mixed forest at 400-800 m, with *Picea* and *Abies* forest and *Betula costata* forest at higher elevation (800-1,200 m).

Field data and tree sampling

A stand inventory of 14 plots of 50 × 50 m size was established in an even-aged natural *Pinus koraiensis* mixed with broadleaf forest in 1988. All trees ≥ 5 cm in diameter at breast height (*DBH*) within the plots were measured for *DBH* and crown diameter (*CD*). The measured trees, totaling 2733 individuals and belonging to ten major species, were felled for the determination of height (*H*), crown length *(CL)* and crown width (*CW*).

From 2010 to 2011, 109 trees belonging to ten species were harvested in the same stand. For each species, one tree was selected from each 5 cm diameter class and stem disks were taken from 0.1 m, 1 m, 1.3 m, 3.0 m, and then every 2 m above. The disks were taken as two pieces of fan-shaped wood, one for determining the moisture content and the other for the volume of wood and bark.

In 2011, another group of 120 individual trees were selected for determination of branch and foliage biomass, one tree being sampled also from each diameter class of 5 cm. Besides *H*, *DBH* and *CW* of sampled trees, were measured for length and diameter (at base, middle, and top) all the first-order (1-B) and second-order branches (2-B). The third-order branches (3-B) were only measured for length and basal diameter (*BD*). Branches were grouped by *BD* on classes of 1 cm for 1-B, 0.5 cm for 2-B, and 0.1 cm for 3-B.

The measurement of the branch *WSG* depended on the branch type. Two pieces of twig 3 cm long were sampled 1 m apart until the 1-B was less than 1 m in length, each two 1-B samples (one for moisture and the other for volume determination) being taken at the base and every 1 m from the base until the branch top. 2-Bs were usually shorter than 1-Bs and the two branch samples were taken at three locations (base, middle and top). 3-Bs were only measured for dry weight at 80°C, but not for wood density. Foliage was separated from 3-Bs and weighted until fresh and constant weight at 80°C.

The *WSG* of wood and branch was calculated using the following equation.

$$WSG = m_1 \cdot (m_2' / m_2) / V_1 \tag{1}$$

where m_1 and m_2 are the green mass (g) of sample 1 and 2, m_2' is the dry mass of the sample 2 (g), V_1 is the green volume (cm^3) of sample 1 and WSG is the wood-specific gravity (g cm^{-3}).

The volume of a trunk or branch section was approximated with an averaged basal area:

$$V = \pi (d_0^2 + d_n^2) L / 8 \tag{2}$$

where L is the length of the section and d_0 and d_n are the diameters of the small and large ends of a section, respectively.

The biomass of a tree trunk was calculated with the equation:

$$M = \sum_{i=1}^{n} V_i \cdot WSG_i \tag{3}$$

where M is biomass, V is the volume (cm^3) and WSG is the wood-specific gravity (g cm^{-3}).

The branch biomass was calculated using the equations 4–6:

$$M_{bi} = M_{bi-main} + \sum_{i=1}^{n} M_{ci} \cdot N_i \tag{4}$$

$$M_{ai} = M_{ai-main} + \sum_{i=1}^{n} M_{bi} \cdot N_i \tag{5}$$

$$M_{Br} = \sum_{i=1}^{n} M_{ai} \cdot N_i \tag{6}$$

where M_{bi} is the biomass of a 2-B and includes its main stem biomass ($M_{bi\text{-main}}$) and biomass of each 3-B (M_{ci}). Similarly, M_{ai} is the biomass of a 1-B and includes its main stem biomass ($M_{ai\text{-main}}$) and each 2-B biomass (M_{bi}). M_{Br} is the biomass of total branches of a tree and N is the number of corresponding branches.

The foliage biomass of a tree (M_L) was the total foliage biomass, summed from 3-B ($M_{ci\text{-}1}$) to 2-B ($M_{bi\text{-}1}$), and then to 1-B ($M_{ai\text{-}1}$).

$$M_{bi-l} = \sum_{i=1}^{n} M_{ci-l} \cdot N_i \tag{7}$$

$$M_{ai-l} = \sum_{i=1}^{n} M_{bi-l} \cdot N_i \tag{8}$$

$$M_L = \sum_{i=1}^{n} M_{ai-i} \cdot N_i \tag{9}$$

The aboveground biomass of a tree (AGB) was therefore the sum of trunk (M_T), bark (M_{Ba}), branches (M_{Br}), and foliage (M_L):

$$AGB = \sum M_T + \sum M_{Ba} + \sum M_{Br} + \sum M_L \tag{10}$$

Fitting and evaluation of allometric AGB models

Aboveground biomass components of a tree, trunk, bark, branches, foliage, and *AGB* were modeled with independent variables of *DBH, H, CL, WSG* and their interactions (see Table 1 for all the models tested). Some of the models have been used previously, e.g. M4 by Niklas (1994) and TerMikaelian & Korzukhin (1997), M10 by Brown et al. (1989) and M6 by Loetsch et al. (1973) and Chave et al. (2005).

The fitted models were evaluated by (i) the proportion of variance explained by the model (i.e. adjusted R^2, PRESS)(Zeng et al. 2011) and (ii) Akaike Information Criterion (*AIC*) (Kennth & David 2002) and the correction factor (*CF*)(Sprugel, 1983), as in equations 11–15.

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \right] \tag{11}$$

R^2 is the coefficient of determination, where

y_i, $\hat{y}_i$, $\overline{y}$ are the observed value, predicted value and average value respectively, and n is the number of trees.

$$PRESS = \sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{12}$$

PRESS is the prediction error sums of squares (PRESS residuals). y_i is the observed value, $\hat{y}_i$ is the predicted value, n is the number of trees.

$$AIC = n \cdot Log(\hat{\sigma}^2) + 2K \tag{13}$$

where $\hat{\sigma}^2 = \sum \hat{\varepsilon}_i^2 / n$ and $\hat{\varepsilon}_i^2$ are the estimated residuals for a particular candidate model, K is the total number of estimated regression parameters, and n is the number of trees.

$$\Delta AIC_i = AIC_i - AIC_{\min} \tag{14}$$

where Δ*AIC* is the *AIC* difference (Kennth & David 2002). The models perform best when Δ*AIC* = 0, whereas the model prediction might not be valid when Δ*AIC* >10, so these cases were excluded for further consideration.

$$CF = \exp(SEE^2 / 2) \tag{15}$$

CF (>1) was calculated from standard error estimate (*SEE*). A smaller *SEE* and *CF* indicates a higher model precision.

