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A model for converting forest volume to aboveground biomass by allometric equations

Jia Wang [1,2*], Huiqiao Yang [1,2], Zhongke Feng[1,2]
[1]Beijing Key Laboratory of Precision Forestry, Beijing Forestry University, (CHINA)
[2]College of Forestry, Beijing Forestry University, (CHINA)

ABSTRACT

Forest biomass study takes great sense in estimation of carbon release which is an important in increasement of carbon dioxide. There are many models to estimate forest biomass by the volume data, among them allometric equations is widely studied and highly recommended. The paper proposed a new model $B = cV^d$ (B stands for aboveground biomass, V for forest volume, c and d for parameters of the new models) to estimate the aboveground biomass (AGB) by the allometric equations and the Squrr Equation, followed the assumption of the new model, a set of new equations to estimate forest biomass in a sample plot can be drew. In order to prove the new model is superior to traditional ones in converting volume to biomass, the experiments were carried out in Dangchuang forest farm, Gan Su province in China, 32 trees of *Quercus aliena Var. cuteserata* were fell, measured the volume and AGB, fitted by two tranditional models and the new one then did a comparison. The results showed that new model was better and the relationship between the AGB and tree volume is exponential not linearity. In practical, the volume can be estimated by Squrr Equation, also by the Yamamoto formula and Herschel formula. And the volume estimated by these theoretical equations which includes Squrr Equation, Yamamoto formula and Herschel formula can be used to estimate AGB.

KEYWORDS

Forest aboveground biomass;
Forest volume;
Allometric equations;
Squrr equation;
Tranditional models.

INTRODUCTION

The increasement of carbon dioxide in atmospheric over the past 100 years is a mainly global concerned issue today and its potential can change the world climate. Some hot issues about the estimation of C release depend on the biomass data[2]. As it is known to all that forest biomass measurement is a laborious and time consuming approach and most of time needs tree destruction, so the estimation of forest biomass by existing data and new effective approaches is highly recommonded and widely studied.

Judging from the current studies, the relative models between biomass (B) and volume (V) mainly include: (1) $B = aV$ (N. MonteÁs, 2000), among them a need to be determined;

(2) $B = BEF \cdot \gamma \cdot V$, γ serves as the wood den-

FULL PAPER

sity[15], BEF the expansion factor[5,16].;

(3) $B = a + bV$ [9], among them , need to be determined.

(4) $B = \frac{V}{a + bV}$ [6,12]

Model (1) and (2) are consistent substantively. In the model (2), may strongly depend on location, climate, and possible management[18]; And is not a constant, it may decrease with increasing volume. Only when forest volume is very large, is close to a constant. Model (3) suggests the relationship between the volume and AGB is linearity, however model (4) nonlinearity. Model (4) developed by Zhou et al.[6] just for Larix forest in China.

Allometric biomass equations aim to relate tree biomass (B_i) to quantities (Q_i) that can be easily and nondestructively measured on trees: $B=f(Q_1,Q_1,...)$, the most commonly used funcitons are polynomials and power models of the form $f(Q) = aQ^b$and their combinations, the power funciton form is widely found within biology[7], however, it did not fit the relationship between all plants and the total[8], the commonest used are H (Height) and D (Breast Height Diameter, BHD) instead of variable Q_i, namely $B=a(D_2H)^b$. Several authors have shown that the inclusion of H generally gives only a slight improvement in the fraction of variance explained by the model for a given site, the relationship between H and D is $H=kD^c$ [18]. However, the relative errors in biomass estimates between BHD-only, BHD–H combined, and generalized equations are unknown for Chinese temperate forest tree species. By experiments, Chuankuan Wang suggested BHD-only equations be more suitable for total biomass estimation, BHD–H combined more precise estimation of such component biomass[1].

Since 1970s, China has carried out large-scale National Forest Resources Inventory (NFI), in which we accumulated plenty of vlume data, we believed that this data can contribute to estimate AGB. The major objectives of this study were to: design a new model to estimate AGB based on allometric equations and Squrr Equation, using the forest volume data.

METHODS AND MATERIALS

Assumptions

We design the model based on the following assumptions:

The volume models[22]

Based tree height for H, tree diameter at breast height for the D, the volume of individual tree can be expressed as follow by the allometry method:

$$V=a'(D_2H)^{b'} \quad (1)$$

Among the model a', b' act as parameters to be determined.

According to the equation (1), the total volume of a region (sample plot) can be estimated by the following three methods:

(a) the method by average tree (BHD) and height;

(b) the method by mean BHD and height in diameter class;

(c) the one by individual trees' BHD and height.

