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The Relationship between Breast Height Form Factor and Form Quotient of *Liquidambar formosana* in the Eastern Part of Taiwan

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Abstract: The breast height form factor and quotient of trees are important parameters for calculating the stumpage volume in forest management. However, many types of datasets can only be accumulated by cutting down many trees. This research studied different thinning intensities of Formosan sweet gum (*Liquidambar formosana*) in the Danongdafu Forest Park, Guangfu Township, Hualien County, Taiwan. The relationship and transformation modes of the breast height form factor ($F_{1.3}$) and the normal form quotient (Q_n) were examined using a nondestructive terrestrial laser scanning (TLS) system, which can replace the conventional method of obtaining $F_{1.3}$. The results demonstrated that the average $F_{1.3}$ and Q_n in the low-intensity thinning area were 0.40 and 0.56, respectively. The average $F_{1.3}$ and Q_n in the high-intensity thinning area were 0.48 and 0.68, respectively. Whether the stand density was low- or high-intensity could be determined statistically depending on the optimal results of $F_{1.3}$. There was one mode of estimation when the stand density was 1200 trees ha^{-1} and another when it was 600 trees ha^{-1}. The root mean square error of the equations used was 0.002, and the mean absolute error was <0.02. The mean percentage error was ±2.3%, and the mean absolute percentage error was <5%. If the TLS system can obtain datasets of quotient and height with surveys in the future, this would enable the calculation of $F_{1.3}$. The stock volume would be calculated precisely, and the calculation error would be improved.

Keywords: plantation density; thinning; normal form quotient; form factor

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1. Introduction

The volume of forest stock reflects the overall level of forest resources in a country or region [1]. The amount of stock can not only reflect the abundance of forest resources in the area, but is also an important basis for measuring the condition of the forest ecosystem [2]. Therefore, the accurate measurement and estimation of the forest stock volume are two of the main items used by forestry personnel and related business units to elucidate the status of forest resources [3]. The acquisition of forest stock volume data is primarily obtained by summing the volumes of all the trees. When estimating the stock volume, predictions of a tree's volume prior to cutting can be accurately obtained if its form is known [4]. Due to the difficulty in defining the form of a stem, which could have a variety of forms at different heights, it is common to use the form factor to calculate the volume [5].

For example, in Taiwan, the Forestry Bureau of the COA provides the regulation "Taiwan Forest Products Disposition and Inventory Table of Standing Wood Volume". It stipulates that the volume of *Cunninghamia lanceolata*, *Cryptomeria japonica*, *Pinus luchuensis*, *P. taiwanensis*, *Acacia confusa*, some Lauraceae, and Fagaceae should be calculated according

to the standing timber volume formula. For the other tree species, the breast height form factor ($F_{1.3}$) was specified to be 0.45 or the actual measurement data. At this time, the form factor can be regarded as the percentage of the real volume constituted by the volume of a cylinder [6].

Muukkonen [7] described how the concept and history of the development of the form factor began in the 19th century. The form factor of a trunk was defined as the trunk volume, expressed as a proportion of the volume of a cylinder of the same height, with a diameter equal to the trunk diameter at the selected reference point. Thus, the form factor is an important parameter for calculating the volume, but the data were obtained through the calculation of the actual measurement of felled trees [7]. Therefore, the concept of the form quotient was created to find an index that can be directly measured and reflect differences in the shape of tree trunks [8,9].

Schuberg [10] first described the tree shape using the ratio of the height central diameter ($d_{1/2}$) and the diameter at breast height (DBH). Schiffel [11] called it the normal form quotient (Q_n), and in a 1902 study, he attempted to use the quotient and height to estimate the form factor and calculate the volume. Its wide application inspired the development of other formulae and adjusted equations in Europe [9,12]. Figure 1 shows the calculation of $F_{1.3}$ and Q_n.