Results

Main species characteristics and wood specific gravity

The characteristics of the ten tree species are presented in Table 2. *Abies nephrolepis* and *Picea koraiensis* were the most common trees, constituting 46.29% of the stand density and 54.76% of the basal area. These two species were also among the largest *DBH* (51.3 cm and 55.9 cm) and height (26.2 m and 29.2 m). *Acer mono, Betula costata, Pinus koraiensis,* and *Tilia amurensis* were the next most abundant, with 11.2, 9.81, 12.22, and 13.83 percents of the stand density, respectively. *Fraxinus mandshurica* was a valuable and endangered species that constituted only 1.32% of the stand density.

The tree of *Pinus koraiensis* had maximum

Table 1 Allometric equations used for the estimation of the total aboveground biomass of trees

Model	Equation type	Model	Equation type
M1	$Y = a \cdot (D \cdot H \cdot WSG)^b$	M13	$Y = a + b \cdot D$
M2^{I}	$Y = a \cdot (D2 \cdot H \cdot WSG)^b$	M14	$Y = a + b \cdot D \cdot H + c \cdot D \cdot WSG$
M3^{II}	$Y = a \cdot D^b$	M15^{II}	$Y = a + b \cdot D^2$
M4^{II}	$Y = a \cdot D^b \cdot H^c$	M16	$Y = a + b \cdot D^2 \cdot H$
M5	$Y = a \cdot D^b \cdot H^c \cdot WSG^d \cdot CL^e$	M17	$Y = a + b \cdot D^2 \cdot H \cdot WSG$
M6^{III}	$Y = a \cdot D^b \cdot WSG^c \cdot H^d$	M18	$Y = a + b \cdot D^2 \cdot H \cdot WSG + c \cdot CL$
M7	$Y = a \cdot D^b \cdot WSG^c \cdot H^d + CL^e$	M19	$Y = a + b \cdot D^2 \cdot WSG$
M8	$Y = a \cdot H^b$	M20	$Y = a + b \cdot D^c \cdot WSG^d \cdot H^e \cdot CL^f$
M9	$Y = a + b \cdot (D \cdot H) + c \cdot D \cdot CL$	M21	$Y = a + b \cdot D^c \cdot WSG^d \cdot H^e + CL^f$
M10^{I}	$Y = a + b \cdot (D^2 \cdot H)\ c$	M22	$Y = a + b \cdot H$
M11	$Y = a + b \cdot (D^2 \cdot H)^c + d \cdot WSG^e$	M23	$Y = a + b \cdot H^2$
M12	$Y = a + b \cdot (D2 \cdot H)^c + d \cdot WSG^e + f \cdot CL^g$		

Note. Abbreviations: *a, b, c, d, e, f,* and *g* are fitted parameters, *Y* - aboveground biomass of a tree [kg], *D* - diameter at breast height [cm], *H* - height [m], *WSG* - wood-specific gravity (i.e. weight of dry wood per unit volume) [g cm^{-3}], *CL* - the crown length [m], ^{I} - from Brown (1989), ^{II} - from Niklas (1994), TerMikaelian & Korzukhin (1997), ^{III} - from Loetsch (1973) and Chave (2005).

mean *DBH* (20.9 ± 0.6 cm), while the minimum was in *Larix olgensis* (10.2 ± 0.5 cm). Since *Abies nephrolepis* and *Picea koraiensis* had the most of individuals (632 and 633, respectively), and also of maximum basal area (7.22 m^2 ha^{-1} and 6.30 m^2 ha^{-1} respectively).

WSG varied among and within tree species. The mean *WSG* was maximum in *Acer mono* (0.707 ± 0.003 g cm^{-3}), followed by *Fraxinus mandshurica* (0.652 ± 0.003 g cm^{-3}), and the minimum was that of *Picea koraiensis* (0.375 ± 0.001 g cm^{-3}). In the case of *WSG* within species, it increased with tree size, yet significantly varied with the largest range in *Abies nephrolepis* (0.387–0.619 g cm^{-3}); the opposite was in *Betula platyphylla* (0.534–0.550 g cm^{-3}) and *Larix olgensis* (0.622–0.622 g cm^{-3}). The *WSG* at different heights on a tree might vary however, we didn't find out any regularity with it. The values of *WSG* (g cm^{-3}), in broadleaf trees were larger than that in coniferous trees: in broadleaf trees of *Acer mono* (0.707), *Fraxinus mandshurica* (0.652), *Betula costata* (0.576), *Betula platyphylla* (0.535), *Tilia amurensis* (0.463), *Populus davidiana* (0.452) and in coniferous trees of *Abies nephrolepis* (0.445), *Pinus koraiensis* (0.418), and *Picea koraiensis* (0.375). However, the value of a coniferous tree, *Larix olgensis* (0.622) was exceptional.

Aboveground biomass

The total *AGB* (including trunk, bark, branches and foliage) of the 10 tree species was 387,553.15 kg. The stand-level *AGB* in plots ranged from 86.692 to 160.592 kg ha^{-1}, with an average of 110,729 kg ha^{-1} (Figure 1).

Among the ten tree species (Figure 2), the biomass proportion of trunk was maximum in *Larix olgensis* (83.24), followed by *Pinus koraiensis* (81.36), and *Abies nephrolepis* (76.11) and *Betula costata* (75.52). The biomass proportion of bark was maximum in *Tilia amurensis* (14.47), followed by *Abies nephrolepis* (11.46) and *Pinus koraiensis* (11.41), while the proportion of the branch biomass was maximum in *Tilia amurensis* (17.27), followed by *Fraxinus mandschurica* (14.90) and *Acer mono* (13.95). The minimum was found on *Larix olgensis* (2.95). The proportion of foliage biomass in *AGB* was maximum in *Picea koraiensis* (11.79) and minimum in *Betula platyphylla* (1.76).

The proportion of each biomass component was 73.39 for trunk, 9.71 for branches, 6.35 for foliage and 10.55 for bark. On species, on *Abies nephrolepis* was 28.96% of total *AGB* (32,062 kg ha^{-1}), followed by *Picea koraiensis* 25.76% (28,527 kg ha^{-1}), *Pinus koraiensis* 15.12% (16,744 kg ha^{-1}); lastly, again was *Larix olgensis*, with only 0.19% (209 kg ha^{-1}).

