Article

Development of Two-way Volume Equation for Bamboo, *Phyllostachys nigra*

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ABSTRACT

A two-way volume equation for one of the three major useful bamboos in Japan, *Phyllostachys nigra* var. *henonis*, is developed and the goodness of fit is evaluated using the data collected from two different districts. The model used here was the generalized theoretical volume equation. The normal form-factors at 0.7 and 0.8 for *P. nigra* were steady at 0.622 and 0.558, respectively. Inserting these values into the generalized theoretical volume equation enabled us to determine the coefficients of the volume equation. Although the estimated apparent culm volume was significantly smaller than actual one, the relative mean error of the estimated volume was comparatively small. The volume equation for *Phyllostachys bambusoides* Sieb. et Zucc. could be directly applied to *P. nigra*, whereas that for *Phyllostachys pubescens* Mazel et Houz. could not. This fact indicated that the inter-species characteristics of culm form should be carefully considered when evaluating the bamboo resources by the volume equation. In conclusion, the generalized theoretical volume equation would be effective when evaluating the resources and comparing the stand productivity for *P. nigra*.

Keywords: apparent culm volume; bamboo, culm form, generalized theoretical volume equation, normal form-factor

INTRODUCTION

Bamboo is highly versatile and rapidly renewable, long been used as a timber alternative for flooring, construction, furniture, charcoal, crafts and food (BUCKINGHAM *et al.*, 2011). In addition, recent technological developments cleared way for bamboo to be used extensively in manufacturing the reconstituted panel and board products, fuel, pulp and paper (DRUST *et al.*, 2004). ZHOU *et al.* (2005) also reviewed the environmental functions of bamboo forests such as soil conservation and carbon fixation. Because of these economic and environmental values, bamboo has received increasing attention over the last two decade in Asia, Africa and Latin America (RUIZ-PEREZ *et al.*, 2001) and is expected to contribute to development in bamboo growing rural areas as "poor man's timber" (LOU *et al.*, 2010).

In Japan, there are more than 150,000 hectares of

bamboo forests (LOVONIKOV *et al.*, 2007). New shoots occur naturally and annually without planting or seeding in bamboo forests, and they reach the mature size in a matter of two or three months (ZHOU *et al.*, 2005). Therefore, bamboo has a potential as plentiful biomass resources in Japan, but not used effectively (MINAMI and SAKA, 2005). In order to establish the effective utilization of bamboo resources and sustainable management of bamboo forests, reliable data and information with regards to their resources are required (KLEINN and MORALES, 2006). Culms are major component among aboveground parts of bamboo (e.g., SUZUKI and UCHIMURA, 1980; YEN *et al.*, 2010; YEN and LEE, 2011), and are more useful compared to branches and leaves. Culm volume is therefore one of the most important information when evaluating bamboo resources (INOUE *et al.*, 2011; SUGA *et al.*, 2011) and comparing stand productivities (AOKI, 1955; CAMARGO and KLEINN, 2010). However, there is still a lack of availability of basic models for estimating apparent culm volume, i.e., the total culm volume including the hollow part, or wood volume, i.e., the volume of the woody walls of the culms (KLEINN and MORALES, 2006; CAMARGO and KLEINN, 2010).

Phyllostachys nigra var. *henonis*, which is native to China (LI *et al.*, 2005), is one of the three major useful bamboos in Japan along with *Phyllostachys pubescens* Mazel et Houz. and *Phyllostachys bambusoides* Sieb. et Zucc. (UCHIMURA, 2009). *P. nigra* was probably introduced from China about 800 years ago, and have been traditionally used for edible shoots and industrial arts (SUZUKI and NAKAGOSHI, 2011). Although *P. nigra* occupies only about 0.4% of the total bamboo growing

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area in Japan (UCHIMURA, 1980), its area exceed more than 20% of bamboo growing area in a certain district (e.g., FORESTRY and FISHERIES DEPARTMENT of KUMAMOTO PREFECTURE, 2005). This implies that *P. nigra* might be useful biomass resources in its much growing area. However, studies on *P. nigra* are extremely scarce, which involve the culm form (OTA, 1950), productivity (SUZUKI and UCHIMURA, 1980), amounts of litter fall and sheaths (WATANABE, 1983), fuel properties (SCURLOCK et al., 2000), growth behavior (LI et al., 2005), stand dynamics (SAROINSONG et al., 2006) and spatial pattern (SAROINSONG et al., 2007).