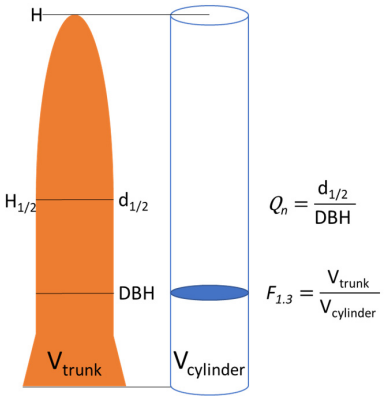


Figure 1. Calculation of breast height form factor ($F_{1.3}$), and normal form quotient (Q_n), where V_{trunk} is the trunk volume; $V_{cylinder}$ is the volume of a cylinder with a diameter at 1.3 m of the tree height; *DBH* is the diameter at breast height; $d_{1/2}$ is the diameter at 1/2 the height of the tree; H is the tree height; and $H_{1/2}$ is the position at 1/2 the height of the tree.

However, Q_n is easily affected by the height and cannot correctly represent the shape. To overcome this shortcoming, other researchers proposed different methods of calculation. For example, the ratio of the diameter of the trunk at midlength between the top and breast height to the DBH ($D_{(h-1.3)/2}$/DBH) was designated the absolute form quotient (Q_a) [13,14]. Other different formal quotients have been proposed by Pereira et al. [15], such as Girard's, which is defined by the ratio between the diameter measured at 5.2 m in height and the DBH [16], and the quotient recommended by Espanha [17], which considers the ratio between the diameter at the first bifurcation height and the DBH. In works by Cunha Neto et al. [6], Pereira et al. [15], and Şenyurt and Ercanli [18], the adjusted equations. Form factors and form quotients are among the most traditionally used methods of determining stem volume, and they have commonly been cited in the forestry literature over the past several decades. They also stated that the volumetric function, form function, and form factor are the standard parameters used to assess tree volume. The form factor is an option that should be utilized when a quick inventory is required [6]. In addition to calculating the individual tree volume that can be applied to local areas, if the form factor or quotient of the sample tree was used to adjust the adjusted equation, it can be effectively applied to regional surveys of plantation stock volume [19–21].

Liang et al. [22], Stovall et al. [23], and Wei et al. [24,25] showed that the use of a terrestrial laser scanning system (TLS) is a nondestructive way to obtain tree parameters,

such as the DBH, tree height, and the diameter of any position on the trunk, without felling trees or climbing a ladder, which can reduce the time it takes to survey. Compared with traditional measurement methods, the process of obtaining tree parameters using a TLS has been found to be highly accurate and efficient. Based on the principle of an intelligent and nondestructive evaluation using TLS technology, the sectional measurement of the standing timber is conducted with a point cloud image simulation, which preserves the original appearance of the test site.

To date, there have been no studies that have evaluated the quotient and converted the quotient form factor for Taiwanese sweetgum (*Liquidambar formosana*) in Taiwan. Given the information presented above, this study proposed to attempt to obtain the data of individual tree parameters using TLS technology to analyze the relationship between the form quotient and form factor, and the application of the conversion mode.

2. Materials and Methods

2.1. Target Area

The target area (121°4179614′ E, 23°615205′ N) was in Danongdafu Forest Park, Guangfu Township, Hualien County, Taiwan. Sugarcane (*Liquidambar formosana*) was previously planted, and afforestation began in 2003–2004. The area of afforestation has reached approximately 1000 ha to date, and 18 types of hardwood trees have been planted [26]. The climate data collected in this study were obtained from grid observations of the Taiwan Climate Change Projection Information and Adaptation Knowledge Platform (TCCIP) and were calculated and mapped using the temperature and rainfall in the target area from 2000 to 2015. The annual temperature in this area is approximately 21.3 °C, and the annual precipitation is approximately 2532 mm, which maintains high or extremely high humidity throughout the year (Figure 2).