Table 2 Values of the main biometrical parameters

Species	N	Basal area (m^2 ha^{-1})	*DBH* (cm)		*H* (m)		*CL* (m)	
			Mean/S.E.	Min/Max	Mean/S.E.	Min/Max	Mean/S.E.	Min/Max
Abies nephrolepis	632	7.22	20.0 (0.4)	6.0 (51.3)	14.7 (0.2)	5.0 (26.2)	9.5 (0.2)	0.8 (20.7)
Acer mono	306	2.18	16.2 (0.4)	5.8 (40.3)	11.8 (0.1)	6.0 (20.2)	7.3 (0.1)	1.7 (12.9)
Betula costata	268	1.61	14.2 (0.5)	5.8 (57.3)	14.0 (0.2)	6.5 (25.2)	7.4 (0.2)	0.8 (14.6)
Betula platyphylla	46	0.31	15.5 (1.1)	6.1 (47.0)	14.4 (0.5)	8.2 (20.8)	9.0 (0.5)	3.0 (16.3)
Fraxinus mandshurica	36	0.21	14.4 (1.3)	5.9 (38.5)	14.3 (0.5)	8.3 (20.8)	7.5 (0.5)	2.6 (14.7)
Larix olgensis	24	0.06	10.2 (0.5)	7.3 (17.8)	10.9 (0.3)	7.9 (13.7)	6.1 (0.3)	1.9 (9.1)
Picea koraiensis	633	6.30	18.4 (0.4)	5.9 (55.9)	13.0 (0.2)	4.4 (29.2)	8.9 (0.2)	0.7 (23.1)
Pinus koraiensis	334	4.15	20.9 (0.6)	5.8 (49.2)	13.1 (0.2)	4.8 (26.2)	8.2 (0.2)	2.8 (15.9)
Populus davidiana	76	0.39	13.6 (0.8)	6.5 (42.0)	14.2 (0.3)	8.6 (21.4)	7.1 (0.3)	1.6 (15.4)
Tilia amurensis	378	2.26	14.5 (0.4)	6.0 (49.7)	11.4 (0.1)	5.9 (21.9)	7.0 (0.1)	1.7 (16.9)

Note. Abbreviations: N - number of trees, S.E. - standard error of the mean.

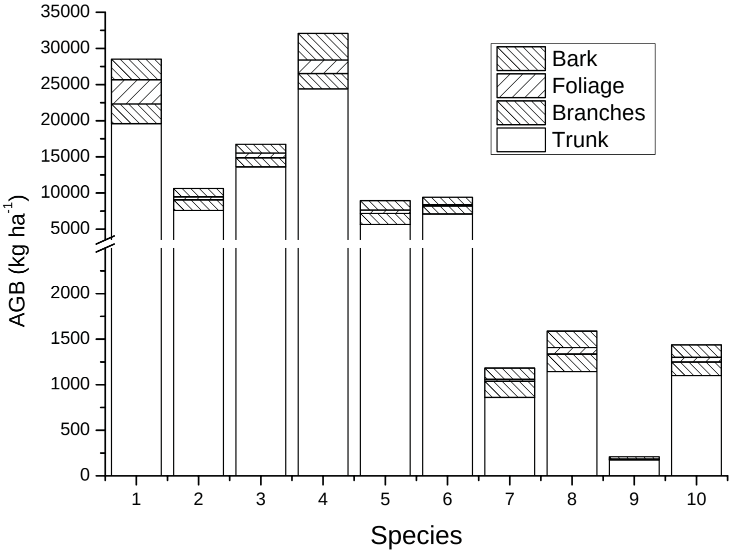

Figure 1 *AGB* of ten tree species per hectare: 1 - *Picea koraiensis*, 2 - *Acer mono*, 3 - *Pinus koraiensis*, 4 - *Abies nephrolepis*, 5 - *Tilia amurensis*, 6 - *Betula costata*, 7 - *Fraxinus mandshurica*, 8 - *Populus davidiana*, 9 - *Larix olgensis*, 10 - *Betula platyphylla*

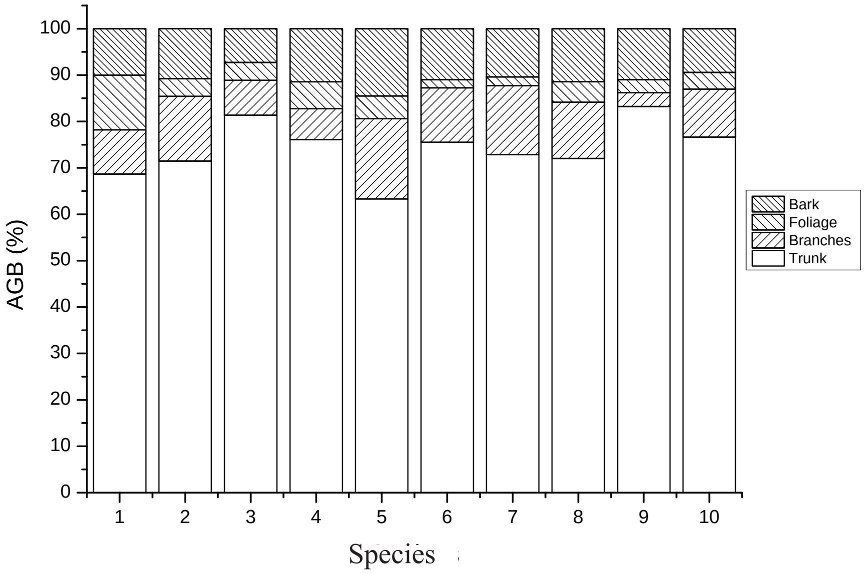

Figure 2 *AGB* allocations for the ten tree species: 1 - *Picea koraiensis*, 2 - *Acer mono*, 3 - *Pinus koraiensis*, 4 - *Abies nephrolepis*, 5 - *Tilia amurensis*, 6 - *Betula costata*, 7 - *Fraxinus mandshurica*, 8 - *Populus davidiana*, 9 - *Larix olgensis*, 10 - *Betula platyphylla*

Allometric models for whole tree

We obtained 23 biomass models from which screened out a set of 3 models for each tree species (Table 3). For biomass determination of trunk, bark, branches and foliage of each tree species, a set of 2 models were recommended (Table 1, Appendix). The *AGB* models of each tree species were all of reasonably higher precision. For instance, for *Abies nephrolepis* (M5, M6, M20), their R^2 were all with the value of 0.987; in addition, the values of *SEE* and *CF*

