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ORIGINAL ARTICLE

Applicability evaluation of tree volume equation for *Abies kawakamii* (Hayata) Ito based on stem analysis data in Taiwan

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ABSTRACT

Abies kawakamii (Taiwan fir) typically constitutes pure forest distributed at 3,100–3,600 m above sea level in Taiwan. Its volume was first investigated in 1963 using aerial photography to identify the growing stock of the forest. In 1973, Taiwan Forestry Bureau established a fir volume estimation equation by considering Taiwan spruce and Taiwan fir stands. However, due to cutting natural forest is not permitted in Taiwan, it was difficult to reconstruct specific volume equation for Taiwan fir. We can only use and collect the uprooted trees as samples for this study by Typhoon Soudelor in 2015. We used these samples for estimation and used the remaining trees for verification and tested the suitability of six equations (models) for Taiwan fir volume estimation. We found that the Schumacher equation was suitable for juvenile trees, and the generalized combined-variable equation was suitable for semi-mature trees. The Schumacher equation (a logarithmic equation) and generalized combined-variable equation demonstrated the better suitability for volume estimation. However, when a juvenile was considered in the estimation, the generalized combined-variable equation provided underestimations. Thus, the Schumacher equation ($V = aD^bH^c$) was the better model for our test. The new tree volume estimation equation for Taiwan fir in the Mt. Xue region is presented as follows: $V = 0.00003663 \times D^{1.6693} \times H^{1.4003}$.

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Abies kawakamii; volume equation; Schumacher equation; generalized combined-variable equation; Shei-Pa National Park

Introduction

Tree volume evaluation is crucial for applications, such as estimation of stand structure and timber stock, forest harvest prediction, carbon storage assessment, and evaluation of forest ecosystem service function (Akindele and LeMay 2006; Yen et al. 2009, 2010, 2020). The tree volume equation used diameter at breast height (DBH), tree height, and other variables to construct tally charts (Vasilescu et al. 2017). As research methods progress, some researchers used light detection and ranging devices or aerial photography for getting the forest growing stock. Such a precision of the equation is a key factor in decision-making (Caccamo et al. 2018), but traditional methods are irreplaceable. Many tree volume equation forms were created appropriately for the corresponding target tree to be closer to the reality volume (Schumacher and Hall 1933; Stoate 1945; Spurr 1952; Cunia 1964; Honer 1965; Newnham 1967).

Tree volume equations are mainly composed of DBH and height and/or form factors (Vasilescu et al. 2017). Such equations can construct the volume of trees in a forest from stem analysis results. Moreover, volume equations and correlations between certain tree aspects can constitute the basis for estimating a tree volume table (Chen and Chen 2015). Tree volume tables can be estimated using various methods, including graphic, alignment, and least-squares techniques (Bruce 1919; Spurr 1952; Grosenbaugh 1964; Liu 1970). Currently, with continual improvements in calculation techniques, establishing or estimating a tree volume table is relatively more convenient than before. Nevertheless, a critical limitation of estimation methods is determining an accurate and straightforward fitting function (Honer 1965).

This study aimed to develop a tree volume estimation equation. We focused on *Abies kawakamii* (Hayata) Ito (Taiwan fir) is an endemic glacial relic species, one of the subalpine trees distributed 3,100 ~ 3,600 m above sea level in Taiwan (Liu 1971; Boufford et al. 2003). Taiwan fir usually constitutes single-tree forests in high mountainous regions (Wang et al. 2010; Liao et al. 2012, 2013; Tseng and Tzeng 2016). Yang and Lin (1961) and Yang and Dan (1963) have developed the first tree volume equation for *A. kawakamii*. They conducted aerial photography to survey Taiwan fir trees growing on Papaya mountain and Morisaka in eastern Taiwan. The tree volume equation was based on the average crown diameter and average stand height. Thus, they could obtain Taiwan fir stand and stock measurements, which could be used to distinguish forest types first and then calculate the stand volume. In 1973, Taiwan Forestry Bureau used samples obtained from ground-based observations to establish a tree volume table and equation for *A. kawakamii* and *Picea morrisoniola* (Liao et al. 1973). However, there was no record on materials and methods before, so it was difficult to confirm the equation was mainly built from which species or both. Up to now, this equation has been used to estimate the stock of Taiwan fir and Taiwan spruce in the third and fourth forest resource investigations (Taiwan Forestry Bureau 1995; Qiu et al. 2015).