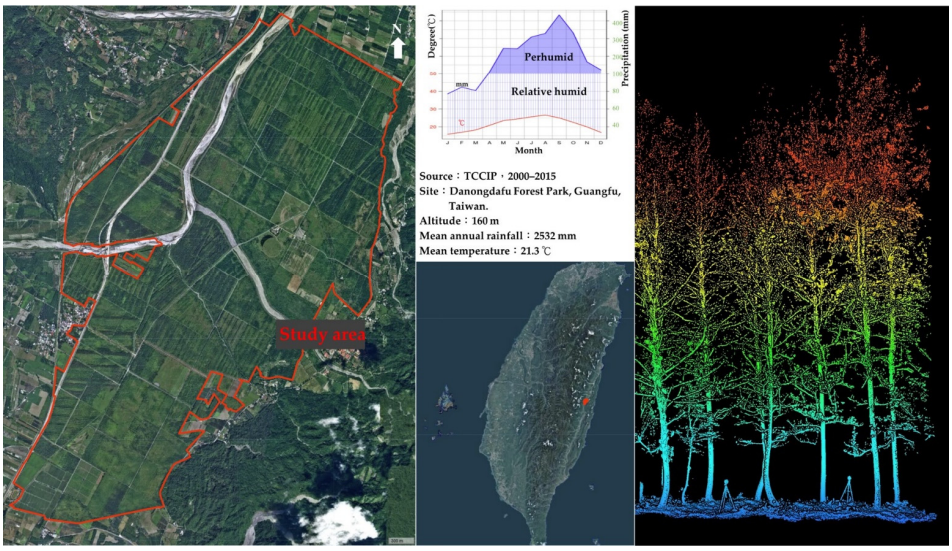


Figure 2. Map of the Danongdafu Farm, Guangfu, Taiwan, showing the afforested area of Danongdafu Forest Park, the climograph, and TLS image. TLS, terrestrial laser scanning.

2.2. Sample Area Selection and TLS Point Cloud Image Data Processing

In this study, the sample plot was established in 2011 (age = 9 years; 1500 ha^{-1}), and the tree species was *L. formosana*. A thinning experiment was then conducted, and the sample plots were adjusted to two stand densities (600 trees ha^{-1}, referred to as high-intensity thinning (HT), and 1200 trees ha^{-1}, referred to as low-intensity thinning (LT)). Four replicates were established for each of the stand densities, with a total of eight plots.

In 2019 (age = 17 years), when the leaves had almost completely dropped, the survey was plotted when there was a light breeze ($\leq$3.3 m s^{-1}) or a calm climate. The TLS images of the eight plots were taken using a FARO FOCUS3D X330 HDR laser scanner. The

commercial software LiDAR360 (Version 4.0 GreenValley, Berkeley, CA, USA) was then used to select 93 single tree (56 trees for 600 trees ha^{-1} and 37 trees for 1200 trees ha^{-1}) point cloud data with straight shapes and unobstructed treetops. A total of 70% of each section was used to evaluate the appropriate conversion formula (Equations (2)–(5)), and 30% to validate the calculations (Equations (6)–(9)).

TLS point cloud image processing was used to obtain the tree diameter (manual interpretation, isospaced 1 m, from the base of the tree (H = 0.3 m) to the top of the tree; final diameter less than 1 cm). Finally, the diameter of the tree at a height of 1.3 m (DBH), the diameter at half the height of the tree ($d_{1/2}$), the tree height (H), and the total volume of the outside bark (referred to as V_{TLS} of Section 3.3) were recorded.

$$V_{TLS} = \sum_{i=1}^{n-1} \left(\frac{(g_i + g_{i+1})}{2} \times l_i \right) + 1/3 \times g_n \times l_n \quad (1)$$

where V_{TLS} is the trunk volume; g_i is the sectional area of the ith segment; g_{i+1} is the sectional area of the $i + 1$ th segment; g_n is the sectional area of the summit; l_i is the length of the ith segment; and l_n is the length of the summit.

2.3. Comparison of the Methods Used to Estimate the Form Factor

The main purpose of studying the relationship between $F_{1.3}$ and Q_n was that the quotient has directly measurable properties, so that the form factor can be evaluated from the quotient obtained. This has important practical implications for calculating the tree volume. Related studies showed that there are four main relationships between $F_{1.3}$ and Q_n [27,28]:

$$F_{1.3} = \frac{V}{V_{1.3}} = \frac{\frac{\pi}{4} d_{1/2}^2 H}{\frac{\pi}{4} \mathrm{DBH}^2 \mathrm{H}} = \frac{d_{1/2}^2}{\mathrm{DBH}^2} = Q_n^2 \quad (2)$$

$$F_{1.3} = Q_n - a \quad (3)$$

$$F_{1.3} = a + b(Q_n)^2 + \frac{c}{Q_n H} \quad (4)$$

$$F_{1.3} = aQ_n + \frac{b}{Q_n H} \quad (5)$$

where a, b, and c are the regression parameters. All data submitted to the nonlinear regression and ANOVA test were analyzed using SPSS version 22.0 (IBM). Q_n is the normal form quotient; V is the volume of the trunk calculated with Huber's formula; $V_{1.3}$ is the volume of a cylinder with a diameter at 1.3 m of the tree height; $d_{1/2}$ is the diameter at 1/2 the height of the tree; DBH is the diameter at breast height, and H is the tree height.