The method by average tree BHD and height

Supposed the total tree number of a regional (sample plot) for N, the average tree height $\overline{H}$ and $\overline{D}$ the average tree breast-height-diameter respectively and, the forest volume (credited as V_T) in the region (sample plot) can be expressed as below by the average cross-section:

$$V_T=na'(\overline{D}^2\overline{H})^{b'} \quad (2)$$

The method by mean tree BHD and height in diameter class

Supposed the average tree height and the average tree BHD of the j^{th} diameter class respectively $\overline{H}_j$ *and* $\overline{D}_j$, the total tree number of the j^{th} diameter class for n_j, the tatol number of the diameter class for N in a regional (sample plot), the forest volume (credited as V_T) in the region (sample plot) can be expressed as below by the method by average tree BHD and height

$$V_T = a'\sum_{j=1}^{N} n_j(\overline{D}_j^2\overline{H}_j)^{b'} = \sum_{j=1}^{N} V_j \quad (3)$$

In the model, means the tree volume of the j^{th} diameter class.

The method by individual trees' BHD and height

Supposed the total tree number of a regional (sample plot) for n, the forest volume can be expressed as below:

$$V_T = a'\sum_{i=1}^{n}(D_i^2H_i)^{b'} \quad (4)$$

The AGB expressed by allometric equations

For a single tree, which includes the main part stem, the bark, the branch and the foliage, the AGB can be expressed by the allometric equations $B=a(D2H)^{b}$[14]. This assumption may cause arguments as follow:

Whether the Allometric Equation is suitable the model for AGB, considering the component biomass? In preliminaries of biomass modeling, a tree was normally separated into three aboveground component: bole, bole bark and crown (branches and foliage), and the component were often subsampled, because subsamples are time consuming and expensive measurement. Then the component of tree biomass combined by nonlinear joint-generalized regression, which was superior to simple combination[17]. Laurent Saint-Andréa, Armel Thongo M'Bou develop a complete set of equations for below- and above-ground biomass of a natural Eucalyptus hybrid in Congo, differences for obtained from the sum of all compartment equations ranged from -17 to 31% (average 5%), for above-ground (they also studied the below-ground equations) from -18 to 23% (average -1%), additivity was verified and showed no significant deviation except for the youngest stand, and the above-ground biomass equations (also the below-ground equations) was preferable to the sum of component equations or to the total biomass equation[10].

Among the Allometric Equation, the model $B=a(D^2H)^b$ is better than other models like $B=aD^b$ to estimate AGB. We considered that the correlation coefficient of the former model was higher than the latter's, the error was smaller[24].

Model design

The new model between the individual tree volume and AGB

Generally, the individual tree biomass can by expressed by the allometry method:

$$B=a(D^2H)^b \qquad (5)$$

n the model a, b serve as parameters need to be determined.

Transform the formula (5), combine with the formula (1) then we can set up the relational model between the individual tree volume and AGB, namely

$$B = a\left[\frac{1}{a'}a'(D^2H)^{b'}\right]^{b/b'} = \frac{a}{(a')^{b/b'}}\left[a'(D^2H)^{b'}\right]^{b/b'}$$

Supposed

$$d=b/b' \qquad (5a)$$

$$c=a/(a')^d \qquad (5b)$$

Combine with the formula (1), we can conclude

$$B=cV^d \qquad (6)$$

The formula (6) just is an expression that can be named as the *CVD* model by its shape.

The relational model between region (sample plot) tree volume and AGB (FengZong-wei, 1999)

Based on the new model $B=cV^d$ which is for a individual tree, the AGB of a sample plot can be drew because the volume of a sample plot can be estimated by BHD and H by three methods mentioned in 2.1.1. The AGB of a sample plot also can be estimated by three methods: The method by average tree BHD and height, The method by mean tree BHD and height in diameter class, The method by individual tree volume.

(a) The method by average tree BHD and height

When we estimate the region (sample plot) biomass by the allometry method, it can be expressed with the average tree BHD and height.

$$B_T=na(\overline{H}\ \overline{D}) \qquad (7)$$

Transform (7), the relational model of V_T and B_T can be expressed as $B_T = na\left[\frac{1}{na'}na'(\overline{H}\ \overline{D}^2)^{b'}\right]^{b/b'} = \frac{n}{(n)^{b/b'}}\cdot\frac{a}{(a')^{b/b'}}\left[na'(\overline{H}\ \overline{D}^2)^{b'}\right]^{b/b'}$

Combine with (5a), (5b) and (2), then conclude

$$B_T = n^{1-d}cV_T^d \qquad (6)$$

and serve as parameters need to be determined.

According to (6), we can determine the regressive value of and by the regression analysis methods (Work the same hereinafter).