In Taiwan, the forest management of *A. kawakamii* is not for commercial purposes but protection so that the soil and water conservation and ecological conservation for this species is quite essential. Moreover, the impacts of global climate change and carbon storage have been increasingly emphasized, and investigating the stock and health of forest trees in

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Table 1. List of six equations (models) for tree volume estimation of *Abies kawakamii*.

Model NO.	Equation name	Equation form	Reference
a	Schumacher	$V = aD^bH^c \log V = \log a + b\log D + c\log H$	Schumacher and Hall (1933)
b	Logarithmic combined variable	$V = a(D^2H)^b \log V = \log a + b\log(D^2H)$	Spurr (1952)
c	Combined-variable	$V = a + bD^2H$	Spurr (1952)
d	Generalized combined variable	$V = a + bD^2 + cH + dD^2H$	Stoate (1945)
e	Generalized logarithmic	$V = a + bD^cH^d$	Newnham (1967)
f	Honer transformed variable	$V = D^2/[a + (b/H)]$	Honer (1965)

V: Volume.
D: DBH.
H: Height.

high mountains in Taiwan is necessary. However, obtaining Taiwan fir samples is challenging because areas containing Taiwan fir trees are protected, where natural forests and protected areas are logging prohibited since 1991 in Taiwan (Lin et al. 2015). Typhoon Soudelor in 2015 passed through and destroyed the Taiwan fir forest on Xue Mountain; consequently, some trees were uprooted or trunks broken. The uprooted trees (trunks were intact) caused by the Typhoon event allow the establishment of the materials for establishing a tree volume equation.

In this study, we collected these uprooted trees as real and mature samples for constructing a tree volume equation using six models: Schumacher (Schumacher and Hall 1933), Logarithmic combined variable (Spurr 1952), Combined-variable (Spurr 1952), Generalized combined variable (Stoate 1945), Generalized logarithmic (Newnham 1967), and Honer transformed variable (Honer 1965) (Table 1). Subsequently, we compared and validated the models to determine a suitable model for tree volume estimation.

Materials and methods

Study area and data collection

We selected the east ridgeline of Mt. Xue in Taiwan, which belongs to the *Abies* forest zone, standing 3,100 ~ 3,500 m above sea level as the study site (Su 1984; Chiu et al. 2008). The geology of Mt. Xue consists of rocks such as shale, slate, and quartzite (Chou 1972; Ho 1986). Compared with the surrounding areas, this region has a lower ratio of rocks to other elements (1.11–2.94%), and its soil is extremely acidic (Yen 2009). Furthermore, the region is characterized by a cold-temperate perhumid climate (Chiu et al. 2008). The perhumid period spans from April to September, with the other months being humid. The region's annual precipitation level is 2,422.84 mm, and the mean annual temperature is 5.27°C (Lu et al. 2010; Figure 1).

In 2015, Typhoon Soudelor passed through Taiwan's northeastern region and uprooted some *A. kawakamii* trees in Mt. Xue. All samples were approved by Shei-Pa National Park Headquarters and allowed by Dongshih Forest District Office, Taiwan Forestry Bureau, before cutting and transport (Figure S1). Our samples were collected mainly from two sites: East Xue trail (Black forest) 8.9–9.0 K and Fountainhead Trail (Water Source Trail) of black forest 0.-5–0.9 K (Table 2; Figure 2) in Mt. Xue. Because the terrain was too steep and the altitude is 3,200 m above the sea level, mechanical transportation carriers could not arrive at the study area. Hence, we used human resources to cut the discs after uprooted trees and transport them by the workforce. Finally, only nine integrated samples that were randomly selected got for parameter estimation and model suitability evaluation.