To evaluate the estimated regression model, the estimated $F_{1.3}$ (estimated from TLS, and Equations (2)–(5), respectively) was compared using the RMSE (root mean square error, Equation (6)), MAE (mean absolute error, Equation (7)), MPE (mean percentage error, Equation (8)), and MAPE (mean absolute percentage error, Equation (9)).

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2} \quad (6)$$

$$\mathrm{MAE} = \frac{1}{n} \sum_{i=1}^{n} |y_i - \hat{y}_i| \quad (7)$$

$$\mathrm{MPE} = \frac{1}{n} \sum_{i=1}^{n} ((y_i - \hat{y}_i)/y_i) \quad (8)$$

$$\mathrm{MAPE} = \frac{1}{n} \sum_{i=1}^{n} (|y_i - \hat{y}_i|/y_i) \quad (9)$$

where y_i is the form factor calculated from the TLS data, and $\hat{y}_i$ is the estimated breast height form factor.

2.4. Comparison of the Trunk Volume

This study attempted to understand the contribution of first evaluating Q_n and then calculating the tree volume to compare the result of the calculation of the tree volume. These calculations were derived from the TLS sectional measurement (considered the actual value), the universal form factor volume ($F_{1.3}$ = 0.45; considered an estimate), and the quotient conversion volume ($F_{1.3}$ = quotient conversion; considered an estimate). Equation (10) was used to estimate the trunk volume.

$$V = g_{1.3} \times H \times F_{1.3} \tag{10}$$

where V is the trunk volume; $g_{1.3}$ is the basal area; H is the tree height; and $F_{1.3}$ is the breast height form factor.

Independent sample *t*-tests were performed to explore whether the two estimated values differed from the value of TLS, and the nonparametric Wilcoxon test was used to verify the different distribution of each individual tree volume using different methods of estimation. Statistical calculations were performed using Excel (Version 2016, Microsoft Corp, Albuquerque, NM, USA) and SPSS (Version 22, IBM Corp, Armonk, NY, USA).

3. Results

3.1. Distributions of Form Factor and Form Quotient

The DBH, tree height, $F_{1.3}$, and Q_n were calculated through measurements with the TLS system; Figure 3 illustrates the distributions. The DBH and tree height were the arithmetic mean, and the breast height form factor and normal form quotient were the geometric averages.

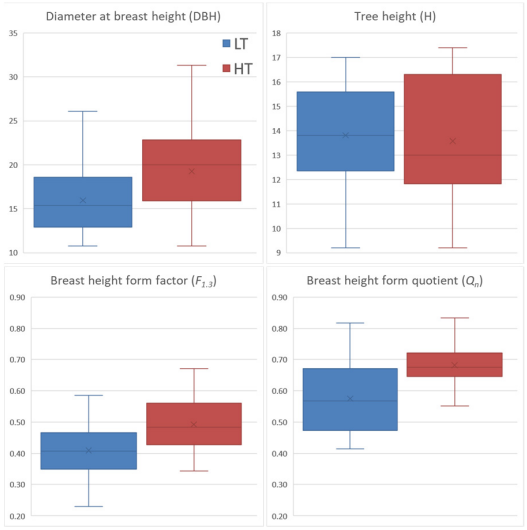


Figure 3. Box plot of the diameter at breast height (DBH), tree height (H), breast height form factor ($F_{1.3}$), and the normal form quotient (Q_n) of 17-year-old *Liquidambar formosana* trees in Hualien, Taiwan. HT = 600 trees ha^{-1}; LT = 1200 trees ha^{-1}.