(b) The method by mean tree BHD and height in diameter class

Supposed the tree volume of the j^th^ diameter class for in a regional (sample plot), the tree number of this diameter class for N, the number of diameter class for , so the total tree biomass in the region (sample plot) can be expressed:

$$B_T = c\sum_{j=1}^{N} n_j^{1-d} V_j^d \qquad (9)$$

n the model, V_j means the tree volume of the j^{th} diameter class.

FULL PAPER

(c) The method by individual tree volume

Supposed the individual tree volume for V_i, the total tree number for n, so the total tree biomass in the region (sample plot) can be expressed:

$$B_T = c\sum_{i=1}^{n} V_i^d \quad (10)$$

Data and method

Data

The experiment was carried out from July to the end of Augst in the year 2004 in Xiaolong Mountain, located in the southeast of Gansu province,China . There we measured BHD, height of the *Quercus aliena Var. cuteserata* of sample trees, 32 trees were felled, then weighed the fresh weight of their various organs. After sampling and drying every organ of the tree, we converted and got the AGB.At the same timeÿwe measured the stemÿs volume accurately by sectional measurement.

Biomass model fitting and estimatation comparisons

Here we chose $B=aV$ and $B=a+bV$ as the tranditional models to convert the tree volume to AGB, then compared them to the new model $B=cV^d$, the parameter *a* and *b* determined by least square *c*, and *d* determined by nonlinear least square[11,21]. We calculated the items of errors of three models to see the compared result.

We calculated the AGB by the parameters and the real-measured volume, then compared to the real-measured AGB, then got the absolute error (*s*) and relative error (*k*). In fact, we got *s* by calculating the difference between the real-measured AGB of individual trees and the one calculated by models, took absolute value and then summed up; *k* is the ratio of *s* and the real measured AGB of relative tree species.

Volume modeling and convert to aboveground biomass

In the experiment, we used the real-measured volumes to study the AGB of trees, however, in the application we hoped that the volumes can be get by theoretical formula $V=a'(D^2 H)^{b'}$ [22] (is trees' height, *D* trees' diameter at breast height, *a'*, *b'* parameters to be determined). Whether there is obvious difference between the theoretical formula and the real measurement, become another focuse of our research. To study the issus mainly because that if the theoretical volume can take place of the real-measured volume, a lot of laborious and time can be saved, and the trees does not need to be destructed.

According to the real-measured volumes and the relative H and BHD, we got the parameters *a'*, *b'* of by $V=a'(D^2 H)^{b'}$ nonlinear least square, finally we can get the theoretical volumes (It is called theoretical volumes, because it is estimated by equations, not by the measurement). To compare the real-measured volumes and the theoretical volumes, we calculated the items of errors. Once the parameters were determined, they can be used in future and the further studies.

Finally, we calculated the AGB of trees by the theoretical volume, wanted to see the difference between the real-measured AGB and the converted biomass (by the new model $B=cV^d$ and the other models). Determine the parameters *c* and *d* of $B=cV^d$ by the real-measured AGB and the theoretical volume, compared the results to the real-measured AGB.

RESULTS

Biomass models and comparison

According to Table 1, we showed the relationship between forest volume and AGB of trees (the Points), and only the result of $B=cV^d$ model (the Curve) was showed in the Figure 1, as we found that it fitted better than twe other models, the results can be see below.

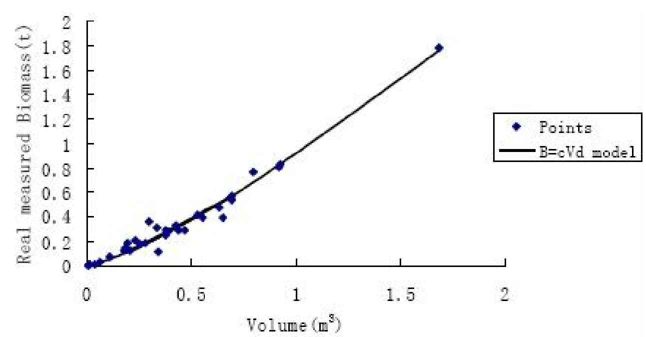

Figure 1 : The relationship between real measured volume and real measured biomass of *Quercus aliena Var. cuteserata*, and the fitting by $B=cV^d$ model

The items of errors of three models were showed below. σ stands for standard deviation of fitting models, ρ for correlation coefficient, R for correlative indexWe can see from TABLE 1- 3 that when three models,$B=aV$, $B=a+bV$ and $B=cV^d$ were used to fit the real-measured volume and the real-measured AGB respectively, the unbiased estimation of standard deviation of biomass is 89.55, 78.76and 56.52respectively. We can drew to the conclusion from the whole view that $B=cV^d$ was superior to two other models, and also better to fit the Points in Figure 1. The evidence also can be found in TABLE 4, that the relative error were 18.00%, 17.60% and 10.70% respectively, compared the converted biomass by three models to the real-measured one. We also can drew to another conclusion that scatter diagram of volume-biomass was exponential not linearity.