The stems of the sample trees were cut at 0.3 m and 1.3 m from the ground level into wood discs. Stem portions higher than 1.3 m from the ground were also cut into discs 2 m intervals regularly. Because some decay was observed on the wood discs, the discs were replaced by evaluating other stem portions before the cutting process. Specifically, if the discs were unrecognizable, we collected the upper or lower

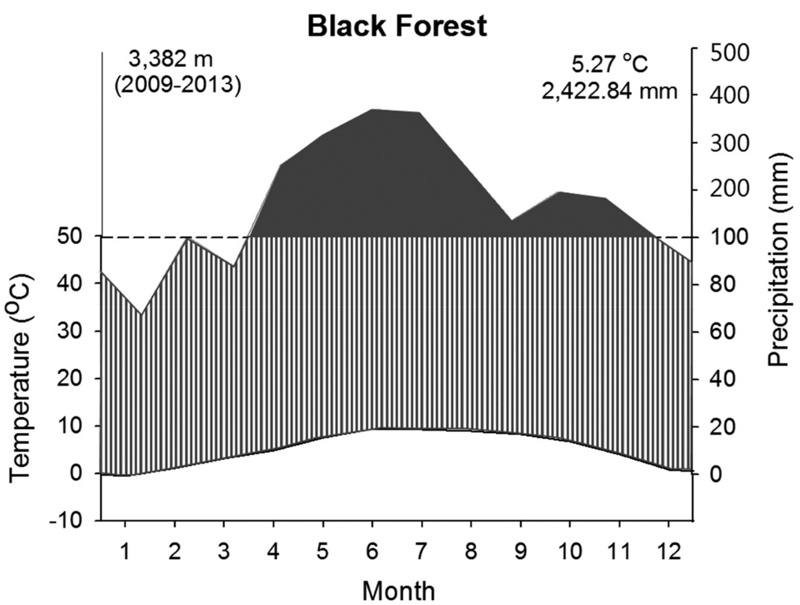

Figure 1. Climate diagram of Black forest in Mt. Xue, Taiwan (Lu et al. 2010).

Table 2. Information about nine sample trees of *Abies kawakamii* in Mt. Xue, Taiwan.

NO.	Site	Age (years)	DBH (cm)	Height (m)	Coordinate (WGS84)		Altitude (m)	Slope (°)	Aspect (°)	Felling direction (°)
5	Black forest	199	75.0	25.0	24.3929	121.2417	3,407	15.0	63.5	291
6	8.9–9 K	254	83.0	22.8	24.3930	121.2417	3,404	20.0	34.0	200
22		191	32.5	19.5	24.3929	121.2417	3,407	31.5	65.0	215
23		239	51.4	20.4	24.3929	121.2416	3,404	15.0	25.0	20
24		222	39.5	23.0	24.3928	121.2420	3,389	15.0	48.0	235
9	Fountainhead Trail of black forest 0.5–0.9 K	149	37.7	17.7	24.3951	121.2486	3,266	36.0	49.0	275
11		205	70.5	25.3	24.3954	121.2480	3,257	28.0	0	190
12		188	51.2	23.9	24.3953	121.2479	3,257	23.0	30.0	286
25		211	59.4	30.4	24.3954	121.2455	3,266	31.0	342.0	250