In the LT area, the average of the DBH, tree height, $F_{1.3}$, and Q_n was 16.0 cm, 13.8 m, 0.40, and 0.56, respectively. In the HT area, the average of DBH, tree height, $F_{1.3}$, and Q_n was 19.3 cm, 13.5 m, 0.48, and 0.68, respectively. There were significant differences in the DBH, $F_{1.3}$, and Q_n between the two stand densities ($p < 0.05$, independent sample *t*-tests).

3.2. Form Factor Estimation Errors

Equations (2)–(5) were used to estimate the mode of conversion from previous studies, and the results of this calculation are summarized in Table 1. The criterion for choosing the best model obeyed the smallest error (Equations (6)–(9)) and the largest coefficient of determination.

Table 1. Four model parameters and estimation errors.

		a	*b*	*c*	R^2	RMSE	MAE	MPE (%)	MAPE (%)
LT	Equation (2)	-	-	-	0.41	0.1085	0.085	21.95	23.45
	$F_{1.3} = Q_n^2$								
	Equation (3)	0.170	-	-	0.39	0.0628	0.054	5.81	13.92
	$F_{1.3} = Q_n - 0.170$								
	Equation (4)	0.025	0.701	1.077	0.61	0.0190	0.017	2.26	4.18
	$F_{1.3} = 0.025 + 0.701Q_n^2 + 1.077/(Q_n\ H)$								
	Equation (5)	0.646	0.276	-	0.55	0.0210	0.017	2.40	4.36
	$F_{1.3} = 0.646Q_n + 0.276/(Q_n\ H)$								
HT	Equation (2)	-	-	-	0.41	0.0295	0.023	3.60	4.88
	$F_{1.3} = Q_n^2$								
	Equation (3)	0.187	-	-	0.55	0.0222	0.019	−2.55	4.05
	$F_{1.3} = Q_n - 0.187$								
	Equation (4)	0.128	0.706	0.313	0.57	0.0208	0.019	−2.26	3.95
	$F_{1.3} = 0.128 + 0.706Q_n^2 + 0.313/(Q_n\ H)$								
	Equation (5)	0.727	0.014	-	0.52	0.0257	0.023	−3.20	4.91
	$F_{1.3} = 0.727Q_n + 0.014/(Q_n\ H)$								

Note: RMSE, root mean square error; MAE, mean absolute error; MPE (%), mean percentage error; MAPE (%), mean absolute percentage error.

In the parameter estimation stage (using 70% of the samples), the statistical indica-tors of R^2, for the four model equations for the relationships between $F_{1.3}$ and Q_n, ranged from 0.39 to 0.61. During the validation phase (using 30% of the sample), among the four models, the error values for RMSE, MAE, MPE, and MAPE were similar in the HT area. However, only Equations (4) and (5) were the best (according to MPE and MAPE) for the LT area.

Throughout the stages of analysis for model selection, Equation (4) showed the best performance on the form factor for *L. formosana* in the two stand densities.

3.3. Volume Errors of the Results Obtained with Different Methods

As shown in Section 3.2, Equation (4) had the best goodness-of-fit (R^2 close to 0.6) and the smallest error value. Therefore, in this section, Equation (4) was used to evaluate the quotient conversion, and Equation (10) was used to evaluate the trunk volume, as shown in Table 2.

Table 2. Average tree volumes obtained with different methods.

	Parameters			*F*	Significance
	Universal Form Factor (0.45)	Quotient Conversion (Using Equation (4))	V_{TLS}		
LT area	0.131 ± 0.071 [a]	0.121 ± 0.069 [a]	0.119 ± 0.071 [a]	0.235	0.791
HT area	0.197 ± 0.111 [a]	0.209 ± 0.106 [a]	0.211 ± 0.120 [a]	0.199	0.819

Note: Different lowercase letters in the same column indicate a significant level of difference of $p < 0.05$. HT, high-thinning intensity; LT, low-thinning intensity; V_{TLS}, sectional measurement of the trunk volume using terrestrial laser scanning.

Using the universal form factor (0.45) and the quotient conversion (using Equation (4)) to evaluate the tree volume, the difference analysis showed that both were not significantly different from the tree volume estimated using the TLS system on the sample plot.

Additionally, to compare the volume of individual trees compared with the TLS measurement, the volume estimated using the two methods had errors in both the HT and LT areas (Figure 4). The Wilcoxon symbol level test sorted the universal form factor volume and the quotient conversion volume to obtain the absolute value of the difference when measuring the TLS measurements, and the ranking bits were marked with + or—, summed to obtain two verification quantities (Table 3).

