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Research Article

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Developing One-variable Individual Tree Biomass Models based on Wood Density for 34 Tree Species in China

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Abstract

Forest ecosystem is the largest carbon bank on land, and biomass models will be essential basis for evaluating carbon sequestration capacity of forests. Based on the general biomass model $M=0.3pD^{7/3}$ presented by Zeng and Tang, one-variable individual tree aboveground biomass models for all 34 tree species or groups in China were established using the data of wood basic density of all tree species published; and based on the mensuration data of the National Forest Biomass Modeling Program, the aboveground biomass models of 14 tree species or genera were validated. Additionally, compatible belowground biomass models and root-to-shoot ratio models for two species groups, coniferous and broadleaved, were developed and evaluated. The results showed that the averages of absolute relative errors of above- and below-ground biomass estimates from one-variable biomass models developed in this study were less than the error allowances 10% and 15%, respectively. The developed biomass models here could be applied to estimate forest biomass at national level and would be important supplement to the ministerial standards on biomass models which were promulgated and implemented in the recent years.

Keywords: Aboveground biomass; Belowground biomass; Wood density; Root-to-shoot ratio

Introduction

In the context of climate change, information on amount of forest biomass has been paid more attention. As the main body of terrestrial ecosystem, forest ecosystem is the largest carbon bank on land, occupying about 80% aboveground biomass carbon and 40% belowground biomass carbon of terrestrial ecosystem [1]. Forest biomass is an important index of sustainable forest management, which can be used not only for evaluating the amount of bioenergy and carbon storage, and also for studying forest health, forest productivity, and nutrient cycle [2]. Forest ecosystem plays an irreplaceable role in maintaining global carbon balance and mitigating climate change. The size of contribution mainly depends on carbon sequestration capacity of forests, and biomass models will be essential basis for assessment of carbon sequestration capability [3].

Since the beginning of the eighth national forest inventory of China, the National Forest Biomass Modeling Program for main tree species has been implemented, and a lot of findings have been achieved and many papers on modeling individual tree biomass has been published [4-21]. Up to now, based on two ministerial technical standards on sample collection and methodology for tree biomass modeling [22,23], 13 ministerial standards on tree biomass models and related parameters to carbon accounting have been published [24-36], involving the following tree species or genera: *Abies, Picea, Larix, Cunninghamia lanceolata, Pinus massoniana, P. yunnanensis, P. tabulaeformis, P. elliottii, Cryptomeria, Quercus, Betula, Schima superba* and *Liquidambar formosana*. The ministerial standard for Populus has also been finished which will be published for application in late 2018. Although these 14-tree species or genera have covered nearly 70% forest resources of China, but in order to obtain accurate estimates of forest biomass and carbon storage of the whole country, we need to establish suitable biomass models for other tree species or groups involved in the remaining 30% of forest resources.

According to the findings from West et al. [37,38], the aboveground biomass of trees is mainly related to the diameter at breast height. And from the latest study by Zeng and Tang [13], the aboveground biomass of trees is highly related to wood density, and the presented general biomass model $M=0.3pD^{7/3}$ has been validated to be applicable [20]. In this paper, based on the above research results, the author will: i) use the data of wood density for various tree species from published literatures [24-36,39] to develop one-variable aboveground biomass models for the corresponding tree species; ii) use the data of the National Forest Biomass Modeling Program to validate some of developed aboveground biomass models, and establish compatible belowground biomass models and root-to-shoot ratio models for two species groups, conifer and broadleaf. All the models developed in this study will provide basis for accurately estimate forest biomass and carbon storage of China in the ninth national forest inventory.

Data and Methods

Data

Data used in this paper include three parts: the first is the data of basic wood density for two hundreds of tree species published by the Institute of Wood Industry, Chinese Academy of Forestry [39], including 453 sets of data and covering information of 2687 sample trees; the second is the data of basic wood density and above- and belowground biomass for 14 tree species or genera in the published or pre-published ministerial standards, involving a total of 6023 sample trees; the third is the data of basic wood density from 138 and 100 sample trees for *Cupressus* and *Pinus densata* respectively, collected by the National Forest Biomass Modeling Program, and some related literatures [40,41].