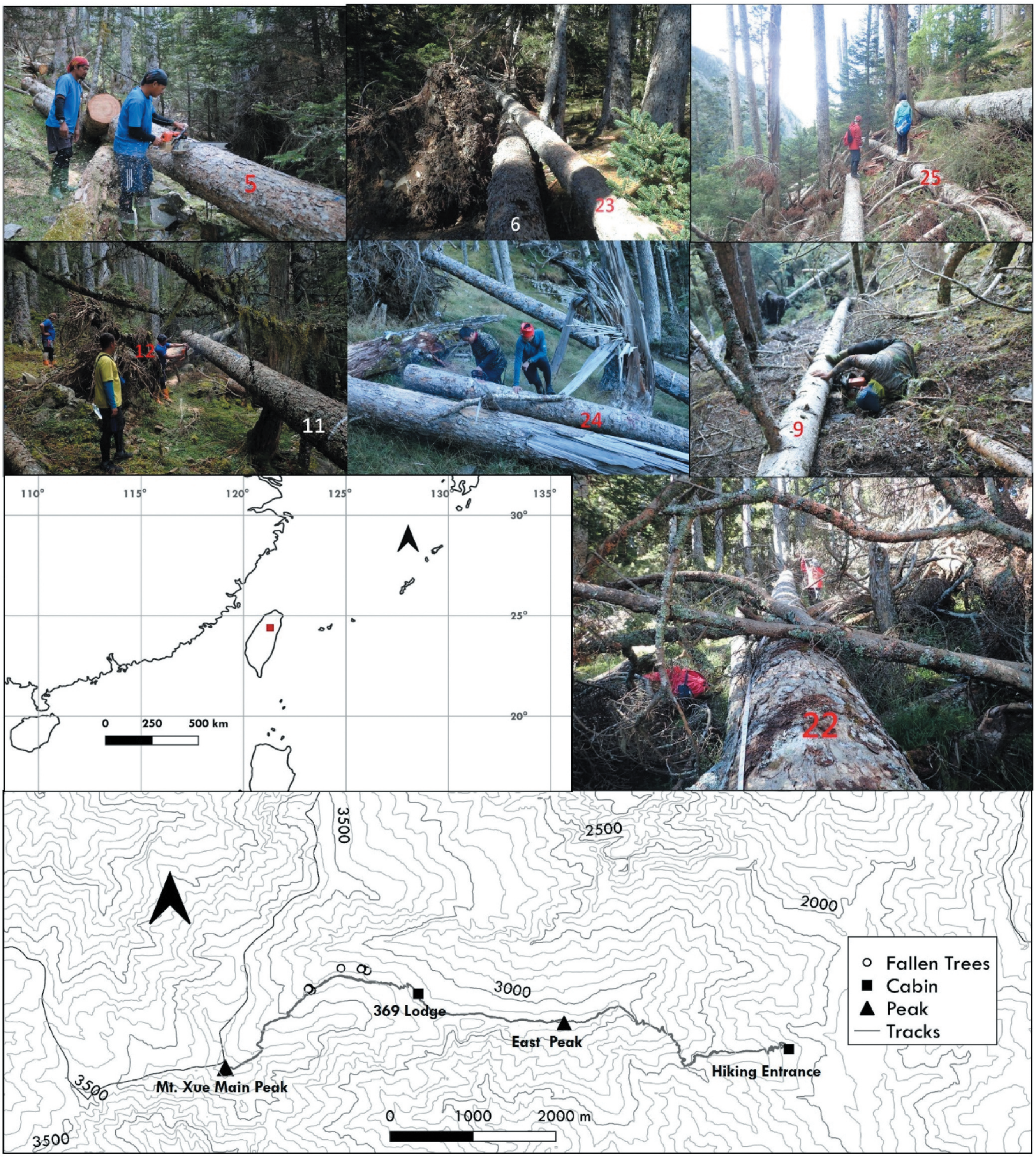

Figure 2. The site of collection and the photos of nine trees in Mt. Xue, Taiwan.

completed parts or replaced the corresponding data with estimates.

Data processing

Stem analysis

After collecting the samples, we obtained a cross-section of the narrow end for drying, polishing, shooting, digitalizing, and tree ring width measurement. We also measured the width with bark. Jong et al. (2006) used ImageJ developed by the National Institutes of Health for measurement. If images were unclear due to polishing scratches, stains, or cracks, we manually corrected the tree rings. Subsequently, we measured the increment for four cardinal directions on the discs and calculated annual increment. We could determine the history of tree growth through stem analysis; thus, we could identify tree features such as age, ring width, disc defect, and outline (Yang and Lin 2003). Through stem analysis, we reconstructed at 2 points of time (50 and 100 years before and round the number to the nearest ten) for each tree. By this data augmentation, we used 27 (9 trees 3 points of time) observations to calculate the volume equation, and the range of DBH, Height, and Volume for the augmented data were 8.7–72.0 cm (without bark), 4.9–30.4 m and 0.011–3.736 m^3 respectively.

Calculation of single tree volume

To determine the volume of a single tree, we adopted the Smalian equation for sectional measurement (Yang and Lin 2003). The volume of the top part (V_t) and that of the bottom part (V_b) of the stem were calculated using the following equation:

$$Vm = Hm \times [(A_{1.3} + A_n)/2 + A_{3.3} + A_{5.3} + \ldots + A_{n-1}] \quad (1)$$

where V_m is the middle part of the stem volume, H_m is the height between A_{n-1} and A_n is the area of a cross-section.

$$Vt = (1/3) \times Au \times Hu \quad (2)$$

where V_t is the top-part stem, a cone shape, H_u is the height between A_u and tip. A_u is the area of the cross-section on the highest part.

$$Vb = 0.3 \times (A_{0.3} + Ab)/2 \quad (3)$$

Where V_b is the bottom-part stem volume, $A_{0.3}$ is the area of cross-section at 0.3 m above the ground, A_b is the bottom area of the tree.