In previous studies (INOUE et al., 2011; SUGA et al., 2011), the two-way volume equations for *P. pubescens* and *P. bambusoides* were derived so that the apparent culm volume can be estimated from diameter at breast height (dbh) and culm height. INOUE et al. (2011) found that there was a need for distinguishing the volume equation among these bamboo species, suggesting that the volume equation for *P. nigra* may also be different from those for the two species. However, to our knowledge, there have been no models for evaluating the culm volume of *P. nigra*. It is also unknown whether the volume equation for the two species can be directly applied to *P. nigra*. For the effective utilization and sustainable management of *P. nigra*, it is necessary to develop a model for evaluating its culm volume.

The objective of the present study was thus to develop the two-way volume equation for estimating apparent culm volume for *P. nigra*. First, the two-way volume equation was determined using the generalized theoretical volume equation (INOUE et al., 2011; SUGA et al., 2011). Second, the goodness of fit and applicability of the determined volume equation were evaluated based on the data collected from two different districts. Third, the volume equation for *P. nigra* was compared with those for other bamboo species, i.e., *P. pubescens* and *P. bambusoides*, determined in previous studies (INOUE et al., 2011; SUGA et al., 2011).

MATERIALS AND METHODS

Data

The data used in this study was collected from two stands of *P. nigra* in Ito campus of Kyushu University (ITO: 33°36' N, 130°13' E, 60 m a.s.l.) in Fukuoka City and in the campus of Fukuoka University of Education (FUE: 33°48' N, 130°36' E, 50 m a.s.l.) in Munakata City, Fukuoka Prefecture, western Japan. These stands were about 40 km away from each other. The average annual temperature and annual rainfall for the last decade at the nearest observatory were, respectively, 16.1 °C and 1,677 mm for ITO and 15.6 °C and 1,640 mm for FUE, indicating that these areas will be a favorable condition for the growth of bamboo (SCURLOCK et al., 2000). Both stands were very dense and their canopies were closed, and hence no other vegetation was found on the forest floors.

In each stand, healthy and living sample culms with various sizes were felled at ground level for direct measurement of height and diameter in October 2011. The number of samples was 100 for ITO and 50 for FUE. The culm height was measured directly with a tape measure to the nearest tenth of a meter. The external culm diameter at 1.2 m height above ground level (dbh) and ten successive points were measured with a digital caliper to the nearest tenth of a centimeter. The measurement points were located along the culm at equal intervals of one tenth of the direct measured culm height (relative height: 0.1, 0.2, ..., 1.0). General description of the samples is given in Table 1.

Analysis Methods

The apparent culm volume for each sample was computed by the sectional measurement method (WEST, 2004). The sample culms collected from ITO were randomly bisected into two sets of data, i.e., modeling and test data ($n = 50$ for each set). The samples from FUE were also pooled for the test data ($n = 50$), so that an applicability of the determined volume equation can be evaluated. For the modeling data, the normal form-factors for the ten relative heights, i.e., $\lambda_{0.1}, \lambda_{0.2}, \dots, \lambda_{1.0}$, were computed, and then their averages and coefficients of variation (CV) were calculated. The dependence of each normal form-factor on the culm sizes, i.e., dbh and culm height, was analyzed with Spearman's correlation coefficient by rank test. From the viewpoints of the smallness of CV and

Table 1 General description of *Phyllostachys nigra* sample culms

	Diameter at breast height (cm)	Culm height (m)	Apparent culm volume (dm ³)
ITO ($n = 100$)			
Average	2.7	6.3	2.4
Standard derivation	0.7	1.4	1.7
Maximum	4.3	9.3	7.5
Minimum	1.1	3.1	0.2
Median	2.6	6.1	1.8
FUE ($n = 50$)			
Average	2.9	7.3	3.6
Standard derivation	1.1	2.0	3.1
Maximum	4.9	11.3	12.2
Minimum	0.9	2.7	0.1
Median	2.9	7.5	2.6

independence on the culm sizes, the steady normal form-factors at two different relative heights were selected. The coefficients of the volume equation for *P. nigra* were then determined by substituting the averages of the steady normal form-factors and their relative heights into the following generalized theoretical volume equation:

$$v = \frac{\lambda_j \pi d_b^2 h}{4[(1 - h_b/h)/j]^{\log(\lambda_i/\lambda_j)/\log(j/i)}} \quad (1)$$

where v : apparent culm volume; d_b : diameter at breast height; h : culm height; h_b : breast height (= 1.2 m in this study); λ_i and λ_j : averages of the steady normal form-factors at relative height i and j , respectively. For the detail of the derivation of Eq. 1, see INOUE *et al.* (2011) or SUGA *et al.* (2011).