Methods

According to the population classification on modeling single tree biomass equations for national biomass estimation in China [4], tree species of the whole country were classified into 34 groups based on the amount of stocking volume. Besides 14 tree species or genera for which ministerial standards on tree biomass models have been published or would be published in 2018, for other 20 tree species or groups only several applicable biomass models can be found in related literatures [40,41], and some of them are two-variable models which are not convenient to be used in the calculation of national forest inventory. In this study, one-variable individual tree biomass models based on wood density for 34 tree species or groups in China will be developed as follows.

Calculating mean basic wood density: According to the classification scheme of tree species by Zeng et al. [4], the following 34 tree species or groups are defined, that is, *Quercus, Abies, Picea, Betula, Larix, Cunninghamia lanceolata, Pinus massoniana, Populus, P. yunnanensis, P. densata, Tilia, Cupressus, Fraxinus mandshurica +Juglans mandshurica+Phellodendron amurense, Schima superb, P. tabulaeformis, P. koraiensis, Ulmus, P. khasya, P. armandii, Tsuga, P. sylvestris var. mongolica, Liquidambar formosana, P. elliottii, Salix, Eucalyptus, Cryptomeria, P. taiwanensis, P. griffithii, Robinia pseudoacacia, Paulownia*, Cinnamomum+Sassafras+Phoebe, other pines, other conifers, and other broadleaves. Furthermore, other broadleaves are classified into 2 types, hardwood and softwood, according to the *Technical Specifications on National Forest Inventory*. Using the data of basic wood density and numbers of sample trees for more than 200 tree species [40], the mean values of basic wood density were computed by weighting method for 34 species or groups. For the 14-tree species or genera aforementioned, the data of mean basic wood density were cited directly from the ministerial standards.

Developing one-variable aboveground biomass models: From Zeng and Tang [13], the general aboveground biomass model can be expressed as follows:

$$M_a=a \times D^{7/3} \quad (1)$$

where M_a is aboveground biomass (kg), D is diameter at breast height (cm), a is the parameter (a=0.3p), and p is the basic wood density (g/cm^3). By multiplying the mean value of basic wood density by 0.3 for each tree species or groups, the estimate of parameter a in eqn. (1) can be obtained. To test prediction precision of the models, the mensuration data of aboveground biomass of the 14-tree species or genera were used for validation, and the relative error was calculated as follows:

$$RE = \left(\sum \hat{y}_i - \sum y_i\right) / \sum y_i \times 100\% \quad (2)$$

where RE is relative error, $\hat{y}_i$ is estimated value of biomass, and y_i is observed value.

Developing one-variable belowground biomass models: Belowground biomass is usually estimated from root-to-shoot ratio model [6]. Because the stocking volume of 14 tree species or genera in the published or pre-published ministerial standards has occupied about 70% of total stocking volume in China, the belowground biomass of other 20 tree species or groups would be estimated by two types, coniferous and broadleaved species. Classifying the mensuration data of above- and belowground biomass of 14 tree species or genera into two types, compatible belowground biomass models for coniferous and broadleaved species can be developed respectively as follows:

$$\begin{cases} M_a = a_1 \times D^{a_2} + \varepsilon_{Ma} \\ M_b = b_1 \times D^{b_2} \times \widehat{M}_a + \varepsilon_{Mb} \\ R = b_1 \times D^{b_2} + \varepsilon_R \end{cases} \quad (3)$$

where M_a and M_b are above-and belowground biomass respectively, R is root-to-shoot ratio (the ratio of belowground biomass to aboveground biomass), D is diameter at breast height, $\widehat{M}_a$ is the estimate of aboveground biomass, ai and bi are parameters, and εi are error items. From eqn. (3), the following belowground biomass model can be obtained: $\widehat{M}_b = c_1 \times D^{c_2}$ (4)

where $\widehat{M}_b$ is the estimate of belowground biomass, and we have $c_1=a_1 \times b_1$ and $c_2=a_2+b_2$. Similarly, based on the results from eqn. (3) or eqn. (4), we can use eqn. (2) to calculate relative errors of belowground biomass estimates for conifer and broadleaf or each tree species/groups.