Volume equation construction and verification

Various volume equation forms are available. Therefore, they must be tested on different tree species to determine the most suitable forms for certain species (Schumacher and Hall 1933; Stoate 1945; Spurr 1952; Honer 1965; Newnham 1967). According to the equation form and method for getting coefficient, the equation forms could be divided into two types: logarithmic and arithmetic equations (Spurr 1952). Our study tested six equations, namely the Schumacher equation, Logarithmic combined-variable equation, Combined-variable equation, Generalized combined-variable equation, Generalized logarithmic equation, and Honer transformed-variable equation.

Parameters were estimated through regression analysis using R function by lm() and nls() from R software. We used root mean square error (RMSE) and coefficient of determination (R^2) as measures for equation validation and determination of the best tree volume equation. Low RMSE and R^2 close to 1 are preferred. Furthermore, these measures were calculated by manual because the RMSE and R^2 from lm() and nls() are not comparable as their different algorithm. Further, RMSE of logarithmic function and arithmetic function are not at the same metric scale. To let both on the same comparable scale, we also measured Furnival's Index (FI) (Furnival 1961).

These measures are outlined as follows:

$$RMSE = \sqrt{\frac{\sum (v-\hat{v})^2}{n-p}} \quad (4)$$

$$R^2 = 1 - \frac{\sum (v-\hat{v})^2}{\sum (v-\bar{v})^2} \quad (5)$$

$$FI = [f'(V)]^{-1} \times RMSE \quad (6)$$

where v is measured value, $\hat{v}$ is the estimated value, $\bar{v}$is average, $f'(V)$ is the derivative of the pendent variable for volume, n is the number of samples, and p is the number of parameters in the model.

We referred to the data obtained by Yatagai (1937) at the old Xueshan cabin for further verification. Yatagai (1937) divided the Taiwan fir forest structure into four types, namely mature (I), mature and semi-mature (II), single-layer juvenile and mature (III), and non-single-layer juvenile and mature (IV); he also recorded the diameter class, height, and number. We used this data to calculate the volume by the model we constructed and choose the one which close to the volume Yatagai recorded to determine the best tree volume equation in Taiwan.

Results

According to the basic information regarding the nine uprooted trees (Table 2), the D and H (as symbol for DBH and height in the text and equation) of the sample trees were 32.5–83 cm (with bark) and 17.7–30.4 m, respectively, and the age of the samples were 149–254 years. All sampled trees were distributed within an elevation of 150 m (3,257–3,407 m). Through stem analysis, we obtained 27 data items from the 9 sample trees. Regarding tree volume equation validation, Combined-variable equation (Model-b) had the highest (RMSE) value (*i.e.* 0.192; Table 3 and Figure 3). The Generalized combined-variable equation (Model-d) had the lowest RMSE value (*i.e.* 0.114). Furthermore, the R^2 values of all models were higher than 0.9, with Model-d having the highest value (R^2 = 0.988). Also, the FI of the

Table 3. Validation statistics of six models for *Abies kawakamii* in Mt. Xue, Taiwan.

Model Statistic[a]	a	b	c	d	e	f
RMSE	**0.118**	0.192	0.175	**0.114**	0.118	0.159
R^2	**0.987**	0.969	0.970	**0.988**	0.987	0.979
FI	**0.092**	0.149	0.175	-	0.118	-

[a]Model a-f were as Table 1.
[b]Nonlinear regression did not evaluated FI.
[c]RMSE & R^2 were calculated by manual