For the test data from ITO and FUE, the apparent culm volume for each sample culm was estimated by inserting the measured dbh and culm height into the determined volume equation. For each district, the goodness of fit of the volume equation was evaluated by the mean error (ME), relative mean error (%ME), root mean square error (RMSE) and relative root mean square error (%RMSE). The estimated apparent culm volume was compared with the actual one with Wilcoxon signed-rank test. All statistical procedures were performed with the R software (R DEVELOPMENT CORE TEAM, 2006).

RESULTS

Normal Form-factors for *P. nigra*

Fig. 1 depicts the average and coefficient of variation (CV) of the normal form-factors for *P. nigra*. The average of the normal form-factor decreased from culm tip to base. CV of the normal form-factor was the smallest at 0.8 in relative height, and gradually increased from there toward both ends of culm. CVs of the normal form-factors from 0.5 to 0.9 in relative height were less than 10%, indicating that the variations in

these normal form-factors were smaller than those in other form-factors.

The correlation coefficients between normal form-factors and culm sizes are given in Fig. 2. Spearman's correlation coefficient by rank test indicated that $\lambda_{0.2}$, $\lambda_{0.7}$ and $\lambda_{0.8}$ were not significantly correlated with diameter at breast height ($r = -0.106$, $P = 0.463$ for $\lambda_{0.2}$; $r = -0.224$, $P = 0.119$ for $\lambda_{0.7}$ and $r = 0.001$, $P = 0.993$ for $\lambda_{0.8}$), whereas $\lambda_{0.1}$, $\lambda_{0.2}$, $\lambda_{0.7}$ and $\lambda_{0.8}$ were not significantly correlated with the culm height ($r = 0.207$, $P = 0.149$ for $\lambda_{0.1}$; $r = -0.027$, $P = 0.850$ for $\lambda_{0.2}$; $r = -0.184$, $P = 0.201$ for $\lambda_{0.7}$ and $r = 0.081$, $P = 0.578$ for $\lambda_{0.8}$). On the other hand, other normal form-factors were significantly correlated with either diameter at breast height and culm height ($P < 0.05$).

Determination and Goodness of Fit of the Volume Equation

Because of the smaller variation and independency on culm sizes, $\lambda_{0.7}$ and $\lambda_{0.8}$ were selected to determine the coefficients of the volume equation. Relationships of $\lambda_{0.7}$ and $\lambda_{0.8}$ to culm sizes are shown in Fig. 3, indicating that these normal form-factors were independent of the culm sizes. Substituting their averages, i.e., $\lambda_{0.7} = 0.622$ and $\lambda_{0.8} = 0.558$, and the relative heights into Eq. 1, we obtained the following two-way volume equation for *P. nigra*:

$$v = \frac{0.622\pi d_b^2 h}{4[(1 - h_b/h)/0.7]^{0.893}} \quad (2)$$

Fig. 4 compares the estimated and actual apparent culm volume for *P. nigra* collected from ITO and FUE. The mean error (ME), relative mean error (%ME), root mean square error (RMSE) and relative root mean square error (%RMSE) are summarized in Table 2. For ITO, there was a slightly significant difference between estimated and actual apparent culm volume ($P < 0.01$), with ME and RMSE being -0.092 dm^3 and 0.013 dm^3 , respectively. The estimated culm volume for FUE was also significantly smaller than the actual one ($P <$

Fig. 1 Average and coefficient of variation (CV) of normal form-factors for *Phyllostachys nigra*

Fig. 2 Correlation coefficients between normal form-factors and culm sizes for *Phyllostachys nigra*. The black and white bars indicate significant and insignificant correlation coefficients at 5% level, respectively.

0.001), with ME and RMSE being -0.232 dm^3 and 0.460 dm^3 , respectively. %ME and %RMSE were, respectively, -3.936% and 0.557% for ITO and -6.422% and 12.703% for FUE.

DISCUSSION

Culm Form of *P. nigra*

In this study, the generalized theoretical volume equation was applied to the development of the two-way volume equation for *P. nigra*. The coefficients of this volume equation are determined based on the analysis of the normal form-factors. As shown in Fig. 1, the coefficients of variation (CV) of the normal form-factors from 0.5 to 0.9 in relative height were less than 10%. Similar findings were reported for *P. pubescens* (SUGA et al., 2011) and *P. bambusoides* (INOUE et al., 2011). This supports that these normal form-factors will be effective in determining the coefficients of the generalized theoretical

volume equation for bamboo species (INOUE et al., 2011).