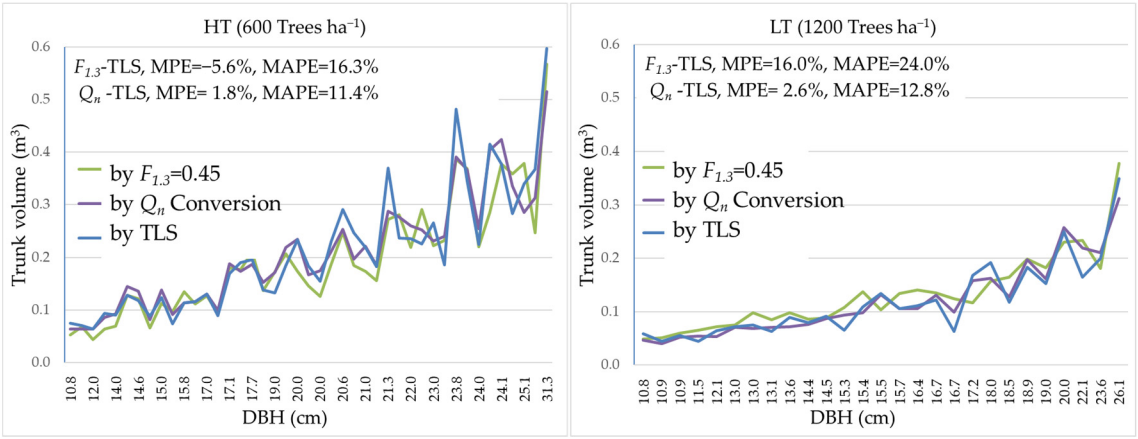


Figure 4. The percentage error (%) in the trunk volume when used at both stand densities was transformed with the universal form factor ($F_{1.3}$ = 0.45) and the quotient conversion. Q_n was the result of Section 3.2 and was calculated based on Equation (4). The trunk volume, calculated with the TLS system, was assumed to be accurate. MPE, mean percentage error; MAPE, mean absolute percentage error; TLS, terrestrial laser scanning.

Table 3. Wilcoxon symbol grade verification for the form factor volume, quotient conversion volume, and TLS sectional measurement.

		+ [a]	− [b]	= [c]	*z* Value	Significance (Double Tail)
HT	Form factor-TLS	14	27	2	−1.90	0.58
	Quotient-TLS	23	18	2	−3.36	0.72
LT	Form factor-TLS	20	7	0	−2.13	0.03*
	Quotient-TLS	12	15	0	−1.20	0.90

[a] Q_n and $F_{1.3}$ > TLS. TLS, terrestrial laser scanning; [b] Q_n and $F_{1.3}$ < TLS; [c] Q_n and $F_{1.3}$ = TLS; and * $p < 0.05$.

4. Discussion

4.1. The Differences between $F_{1.3}$ and Q_n at Two Stand Densities

Siemon [29] showed that thinning modifies the depth of the green crown because a major long-term effect of reasonably heavy thinning increases both the crown width and length [30], and thinning affects the development of individual branches, even down to the lowest green branch [31]. Any change in crown development that results from thinning would be reflected by a change in the stem form [32]. This finding assisted in interpreting the observed variation in both $F_{1.3}$ and Q_n following thinning.

In Section 3.1, both the $F_{1.3}$ and Q_n of trees in the HT area were higher than those of trees in the LT area, indicating that the shape of the artificial forest could be improved through proper thinning. It has been demonstrated that the form factor can be regarded as a characteristic that reflects the shape of the trunk. Therefore, the influence of different stand densities on shape evolution can be reversed by the form factor. Nevertheless, this situation varies depending on the tree species and growth environment. For example, Gao [28] compared the $F_{1.3}$ and Q_n of 9–10-year-old poplars (*Populus* sp.) in four types of stand densities in an artificial forest that had not been thinned. An increase in the density of afforestation resulted in an increase in the $F_{1.3}$ and Q_n, and the shape of the