Results and Analysis

Aboveground biomass models

According to the aforementioned method, the mean basic wood densities of 34 tree species or groups were calculated out. For 14 tree species or genera having published or pre-published ministerial standards, the data of mean basic wood density were cited directly. Because there are no data of *P. koraiensis* in Institute of Wood Industry, Chinese Academy of Forestry [39], the one-variable aboveground biomass model of *P. koraiensis* in Chen CG and Zhu JF [40], was converted to general one-variable aboveground biomass model at the point D=16 cm, which is close to the mean diameter at breast height of all sample trees [24-36]. Similarly, because there are only a few data of Tilia in Institute of Wood Industry, Chinese Academy of Forestry [39], the one-variable aboveground biomass model of Tilia was used like *P. koraiensis* to obtain the corresponding mean wood density and get the average values of two mean wood density [40]. The number of sample trees of Cupressus is 51, which meets the need of a large sample [39]. Considering that the data of 138 Cupressus sample trees are available from the National Forest Biomass Modeling Program, the weighted average values of two mean wood density were used here to achieve more accurate estimates. Also, the basic wood density of *P. densata* is the weighted average value of two mean wood density involving a total of 106 sample trees. The mean values of basic wood density and sample tree numbers of all 34-tree species or groups (other broadleaved species are further classified into hardwoods and so twoods) are listed in Table 1. Based on the basic wood density p, the estimate of parameter a in eqn. (1) can be calculated (see Table 1).

Tree species/groups	Estimate of parameter *a*	Basic wood density *p*	Number of sample trees	References

Quercus	0.1729	0.5762	670	[33]
Abies	0.1039	0.3464	751	[30]
Picea	0.1119	0.373	901	[31]
Betula	0.1454	0.4848	690	[33]
Larix	0.1218	0.4059	602	[29]
Cunninghamia lanceolata	0.0929	0.3098	301	[28]
P. massoniana	0.1343	0.4476	301	[27]
Populus	0.1253	0.4177	901	①
P. yunnanensis	0.105	0.3499	150	[26]
P. densata	0.1416	0.472	106	[39]
Tilia	0.096	0.32	u	[39,40]
Cupressus	0.1792	0.597	189	[39]
F-J-P	0.1392	0.464	19	[39]
Schima superb	0.1669	0.5563	150	[35]
P. tabulaeformis	0.1273	0.4243	149	[24]
P. koraiensis	0.094	0.313	u	[40]
Ulmus	0.1374	0.458	27	[39]
P. khasya	0.1362	0.454	17	[39]
P. armandii	0.1179	0.393	29	[39]
Tsuga	0.1326	0.442	34	[39]
P. sylvestris var. mongolica	0.1125	0.375	22	[39]
Liquidambar formosana	0.1511	0.5035	152	[36]
P. elliottii	0.1235	0.4118	154	[25]
Salix	0.1323	0.441	29	[39]
Eucalyptus	0.1746	0.582	110	[39]
Cryptomeria	0.1048	0.3493	150	[32]
P. taiwanensis	0.1354	0.451	34	[39]
P. griffithii	0.1014	0.338	3	[39]
Robinia pseudoacacia	0.2022	0.674	25	[39]
Paulownia	0.0711	0.237	56	[39]
C-S-P	0.138	0.46	90	[39]
Other pines	0.1351	0.45	88	[39]
Other conifers	0.1182	0.394	54	[39]
Other hardwood broadleaves	0.1875	0.625	410	[39]
Other softwood broadleaves	0.1329	0.443	474	[39]

① State Forestry Administration, Tree biomass models and related parameters to carbon accounting for Populus (exposure draft of ministerial standard), 2017.