The normal form-factors at 0.6 and 0.9 in relative height, $\lambda_{0.6}$ and $\lambda_{0.9}$, for *P. pubescens* and *P. bambusoides* were not correlated with culm sizes (INOUE et al., 2011; SUGA et al., 2011). By contrast, these normal form-factors for *P. nigra* were significantly correlated with culm sizes, and $\lambda_{0.7}$ and $\lambda_{0.8}$ were not alternatively correlated (see Fig. 2). The result suggests that the steady normal form-factors would vary with bamboo species. Our data also demonstrated that $\lambda_{0.6}$ was negatively correlated with culm sizes, whereas $\lambda_{0.9}$ was positively correlated. Since $\lambda_{0.6}$ was larger than $\lambda_{0.9}$ (see Fig. 1), the difference between $\lambda_{0.6}$ and $\lambda_{0.9}$ becomes smaller with an increasing in culm sizes. This fact means that the culm form for *P. nigra* becomes non-tapering with the culm sizes, whereas $\lambda_{0.7}$ and $\lambda_{0.8}$ are steady at constant levels.

Goodness of Fit of the Determined Volume Equation

Table 2 Mean error (ME), relative mean error (%ME), root mean square error (RMSE) and relative root mean square error (%RMSE) between estimated and actual apparent culm volume for *Phyllostachys nigra*

	ME (dm^3)	%ME (%)	RMSE (dm^3)	%RMSE (%)
Estimation from the volume equation for <i>Phyllostachys nigra</i> (Eq. 2 in the text)				
ITO ($n = 50$)	- 0.092	- 3.936	0.013	0.557
FUE ($n = 50$)	- 0.232	- 6.422	0.460	12.703
Estimation from the volume equation for <i>Phyllostachys pubescens</i> (Eq. 3 in the text)				
ITO ($n = 50$)	- 0.185	- 7.881	0.386	16.493
FUE ($n = 50$)	- 0.484	- 13.380	0.815	22.509
Estimation from the volume equation for <i>Phyllostachys bambusoides</i> (Eq. 4 in the text)				
ITO ($n = 50$)	0.049	2.097	0.229	9.791
FUE ($n = 50$)	- 0.013	- 0.349	0.297	8.212

Fig. 3 Relationships of normal form-factors to diameter at breast height and culm height for *Phyllostachys nigra*. The triangle and circle indicate the normal form-factors at 0.7 and 0.8 in relative height, respectively.

Fig. 4 Comparison of the estimated and actual apparent culm volumes for *Phyllostachys nigra*. The broken line indicates 1:1.

The generalized theoretical volume equation used in this study was originally proposed as the theoretical volume equation for estimating the stem volume of coniferous tree species (INOUE and KUROKAWA, 2001). INOUE *et al.* (2011) and SUGA *et al.* (2011) generalized this volume equation to apply to the bamboo species as well as the coniferous tree species. INOUE and KUROKAWA (2001) reported that the relative mean error of the theoretical volume equation was 1.543% for *Cryptomeria japonica* D. Don and 8.402% for *Chamaecyparis obtusa* Endl. INOUE *et al.* (2002) also found that the relative

mean error of the volume equation ranged from 1.091% to 11.400% for *Larix kaempferi* grown in four different districts. In addition, INOUE (2006) applied the volume equation to *C. japonica* grown in three districts with different management regimes, and reported that relative mean error ranged from 0.923% to 15.908%. Furthermore, the empirical volume equations used widely produced a comparable goodness of fit of the theoretical volume equation (INOUE, 2006; INOUE and KUROKAWA, 2001; INOUE *et al.*, 2002). INOUE (2006) applied the generalized theoretical volume equation to *P. pubescens*, with

the relative mean error being 0.172%. For *P. bambusoides*, SUGA et al. (2011) also reported that the relative mean error of the generalized theoretical volume equation ranged from -5.558 to 1.122%.

The result of this study showed that the estimated apparent culm volume was significantly smaller than actual one for both districts, with the relative mean error being -3.936% for ITO and -6.422% for FUE (see Fig. 4 and Table 2). There are no clear difference in relative mean error of the estimated volume between the previous studies and this study. Therefore, the significant difference between the estimated and actual apparent culm volume for *P. nigra* does not always deny the effectiveness of the determined generalized theoretical volume equation, Eq. 2. When estimating the volume for bamboo and coniferous tree species, it should be noted that the generalized theoretical volume equation would produce a comparable relative mean error found in this study and previous ones, i.e., about $\pm 10\%$ (INOUE, 2006; INOUE and KUROKAWA, 2001; INOUE et al., 2002, 2011; SUGA et al., 2011).