Table 3 Best selected allometric AGB models

Species	Model	Model parameters						Model performances					
		a	*b*	*c*	*d*	*e*	*f*	R^2	*PRESS*	*AIC*	Δ *AIC*	*SEE*	*CF*
Abies nephrolepis	5	0.052	1.833	1.100	0.687	-0.073		0.987	291257	3894	0.000	0.047	1.001
	20*	1.445	0.048	1.844	0.695	1.109	-0.073	0.987	290965	3895	1.368	0.061	1.002
	6	0.053	1.82	0.679	1.038			0.987	299560	3908	13.766	0.047	1.001
Acer mono	21*	15.497	0.001	4.051	2.381	0.236	1.25	0.952	411268	2224	0.000	0.136	1.009
	20	23.881	0.001	3.942	2.389	0.283	-0.025	0.952	415114	2227	2.848	0.140	1.010
	7	0.001	4.004	2.699	0.235	1.537		0.95	427967	2234	10.179	0.134	1.009
Betula costata	5*	0.036	1.832	1.473	1.424	-0.186		0.986	172736	1752	0.000	0.058	1.002
	6	0.029	1.784	1.372	1.443			0.984	186413	1768	16.421	0.061	1.002
	7	0.029	1.787	1.381	1.447	-0.325		0.984	186315	1772	20.280	0.057	1.002
Betula platyphylla	6	0.002	1.872	-5.004	0.888			0.995	4075	220	0.000	0.039	1.001
	4	0.062	1.712	0.946				0.994	4545	221	1.012	0.055	1.002
	20*	-7.156	0.011	1.771	-3.245	0.929	-0.135	0.995	3728	222	1.906	0.053	1.001
Fraxinus mandshurica	4	0.278	1.806	0.383				0.984	9799	212	0.000	0.121	1.007
	3	0.590	1.914					0.981	11619	214	2.132	0.139	1.010
	6*	0.317	1.801	0.375	0.4			0.984	9493	215	2.859	0.122	1.008
Larix olgensis	4	0.012	1.111	2.175				0.939	297	70	0.000	0.062	1.002
	20*	10.588	0.001	1.767	6.531	3.899	-0.352	0.956	213	72	2.086	0.049	1.001
	6	0.279	1.111	6.655	2.175			0.939	297	74	4.000	0.062	1.002
Picea koraiensis	20*	6.102	0.085	1.923	0.658	0.905	-0.134	0.99	262663	3836	0.000	0.146	1.011
	5	0.108	1.885	0.871	0.652	-0.134		0.989	269202	3849	13.566	0.087	1.004
	21	4.715	0.088	1.896	0.667	0.81	0.317	0.989	282112	3881	45.217	0.146	1.011
Pinus koraiensis	6	0.072	2.024	1.136	0.834			0.995	70879	1803	0.000	0.031	1.000
	5*	0.074	2.027	0.836	1.155	-0.011		0.995	70806	1807	3.659	0.031	1.000
	7	0.072	2.024	1.136	0.834	-9.039		0.995	70879	1807	4.000	0.031	1.000
Populus davidiana	5	0.005	1.886	1.879	-0.391	-0.509		0.982	14768	418	0.000	0.089	1.004
	20*	4.538	0.003	1.947	-0.306	1.968	-0.515	0.983	14513	419	0.679	0.104	1.005
	4	0.007	1.677	1.723				0.975	20508	435	16.955	0.075	1.003
Tilia amurensis	20*	2.803	0.024	2.261	0.741	1.072	-0.251	0.979	146262	2272	0.000	0.084	1.003
	5	0.028	2.221	1.057	0.696	-0.240		0.979	147095	2272	0.145	0.071	1.002
	6	0.038	2.202	0.677	0.760			0.976	168641	2320	47.815	0.072	1.003

Note. Abbreviations: *a, b, c, d, e, f,* and *g* are fitted parameters; R^2 - adjusted coefficient of determination, *PRESS* - prediction error sums of squares, *AIC* - the Akaike information criterion, Δ*AIC* - *AIC* difference, SEE - model standard error estimate; *CF* - correction factor; * The optimal models chosen.

in M5 and M6 were same (0.047 and 1.001, respectively). A complicated choice was on *Pinus koraiensis*, where three candidate models (M5, M6, M7) has all a R^2 of 0.995, while the values of *SEE* and *CF* in the three models were almost equal, (0.031 and 1.000 respectively). The values of *AIC* in M5 and M7 were 1807. The determination of best model was done by the analysis of *PRESS* residual. For *Abies nephrolepis*, *PRESS* residuals was ranked as M20

< M5 < M6, so we considered M20 as best fitted. Similarly, we obtained the best model for each tree species (Table 3). Among these M20 was frequently used as best fitted, with a rate of 60%, followed by M5 (20), M21 (10) and M6 (10). By incorporating the best fitted *AGB* model with respective *DBH* (Figure 1), the predictive values coincided well with the observed values.

In Figure 3, low biomass presented relatively smaller residual, higher the larger. This was due to the measurement of young trees with more individuals in stands, while the larger trees were less; therefore, in order to reduce residual, there should be sufficient amount of samples in both larger trees and saplings.

Allometric models of tree components

The same criterion was used for the determination of model for the biomass estimation of every tree part in each tree species (a summary on species is presented on Table 4). As to the models for estimation of tree part biomass, M5 appeared 12 times with the frequency of 30%, followed by M20 (10 times, with the frequency of 25%), M6 (22.5%), M4 (12.5%), M12 (5%), M7 and M17 (2.5%). To those for trunk and bark, M5 appeared at the rate of 50%, while those for foliage were M5, M6 and M20, with the rate of 30% respectively.

Discussion

The aim of this study was to investigate the *AGB* of secondary forest in northeast China based on forest inventory and field experiments. This resulted in improved measurement procedures and allometric models.

The aboveground biomass

The forest type in this study was a secondary forest containing spruce-fir. The stand was a half-matured forest, i.e. some large trees had been cut in the primary forest, thus individual trees were mainly small to middle-sized. The *AGB* of this forest was estimated as 110.7 Mg ha^{-1}, other examples from the area at the same latitude ranging from 34.2–262.8 M ha^{-1} (northeast China, Korea and Japan)(Dixon et al. 1994, Zhou et al. 2000, Choi et al. 2002, Li et al. 2004, Fang et al. 2005).