trunk was plumper. Da Cunha Neto et al. [6] compared the form factor of a 15-year-old teak (*Tectona grandis*) from four different stand densities. This indicated that spacing was one of the silvicultural factors that could affect the form of the trees, depending on the form factor. Despite that, no spacing effect on the dendrometric variable in question was identified, and this could be related to the age of the stands in concert with a lack of thinning. Adegbeihn [33] reported that the form factor of seven-year-old teak plantations remained independent of the effect of spacing. Pérez and Kanninen [34] reported that different intensities of thinning had no effect on the form factor of the teak. Nevertheless, intense thinning had a positive effect on the trunk form and produced trees with the designated DBH/total height ratio. Both form factor and form quotient are values that express the fullness of the trunk's shape. The primary disadvantage of the use of the form factor in calculations is that it cannot be directly measured, but the quotient can be calculated using the ratio between the diameters of different positions of the backbone [8,9]. In particular, the use of form quotients tends to be more efficient in rectilinear and uncrossed stem species [15].

Since the form factor is measured as a ratio of volumes, such as the ratio of volume obtained through rigorous cubage to the cylinder volume, it is possible that identical factor forms for different stems do not necessarily imply that the stems have the same form, and stems of the same form do not necessarily have the same form factor [5,6]. The tree form may be influenced by different factors, including species, fertilization, site quality, management, age, and stand density, and although the form factor is not a direct description of the tree form, the form factor is nonetheless influenced by the tree form [6].

The results of this study indicated that with the two stand densities after thinning, the $F_{1.3}$ and Q_n of trees in the LT area were lower than those in the HT area. A high-thinning intensity could shorten the gap between the DBH and diameter at one-half the height and improve the usage ratio.

4.2. Comparison of the Optimal Conversion Mode to Determine the Form Factor

In Section 3.2, Equation (2) had no model parameters, because the form factor was the square of the form quotient. Our analysis of the estimation error for the data in Table 1 indicated that the data were not suitable for application in this study.

Li [27] and Gao [28] showed that the value of Equation (3) easily varies by tree species and applies primarily to tree species with a height of >18 m. When the trees are smaller, the error of the value easily exceeds ±5% [27,28]. In this study, the tree height of each *L. formosana* ranged from 9.2 m to 17.4 m, which was lower than the applicable height of 18 m proposed by Equation (3). Additionally, the MAPE was 13.92% in the LT area. This method of estimation may lead to poor performance. Thus, we do not recommend it.

Equation (4) was proposed by Schiffel [11] and considered to be applicable to all tree species in research at that time. The error was within ±3%. Equation (5) also calculates the form factor through the combination of the quotient and height [27,28]. When looking at the estimated results of the two stand densities in Table 1, Equations (3)–(5) could estimate the MPE within an approximately 5% error. Equation (4) had a maximal R^2 and minimal RMSE and MAE. An MPE of ±2.3% was consistent with the range of error in previous studies, and the MAPE was <5%, which indicated that the mode of estimation was optimized in this study.

In Section 3.3, in the mean volume calculation results shown in Table 2, the *L. formosana* trunk volume assessed using the three methods did not differ significantly. This result was similar to that of Pereira et al. [15]. However, as shown in Figure 4 and Table 3, the use of Q_n to evaluate the trunk volume could reduce the error in some samples and decrease the percentage error (%) and MPE (%) compared with the TLS data. The results of the Wilcoxon test showed that the difference in volume estimated with the quotient conversion was more average than the difference in the universal form factor. However, the volume estimated from the general form factor was sometimes underestimated in the HT region and overestimated in the LT region.

5. Conclusions

In this study, the form factor and form quotient were examined for two stand densities of *Liquidambar formosana*. The results showed that the $F_{1.3}$ range in this study was from 0.23 to 0.67. When calculating the tree trunk volume in Taiwan, 0.45 is usually used as the general $F_{1.3}$; thus, if we could select a suitable $F_{1.3}$ and then evaluate the trunk volume, we could correct the calculation results and obtain values closer to the field conditions. This study determined that the conversion from the form quotient to the form factor was an appropriate method. Benefiting from the rapid development of TLS software and hardware technology, forest measurements based on point cloud data can reduce the process of felling trees, and was more conducive for effectively retaining sample plots or samples for long-term observation.

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