Comparison of the Volume Equations

The generalized theoretical volume equation has been applied to other bamboo species as follows:

$$v = \frac{0.908\pi d_b^2 h}{4[(1 - h_b/h)/0.6]^{1.742}} \quad (3)$$

for *P. pubescens* (SUGA et al., 2011) and

$$v = \frac{0.737\pi d_b^2 h}{4[(1 - h_b/h)/0.6]^{0.761}} \quad (4)$$

for *P. bambusoides* (INOUE et al., 2011). For the test data of *P. nigra*, the apparent culm volume was estimated with these volume equations. The statistics of the goodness of fit are summarized in Table 2. For both districts, the estimated apparent culm volume was significantly smaller than actual one when applying Eq. 3 for *P. pubescens* ($P < 0.01$ for ITO and $P < 0.001$ for FUE). By contrast, there was no significant difference between estimated and actual apparent culm volume when applying Eq. 4 for *P. bambusoides* to *P. nigra* from FUE ($P = 0.717$). Although there was a significant difference between estimated and actual apparent culm volume for *P. nigra* from ITO ($P < 0.05$), the relative mean error was comparatively small (2.097%). This result suggests that the common volume equation, Eq. 2 or 4, could be applied to *P. nigra* and *P. bambusoides*, whereas the different volume equation, Eq. 3, should be applied to *P. pubescens*.

This failure of diversion of Eq. 3 will be caused by the difference in the culm form between the bamboo species: The averages of $\lambda_{0.6}$ and $\lambda_{0.9}$ for *P. nigra* were, respectively, 0.743 and 0.541, whereas these normal form-factors varied with culm sizes (see Fig. 2). By contrast, the averages of $\lambda_{0.6}$ and $\lambda_{0.9}$ were, respectively, steady at 0.908 and 0.448 for *P. pubescens* (SUGA et al., 2011) and at 0.736 and 0.543 for *P. bambusoides* (INOUE et al., 2011). The difference between $\lambda_{0.6}$ and $\lambda_{0.9}$ is smaller for *P. nigra* than *P. pubescens*, indicating that *P. nigra* holds a non-tapering culm form compared to *P. pubescens*. For this reason, the apparent culm volume for *P. nigra* having more non-tapering culm form will be underestimated when applying the volume equation for *P. pubescens* having more tapering

form. Similar result was reported between *P. pubescens* and *P. bambusoides* (INOUE et al., 2011). By contrast, no clear differences in the normal form-factors were found between *P. nigra* and *P. bambusoides*, suggesting that the culm form of *P. nigra* would be similar to that of *P. bambusoides*. Because of the similarity of the culm form, the apparent culm volume of *P. nigra* could be successfully estimated by applying Eq. 4 for *P. bambusoides*. These facts indicate that the species characteristics of culm form should be carefully considered when evaluating the bamboo resources by the volume equations.

Recommendation for Future Studies

In the world, there are 1250 bamboo species within 75 genera, and most of them would be overlooked biomass resources (SCURLOCK et al., 2000). Although the utilization and management of bamboo require information on the amount of the resources (KLEINN and MORALES, 2006), it is impractical to separate the volume equation by each bamboo species. In reality, various bamboo species are classified into several groups based on the patterns of their culm forms, and then the volume equations should be prepared for each group. For instance, *P. nigra* and *P. bambusoides* are ascribed as the same group of bamboo and the common volume equation, i.e., Eq. 2 or 4, is applied to these species. By contrast, *P. pubescens* should be distinguished from *P. nigra* and *P. bambusoides*, and it is necessary to apply the different volume equation, i.e., Eq. 3.

Various measures have been proposed and used for quantifying the stem form of a tree (e.g., INOUE, 2005). Among them, the normal form-factors used in this study might be one of the most effective measures for classifying various bamboo species into several groups, since their steady values can be directly used for determining the coefficients of the generalized theoretical volume equation. From this viewpoint, there is a need for further studies on the inter-specific variation in normal form-factors of culms across a wide range of bamboo species.

ACKNOWLEDGEMENTS

The authors wish to sincerely thank Drs. Takeshi OHUCHI and Kenji HIRAO for their consent and support for the research in Fukuoka University of Education. Field assistance was provided by the students of the Laboratory of Forest Ecology, Faculty of Environmental and Symbiotic Sciences, Prefectural University of Kumamoto, whose help is greatly appreciated.

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* These English titles are tentative translations by the authors of this paper from the original Japanese titles.

(Received 25 January 2012)

(Accepted 9 February 2012)