This study compared also the *AGB* of the forest inventory with the same forest type, from the same area: the *AGBs* reported by some authors (Li et al. 1981, Wang et al. 2008, Zhu et al. 2010) were significantly greater than the results of our study. This was because these studies investigated primary forests with mature stands, whereas the current study focused on secondary forests, with immature stands. It is reasonable to assume that primary forest would have a higher *AGB*, which makes it a major carbon sink. The *AGBs* reported by oth-

Table 4 Best fitted model for tree components, on species

Species	Trunk model	Bark model	Branches model	Bark model
Abies nephrolepis	M20	M20	M5	M5
Acer mono	M6	M12	M6	M6
Betula platyphylla	M6	M17	M5	M6
Fraxinusmandshurica	M6	M5	M6	M6
Larix olgensis	M4	M4	M4	M4
Picea koraiensis	M20	M20	M5	M20
Pinus koraiensis	M5	M4	M6	M5
Populus davidiana	M5	M20	M7	M20
Tilia amurensis	M20	M5	M5	M20

Note. This table is a summary of Table 1, Appendix.

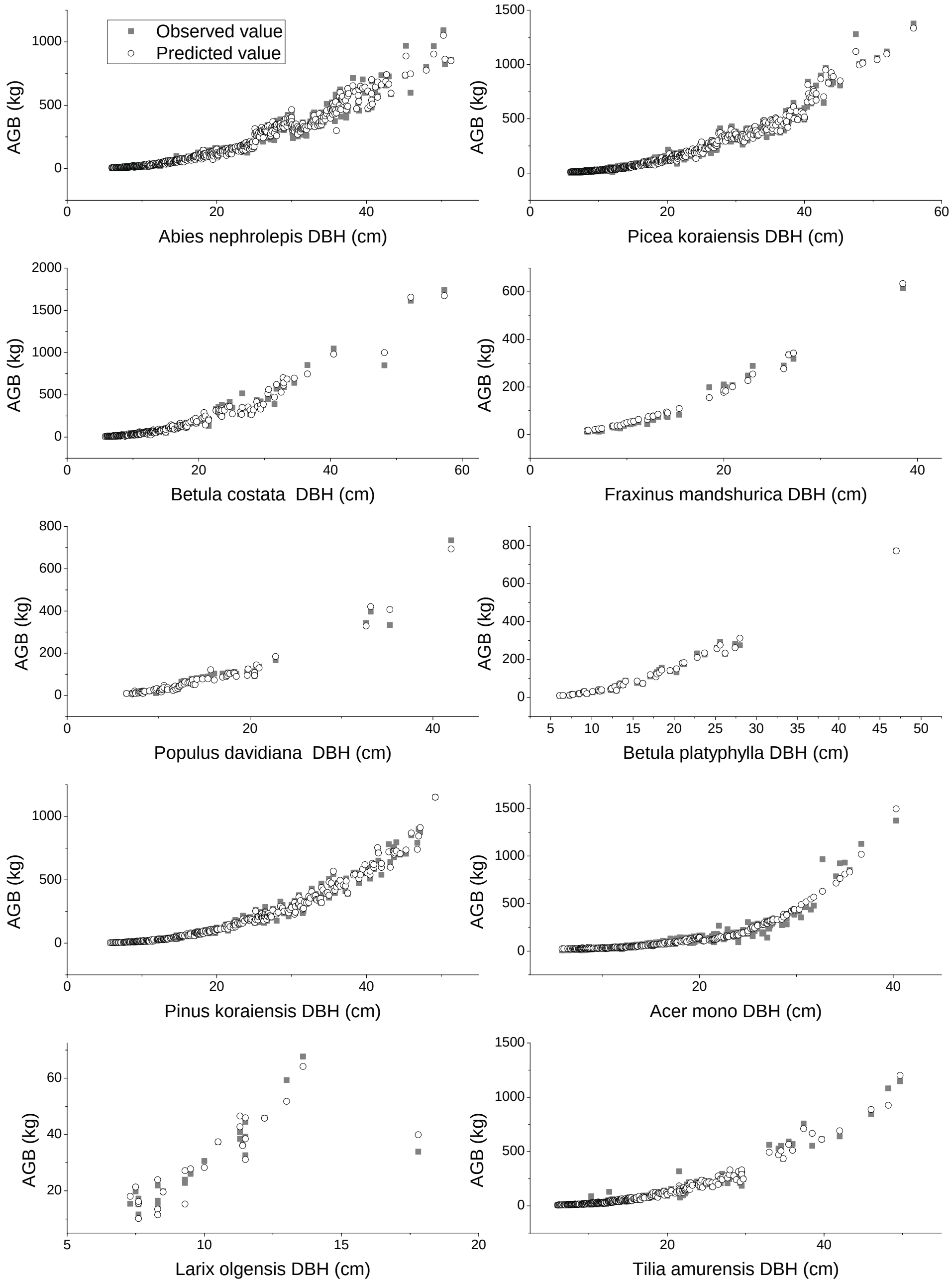

Figure 3 *AGB* based on predicted and observed values for ten tree species

er studies were similar (34.2-120.1 kg ha^{-1}) or significantly lower than our results (Mu et al. 1995), showing that the planted forest of the same type had a lower biomass than secondary forest. The *AGB* of the primary and mature broadleaf forests was substantially greater, presumably due to the high latitude and abundant rainfall in the study areas (Wang et al. 2008, Zhu et al. 2010). However, this was not always true: the *AGBs* reported in some other studies were low, even in primary forests. In mixed coniferous and broadleaf forests, the *AGB* was relatively higher than that of other forests. In general, the ratio of *AGB* to the total biomass was about 0.72–0.85, although the *AGB* in this ratio was calculated from the total biomass by some authors (Dixon et al. 1994, Zhou et al. 2000, Choi et al. 2002, Li et al. 2004, Fang et