Table 1: Mean basic wood density and parameter values of the general one-variable aboveground biomass model for all tree species or groups. **Note:** 1) The basic wood density of *P. densata* is the weighted average value of two mean basic wood densities, one is 0.413 from 6 sample trees in Institute of Wood Industry, Chinese Academy of Forestry [39] and another is 0.4754 from 100 sample trees collected by the National Forest Biomass Modeling Program. 2) The basic wood density of *Tilia* is the arithmetic average value of two mean basic wood densities, one is 0.343 from 10 sample trees in Institute of Wood Industry, Chinese Academy of Forestry [39] and another is 0.297 from the converted one-variable biomass model of *Tilia amurensis*. 3) The basic wood density of Cupressus is the weighted average value of two mean basic wood densities, one is 0.482 from 51 sample trees in Institute of Wood Industry, Chinese Academy of Forestry [39] and another is 0.6400 from 138 sample trees collected by the National Forest Biomass Modeling Program. 4) The basic wood density of *P. koraiensis* is derived from the general model, a conversion of the one-variable aboveground biomass model of *P. koraiensis* in Chen CG and Zhu JF [40] at the point D=16 cm which is close to the mean diameter at breast height of all sample trees in [24-36]. 5) F-J-P means *Fraxinus mandshurica+Juglans mandshurica+Phellodendron amurense*, and *C-S-P* means *Cinnamomum+Sassafras+Phoebe*. 6) The estimates of parameter a are all kept 4 decimal digits (3 or 4 significant digits). 7) The basic wood density values in [24-36] have 4 decimal digits, and those in Institute of Wood Industry, Chinese Academy of Forestry [39] have only 3 decimal digits. 8) "u" in this table means the number of sample trees unclear for *Tilia* and *P. koraiensis*.

To evaluate the applicability of aboveground biomass models in Table 1, the mensuration data of aboveground biomass of 14 tree species or genera were used to calculate relative errors (*REs*), and the results are listed in Table 2. It is showed that REs of models for 11 tree species are less than ± 10%, only the *REs* of models for *Cryptomeria, Liquidambar formosana*, and *Robinia pseudoacacia* exceed ± 10%, but less than ± 20%. By summarizing, the total *RE* for 14 tree species/genera is -2.10%, no exceeding the common allowance ± 3%, and the average of absolute *RE* is 6.37%, less than the error allowance 10% [22]. Consequently, as for the biomass models of other 20 tree species or groups in Table 1, even though the predicted estimate for a special one may have uncertainty to some extent, but the predicted estimates for all the species should not exceed the error allowance, then the models are suitable for estimation of forest biomass at national level.

Species/genera	***RE*/%**	**Species/genera**	***RE*/%**
Quercus	-0.98	*Populus*	-3.89
Abies	-9.86	*P. yunnanensis*	1.26
Picea	-7.41	*Liquidambar formosana*	19.72
Betula	4.06	*P. tabulaeformis*	-2.32
Larix	1.25	*Robinia pseudoacacia*	-12.78
Cunninghamia lanceolata	-0.40	*P. elliottii*	4.29

P. massoniana	-1.13	*Cryptomeria*	19.89

Table 2: Test results on applicability of the general one-variable aboveground biomass models for 14 tree species or genera.

Belowground biomass models

The mensuration data of biomass of 14 tree species or genera aforementioned were classified into two sets, coniferous and broadleaved. There are 2021 sample trees having both above- and belowground biomass data, where 1150 are coniferous and 871 are broadleaved. The compatible belowground biomass models and root-to-shoot ratio models for coniferous and broadleaved species were estimated respectively as eqn. (3), and the parameter estimates are listed in Table 3. It is showed that the estimate of second parameter b_2 in root-to-shoot ratio model for coniferous species is close to 0, which is not significantly different from zero. That means the root-to-shoot ratio is close to a constant, almost having no relation to diameter of trees. Therefore, the average value 0.248 of root-to-shoot ratio can be used to estimate belowground biomass for coniferous species. The average value of root-to-shoot ratio for broadleaved species is 0.294, which is larger 18.5% than that of coniferous species. However, the root-to-shoot ratio for broadleaved species is significantly related to diameter of trees, thus it will be more accurate to estimate belowground biomass using the root-to-shoot ratio model.