TABLE 1 : The parameters of model $B = aV$ constructed by tree's measured volume

Tree species	a	$\hat{\sigma}_a$	$\hat{\sigma}/kg$	ρ
uercus aliena Var. cuteserata	0.879465	0.0295	89.55	0.975

TABLE 2 : The parameters of model $B = a + bV$ constructed by tree's measured volume

Tree species	a	b	$\hat{\sigma}_a$	$\hat{\sigma}_{ab}$	$\hat{\sigma}_b$	$\hat{\sigma}/kg$	ρ
uercus aliena Var. cuteserata	-0.06955	0.979459	0.0219	-0.0007	0.0408	78.76	0.9750

TABLE 3 : The parameters of model $B = cV^d$ constructed by tree′s measured volume

Tree species	c	d	$\hat{\sigma}_c$	$\hat{\sigma}_{cd}$	$\hat{\sigma}_d$	$\hat{\sigma}/kg$	R
uercus aliena Var. cuteserata	0.912119	1.266505	0.0191	0.00002	0.0390	56.52	0.9872

TABLE 5 : The absolute error(s) and relative error(k) of the sample tre's AGB translated by measured volume

$B = aV$		$B = a + bV$		$B = cV^d$	
s/kg	$k/\%$	s/kg	$k/\%$	s/kg	$k/\%$
1940.80	18.00	1901.00	17.60	1149.90	10.70

Volume models and convert to AGB

According to the theoretical formula $V=a'(D^2H)^{b'}$, the parameters and were determined by real measured volumes and the relative tree height and BHD, the items of errors was also listed in TABLE 5.

TABLE 6 : The parameters of the tree's volume model $V = a'(D^2H)^{b'}$

a'	b'	$\hat{\sigma}_{a'}$	$\hat{\sigma}_{a'b'}$	$\hat{\sigma}_{b'}$	$\hat{\sigma}/m^3$	R
0.374653	0.881087	0.0126	0.0003	0.0303	0.0600	0.9875

We can see that the difference between the real-measured volume and the theoretical volume is not obviously, and believe that theoretical volume can be applied in converting to forest biomass practically.

Use the theoretical volume to estimate the AGB, also by the three model ,$B=aV$, $B=a+bV$ and $B=cV^d$ and nonlinear least square method. The parameters of each models and the items of errors were listed in TABLE 6-8:

TABLE 6 : The parameters of model $B = aV$ constructed by tree's theoretical volume

a	$\hat{\sigma}_a$	$\hat{\sigma}/kg$	ρ
0.886974	0.0273	82.51	0.9816

TABLE 7 : The parameters of model $B = a + bV$ constructed by tree's theoretical volume

a	b	$\hat{\sigma}_a$	$\hat{\sigma}_{ab}$	$\hat{\sigma}_b$	$\hat{\sigma}/kg$	ρ
-0.07708	0.997608	0.019	-0.0005	0.0355	67.83	0.9816

Finally compare the real-measured AGB and the converted biomass by three models, the absolute error (s) and relative error (k) were listed in TABLE 9.

We also can see that it agreed to the conclusion drew above. Wang Zhongfeng did similar experiments that the volume estimated by Yamamoto formula and Herschel formula, and then estimated the AGB by the theoretical volumes, the results were in accord with the same method by the real-measured volume[23]. It has great sense in practical application as saving laborious and time, and no tree destruction.

DISCUSSION

We can see that the new model to convert the volume to AGB is quite simple and can be easily use in practice, the below-ground biomass of trees also can be added into modeling, Wang Zhongfeng showed

TABLE 8 : The parameters of model $B = cV^d$ constructed by tree's theoretical volume

c	d	$\hat{\sigma}_c$	$\hat{\sigma}_{cd}$	$\hat{\sigma}_d$	$\hat{\sigma}/kg$	R
0.922278	1.265410	0.0147	0.00002	0.0296	43.19	0.9925

TABLE 9 : The absolute error(s) and relative error(k) of the sample tree's AGB translated by theoretical volume

$B = aV$		$B = a + bV$		$B = cV^d$	
s/kg	$k/\%$	s/kg	$k/\%$	s/kg	$k/\%$
1825.700	16.90	1636.80	15.19	980.46	9.10

that the $B=cV^d$ model was also suitable to estimate the whole biomass of a tree (WANG Zhoengfeng, 2006). But we have to admit that the new model did not take compatibility of biomass model into consideration, which will become the next research point in the future.

The parameters of $B=cV^d$ and the ones of Squrr Equation need measurement about the real-measured biomass and the real-measured volume, are also different from trees species and the regions, however these parameters take great sense in the precise of estimation. Once they were determined, they will be useful for future.

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