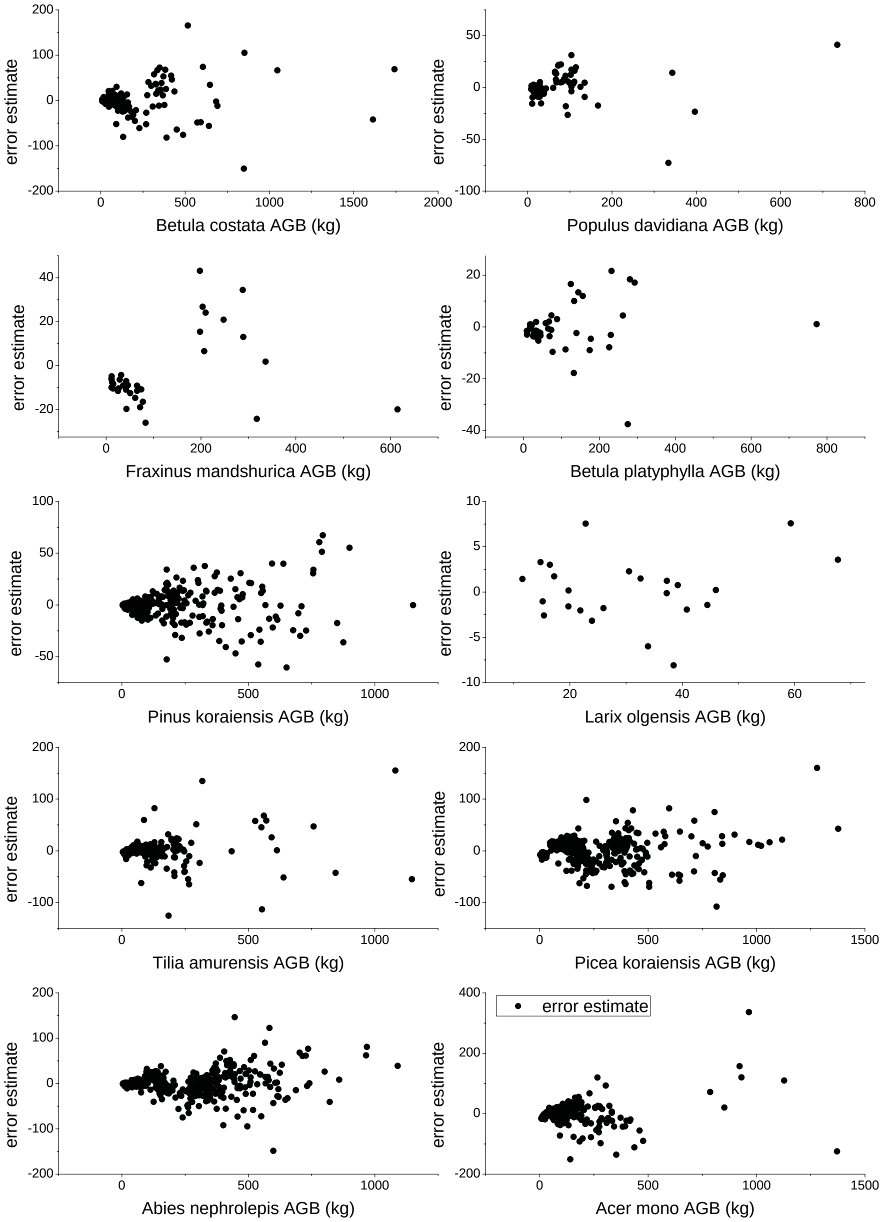

Figure 4 The residual values of *AGB* models for the 10 tree species

al. 2005) and led to a smaller *AGB* at a national scale than found in the current study. This ratio is appropriate at the scale of the temperate forest zone, although the previously reported *AGB* was lower than that estimated in the current study.

Best models

Of all 23 allometric models, only 6 were recommended: M3, M4, M5, M6, M7, M20 and M21. The variables of *DBH*, *H*, *WSG* and *CL* were incorporated in these 6 models, more or less. M3 was a *DBH*-only model and appeared only once, M4 was a *DBH-H* model and was used at the rate of 13.3%, M7 in 23.3% of cases (a *DBH-H-WSG* model), whereas M6, M7, M20 and M21 (*DBH-H-WSG-CL)* were used at the rate of 60%. Therefore, as expected, as more variables incorporated into model it gave rise to more advantage in precision. However, there are difficulties in acquiring data from field and sometimes this is impracticable. In the earlier years, for instance, tree height was difficult to be accurately measured, and it was sometimes obtained by estimation using mathematical models, e.g. from *DBH*. Environmental factors or stand conditions might vary significantly from place to place, limiting their use in models. Single variable models of *DBH* or *DBH-H* were preferred in many cases. Nevertheless, the progress technique of forest measurement made it easier to bring forth simpler ways with precise high measurement. We recommended using full range of parameters in allometric models, to give rise to reliable estimation.

To our best knowledge, few studies have investigated allometric models of forest biomass in northeast China (Wang 2006, Wang et al. 2006, Zhu et al. 2010). Wang (2006) proposed two models for biomass estimation in ten tree species, also tested in the current study (M3, M4). However, these performed badly compared to some of the 23 models tested in this study. Instead, we recommended species-specific models as shown in Table 3. From other authors,Wang et al. (2006) used geographic parameters such as longitude, latitude, and altitude, while the model produced by Zhu et al. (2010) was a special case M10, when the parameter *a* was 0 (Table 3); this model was not ideal, too.

On species, the relative optimal model for biomass estimation of *Picea koraiensis*, *Larix olgensis*, *Betula platyphylla*, *Abies nephrolepis*, *Tilia amurensis* and *Populus davidiana* was M20, for *Fraxinus mandshurica* M6 and for *Acer mono* was M21. These models could be considered as both species-specific and general models, in the order: M5 (20%), M6 (10%), M20 (60%) and M21 (10%). The frequency occurrence of the models for biomass estimation of tree part was: M4 (12.5%), M5 (30%), M6 (22.5%), M7 (2.5%), M12 (5.0%), M17 (2.5%) and M20 (25.0%). The models M5, M6 and M20 together took most of occurrences (77.5%), the cumulative frequency of these 3 models for *AGB* being 90%, which demonstrated that some of these models for *AGB* of tree were also applicable to the estimation of biomass of tree part.

Among them, M5 is a special case of M20 ($Y=a+b\cdot D^{c}\cdot WSG^{d}\cdot H^{e}\cdot CL^{f}$), when the parameter *a* is 0, suggesting the two share common inner structure. It was noteworthy that M6 had widespread occurrences in *Acer mono* (3 times), *Fraxinus mandschurica* (3 times), and *Betula platyphylla* (2 times). These were all broadleaf trees, while there was no parameter of *CL* in M6, suggesting that M6 might be preferred in the usage of that of broadleaf trees to which their first alive branch presented less regularly development as was in coniferous trees. On *Larix olgensis*, M4 present in biomass estimations of its trunk, bark, branches and foliage, owing to less measured samples, with a *DBH* in the range of 7.3–17.8 cm.

The weight of *WSG, H* and *CL* in allometric models

WSG is useful for allometric biomass estimations, but it is inherently variable within or among tree species. Within the same species, it can vary among different *DBH* classes or at different heights within a single tree (Table 3). This uncertainty is possible to be reduced by taking a mean value of it. The current study found that the *WSG* varied to different degrees among the ten tree species, nevertheless, a mean *WSG* being used in models with sufficient precision (e.g. M5, M6, M20, and M21).