Species	a_1	a_2	b_1	b_2	c_1	c_2
Coniferous	0.138	2.28	0.249	-0.001	0.0343	2.28
Broadleaved	0.128	2.36	0.468	-0.200	0.0599	2.16

Table 3: Parameter estimates of compatible belowground biomass models for coniferous and broadleaved species.

To evaluate the applicability of belowground biomass models and root-to-shoot ratio models in Table 3, the mensuration data of belowground biomass of 14 tree species or genera were used to calculate *REs*, and the results are listed in Table 4. It is showed that *REs* of models for 12 tree species are less than ± 20%, only the *REs* of models for *P. yunnanensis* and *Cryptomeria* exceed ± 20%. From analysis, the root-to-shoot ratios of *P. yunnanensis* and *Cryptomeria* are 0.160 and 0.348 respectively, which are just the minimum and maximum values among 9 coniferous species in Table 4. If considering the performance by coniferous and broadleaved species, the total *REs* are 4.81% and 0.15% respectively, no exceeding ± 5%; and the averages of absolute *REs* are 14.85% and 13.45%, less than the error allowance 15% for belowground biomass models [22]. Consequently, applying the models in Table 3 to estimate belowground biomass of other coniferous and broadleaved species except 14 tree species or genera aforementioned, even though the predicted estimate for a special one may have uncertainty to some extent, but the predicted estimates for all the species should not exceed the error allowance, then the models are suitable for estimation of forest biomass at national level.

Species/genera	*RE*/%	Species/genera	*RE*/%
Quercus	2.09	*Populus*	18.69
Abies	11.60	*P. yunnanensis*	54.41
Picea	3.68	*Liquidambar formosana*	-17.53
Betula	-9.00	*P. tabulaeformis*	-0.33
Larix	-4.89	*Robinia pseudoacacia*	-19.93
Cunninghamia lanceolata	7.38	*P. elliottii*	-3.98
P. massoniana	18.60	*Cryptomeria*	-28.77

Table 4: Test results of belowground biomass models for coniferous and broadleaved species.

Conclusion and Discussion

Based on the general biomass model $M=0.3\rho D^{7/3}$ presented by Zeng and Tang and the published data of basic wood density for all tree species, one-variable aboveground biomass models for all 34-tree species or groups were developed. Additionally, using the mensuration data from the National Forest Biomass Modeling Program, the compatible belowground biomass models for coniferous and broadleaved species were established. According to the validation results for 14 tree species or genera, the one-variable biomass models developed in this paper can ensure the averages of absolute relative errors of above- and belowground biomass estimates less than the corresponding error allowances 10% and 15%, respectively. Thus, the developed biomass models can be used for forest biomass estimation at national level, which can be regarded as an important supplement to the ministerial standards on tree biomass models published in recent years.

Because the forest volume estimation in national forest inventory of China is based on one-variable volume tables/models, for forest biomass estimation we should use the compatible one-variable biomass models or biomass conversion factor models and root-to-shoot ratio models. The ministerial standards on tree biomass models recently published for 14 tree species or genera have laid a fine foundation for accurate estimation of nearly 70 percent forest biomass in China. The growing stocks of other 20 tree species or groups only occupy 30 percent of total growing stock. Before the ministerial standards on tree biomass models for these species have been published, the one-variable aboveground biomass models for various species and one-variable root-to-shoot ratio models for coniferous and broadleaved species developed in this paper could be used to estimate above- and belowground biomass. Considering that the sample trees of *P. griffithii* are too few, it is suggested to use the biomass model of *P. densata* instead of that of *P. griffithii*.

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