H is usually an important variable in allometric models, although it is sometimes unavailable in many (early) forest inventories due to difficulties related to its measurement (Chave et al. 2005, Fehrmann & Kleinn 2006, Wang 2006, Ribeiro et al. 2011). The current study used 1988 inventory, where all the trees were cuted down and their heights were measured. This procedure produced exact values; all the best performing models (M4, M5, M6, M20, and M21) incorporated this variable.

CL varied substantially under different conditions, depending on stand or site conditions, branch growth and canopy stratification. *CL* is closely related to the growth in height and its increase reflects biomass accumulation on tree. The introduction of *CL* as a variable in allometric models may increase their precision (Garber et al. 2008). Well-fitted models including *CL* (M5, M20, and M21) were for *Picea koraiensis, Tilia amurensis, Betula costata,* and *Abies nephrolepis*.

Adequate amount of trees was investigated to improve the precision of values predicted using allometric models

During the development of allometric models for the estimation of forest biomass, precision is usually determined by key factors, such as tree species, *DBH*, or the amount of sampled trees. However, many previous studies considered only a small number of trees, due to limitations of manpower or resources, which reduced their precision. *WSG* measurement typically involved samples taken at or near *DBH*. The development of better models demands sampling from different regions of trunk and an adequate amount of trees from different size classes. This calls for a lot of basic data from forest inventories or field measurements, while it was usually difficult to measure the biomass of the branches and foliage on a tree. Previous studies (Djomo et al. 2010) used a measurement based on whole tree sampling, i.e. cutting a whole tree to obtain the biomass of branch and foliage. This procedure was limited by the number of cut trees and the physical demands of such a field work, which means that few samples were available for parameter fitting in models. The current study partially sampled three orders of branches, which might greatly reduce the measurement workload.

Conclusions

This study developed a range of allometric models for biomass estimation of ten common tree species found in a secondary forest of northeast China. The models of *DBH-H-WSG-CL* for both *AGB* the whole tree or its parts provided maximum precision and better utility. Comparing the aboveground biomass of spruce and fir forests in all-cutting plots with the neighboring region, the results suggested the biomass of spruce and fir forests was: (i) less than that in natural primitive forest stand, but higher than that of artificial forest of same tree species, (ii) higher than that of an average broad-leaved tree stand, coniferous and broadleaf mixed forest stand and other coniferous tree stand in the same area, (iii) higher than the average deciduous broadleaf forest, spruce-fir forest and Korean pine forest, (iv) compared with different countries in average, it was higher than in Korea and Japan, and even higher than that of average level of the global total forest biomass. However, in this study it was not possible to include an estimation of the belowground biomass.

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Table 1 Allometric biomass models for the prediction of trunk, bark, branches, and foliage and precision tests for ten tree species

Species	Tree portion	Model	Model parameters							Model performances					
			a	*b*	*c*	*d*	*e*	*f*	*g*	R^2	*PRESS*	*AIC*	*ΔAIC*	*SEE*	*CF*
Abies nephrolepis	Trunk	5	0.044	1.709	1.299	0.994	-0.082			0.987	165504	3537	0.000	0.04	1.001
		20^{*}	-0.665	0.045	1.703	0.988	1.293	-0.082		0.987	165444	3539	1.769	0.04	1.001
	Bark	20^{*}	1.786	0.001	1.956	1.333	1.524	0.065		0.887	45096	2717	0.000	0.16	1.014
		21	-0.118	0.001	2.003	1.337	1.606	0.408		0.887	45124	2718	0.400	0.16	1.013
	Branches	6	0.007	2.376	-0.870	-0.261				0.846	19908	2194	0.000	0.79	1.362
		5^{*}	0.007	2.376	-0.208	-0.865	-0.048			0.846	19891	2198	3.486	0.79	1.364
	Foliage	6	0.005	2.386	-0.870	-0.205				0.853	15251	2026	0.000	0.80	1.381
		5^{*}	0.005	2.387	-0.162	-0.866	-0.039			0.853	15242	2030	3.660	0.80	1.382
Acer mono	Trunk	6^{*}	0.027	1.858	0.533	1.139				0.963	88773	1749	0.000	0.07	1.002
		12	1.199	0.044	0.919	-0.018	-13.712	-0.137	1.513	0.963	88960	1752	2.646	0.07	1.002
	Bark	12^{*}	-0.750	0.001	1.071	22784.890	18.964	0.000	26.584	0.795	11965	1138	0.000	0.14	1.01
		4	0.005	1.541	1.383					0.779	12906	1155	17.169	0.13	1.008
	Branches	6^{*}	0.000	8.657	7.508	-2.119				0.881	161720	1933	0.000	1.16	1.969
		3	0.000	8.723	-2.143					0.879	164210	1933	0.675	1.25	2.175
	Foliage	6^{*}	0.000	8.480	8.353	-2.043				0.882	10034	1082	0.000	1.01	1.659
		3	0.000	8.550	-2.070					0.880	10230	1084	1.907	1.05	1.741
Betula costata	Trunk	5	0.024	1.822	1.558	1.503	-0.207			0.987	85640	1564	0.000	0.06	1.002
		20^{*}	2.724	0.021	1.844	1.568	1.580	-0.205		0.987	85038	1564	0.110	0.05	1.001
	Bark	12^{*}	3.219	0.000	1.180	-0.017	-14.567	0.000	22.206	0.950	7199	898	0.000	0.16	1.013
		11	4.877	0.000	1.416	0.000	-23.525			0.935	9502	972	74.391	0.20	1.02
	Branches	5^{*}	0.007	1.584	1.193	2.247	0.534			0.759	63198	1482	0.000	1.30	2.333
		6	0.011	1.686	2.454	1.365				0.754	64432	1483	1.185	1.33	2.433
	Foliage	5^{*}	0.001	1.584	1.193	2.247	0.534			0.759	1425	466	0.000	1.30	2.333
		6	0.002	1.686	2.454	1.365				0.754	1453	467	1.184	1.33	2.433
Betula platyphylla	Trunk	4	0.026	1.761	1.112					0.996	2146	187	0.000	0.04	1.001
		6^{*}	0.005	1.839	-2.441	1.089				0.996	2082	189	2.613	0.04	1.001
	Bark	17^{*}	0.005	1.849	1.642	1.125	-0.670			0.967	280	101	0.000	0.14	1.01
		5	1.046	0.003						0.961	337	102	0.606	0.14	1.01
	Branches	6	0.000	2.118	-34.741	0.074				0.886	484	122	0.000	0.29	1.044

Table 1 (continuation)

Species	Tree portion	Model	Model parameters							Model performances					
			a	*b*	*c*	*d*	*e*	*f*	*g*	R^2	*PRESS*	*AIC*	*ΔAIC*	*SEE*	*CF*
		5^*	0.000	2.109	-0.006	-34.394	0.082			0.886	482	126	3.864	0.29	1.044
	Foliage	6^*	0.000	2.190	-39.749	0.230				0.873	70	34	0.000	0.29	1.042
		5	0.000	2.176	0.103	-39.176	0.131			0.873	70	37	3.713	0.29	1.042
Fraxinus mandshurica	Trunk	4	0.092	1.909	0.543					0.990	3463	174	0.000	0.05	1.001
		6^*	0.099	1.904	0.210	0.558				0.990	3410	178	3.448	0.05	1.001
	Bark	5^*	0.338	1.800	1.389	5.574	-0.963			0.731	1437	151	0.000	0.21	1.021
		6	2.223	1.491	6.421	0.464				0.697	1614	151	0.203	0.22	1.025
	Branches	6^*	4.400	2.025	6.084	-0.552				0.768	4824	190	0.000	1.22	2.114
		19	-1.438	0.110						0.719	5835	191	0.854	1.03	1.694
	Foliage	6^*	0.551	2.025	6.084	-0.552				0.768	76	41	0.000	1.22	2.113
		19	-0.180	0.014						0.719	92	42	0.853	1.03	1.697
Larix olgensis	Trunk	4^*	0.005	0.652	2.902					0.886	421	79	0.000	0.10	1.005
		6	0.182	0.652	7.580	2.902				0.886	421	83	4.000	0.10	1.005
	Bark	4^*	0.008	0.548	1.999					0.609	20	6	0.000	0.14	1.010
		14	1.674	0.057	-0.892					0.614	20	10	3.656	0.14	1.010
	Branches	4^*	0.000	9.098	3.254					0.978	3	-42	0.000	1.02	1.687
		6	0.000	9.098	24.883	3.254				0.978	3	-38	4.000	1.02	1.687
	Foliage	4^*	0.000	7.066	2.033					0.960	3	-43	0.000	0.78	1.355
		3	0.000	5.476						0.952	3	-43	0.254	0.53	1.148
Picea koraiensis	Trunk	5	0.043	1.831	1.212	0.978	-0.115			0.990	136298	3419	0.000	0.05	1.001
		20^*	1.433	0.040	1.842	0.981	1.223	-0.116		0.991	135872	3419	0.018	0.07	1.002
	Bark	5	0.047	2.436	-0.041	1.829	-0.215			0.850	40656	2653	0.000	0.16	1.013
		20^*	0.699	0.037	2.498	1.901	-0.027	-0.223		0.850	40576	2654	0.753	0.18	1.016
	Branches	5^*	0.022	2.157	0.064	-0.251	-0.202			0.878	23488	2306	0.000	0.58	1.182
		3	0.028	2.047						0.875	24101	2310	4.309	0.57	1.179
	Foliage	20^*	-2.614	0.209	1.427	-0.357	0.082	-0.079		0.882	22829	2289	0.000	0.40	1.081
		21	-3.689	0.203	1.432	-0.357	0.011	0.192		0.881	22916	2292	2.412	0.40	1.082
Pinus koraiensis	Trunk	6	0.064	1.825	1.355	1.110				0.992	71424	1806	0.000	0.03	1.001
		5^*	0.066	1.828	1.111	1.374	-0.012			0.992	71374	1810	3.769	0.03	1.001

Table 1 (continuation)

Species	Tree portion	Model	Model parameters							Model performances					
			a	*b*	*c*	*d*	*e*	*f*	*g*	R^2	*PRESS*	*AIC*	Δ*AIC*	*SEE*	*CF*
	Bark	3	0.012	2.183						0.813	12903	1226	0.000	0.15	1.011
		4^*	0.010	2.059	0.239					0.815	12822	1228	1.913	0.15	1.011
	Branches	4	0.000	3.818	-0.711					0.910	12763	1227	0.000	1.15	1.928
		6^*	0.030	3.805	5.469	-0.708				0.910	12742	1230	3.440	1.01	1.666
	Foliage	6	6.590	2.854	9.576	-0.462				0.952	1338	478	0.000	0.89	1.488
		5^*	5.889	2.842	-0.470	9.490	0.045			0.952	1336	481	3.552	0.89	1.487
Populus davidiana	Trunk	6	0.040	1.755	1.253	1.256				0.996	1362	233	0.000	0.06	1.002
		5	0.039	1.766	1.272	1.233	-0.031			0.996	1352	237	3.446	0.06	1.002
	Bark	20^*	2.407	0.001	3.782	0.273	0.202	-1.032		0.986	226	103	0.000	0.15	1.012
		12	-86.470	0.000	1.363	101.684	0.197	0.000	9.116	0.984	262	110	7.093	0.14	1.01
	Branches	7^*	0.000	16.284	7.304	-2.033	0.968			0.909	2960	296	0.000	1.60	3.583
		5	0.000	-0.949	14.116	-7.294	-1.619			0.883	3824	316	19.448	1.12	1.878
	Foliage	10	2.149	0.000	4.140					0.888	490	152	0.000	1.65	3.868
		20^*	1.941	0.000	10.516	-5.938	-2.709	-6.000		0.899	443	154	2.408	1.63	3.755
Tilia amurensis	Trunk	20^*	-2.234	0.039	2.007	1.043	1.194	-0.327		0.977	56512	1913	0.000	0.09	1.004
		5	0.033	2.051	1.219	1.095	-0.341			0.977	56970	1914	1.060	0.07	1.002
	Bark	6	0.027	1.124	2.005	1.682				0.764	19179	1498	0.000	0.16	1.013
		5^*	0.032	1.110	1.522	2.125	0.176			0.766	19034	1499	1.115	0.17	1.014
	Branches	5^*	0.000	3.417	0.643	0.352	-0.319			0.941	28181	1648	0.000	0.94	1.551
		7	0.000	3.679	0.515	0.122	0.501			0.939	28960	1658	10.315	1.25	2.175
	Foliage	20^*	0.705	0.000	3.704	0.616	0.651	-0.365		0.943	2194	685	0.000	1.26	2.210
		5	0.000	3.417	0.643	0.352	-0.319			0.941	2287	698	13.785	0.94	1.551

Note. Abbreviations: *a, b, c, d, e, f,* and *g* are fitted parameters, R^2 - adjusted coefficient of determination; *PRESS* - prediction error sums of squares; *AIC* - the Akaike information criterion, Δ*AIC* - *AIC* difference, *SEE* - model standard error estimate, *CF* - correction factor, * The optimal models chosen.