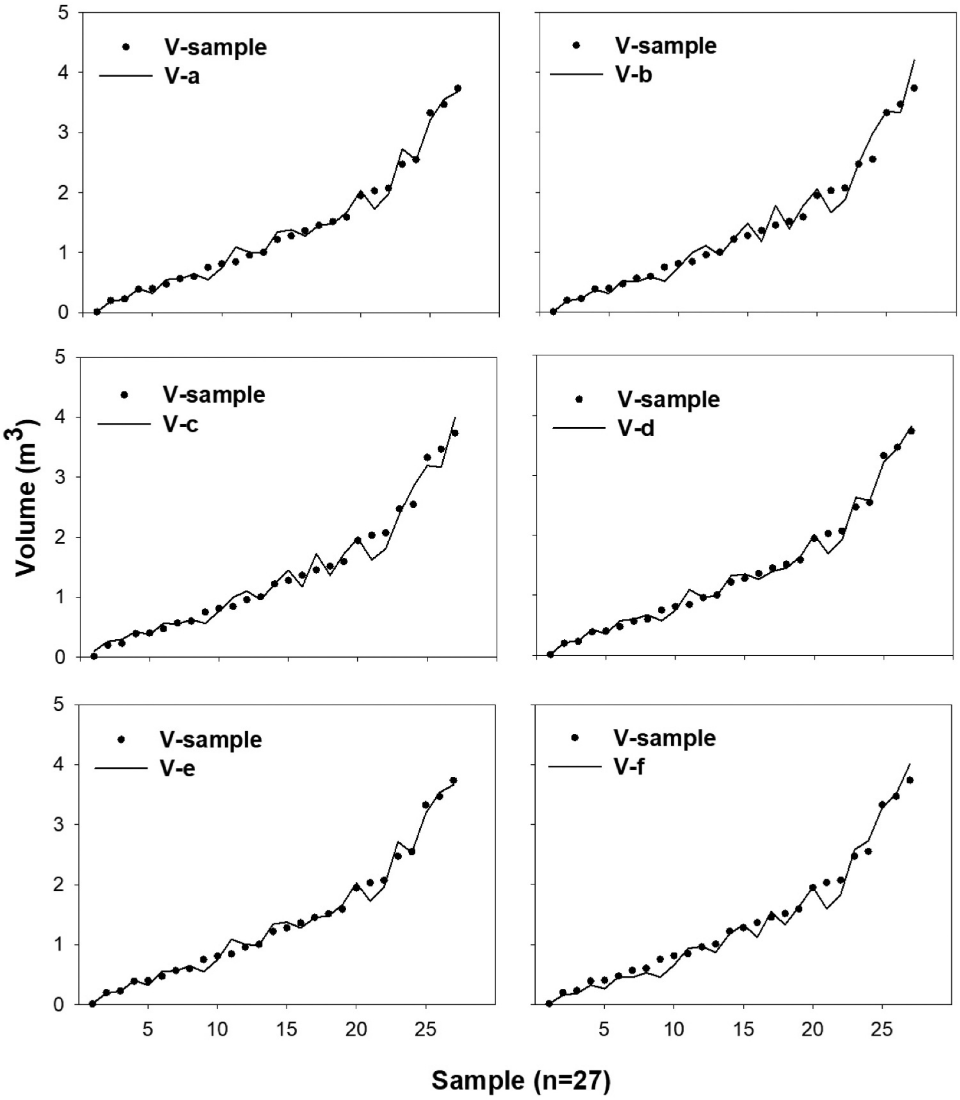

Figure 3. Comparison of measured values with estimated values of *Abies kawakamii* by six volume equations in Mt. Xue, Taiwan. Model a-f were as Table 2. (Horizontal axis represents sample size, sorted by small to large measured volume. V-sample was the measured values by 27 data and V-a ~ f were the estimated values by six volume equations).

Schumacher equation (Model-a) was the lowest (FI = 0.092) compared with the values of the other linear models.

Based on the model validation statistics, we chose Model-d first because it had the lowest RMSE and highest R^2, indicating its relatively high fitness or suitability for volume estimation. Because the coefficient of the logarithmic equation must be expressed in logarithmic form, the validation statistics of the logarithmic equation could not be directly compared with the statistics of the arithmetic equations. Therefore, we used the FI to solve the problem. According to the three equations' validation statistics, we selected the Schumacher equation (Model-a) and generalized combined-variable equation (Model-d) as representative linear and nonlinear equations, respectively, with the best fitness or suitability. These two models were used for further analysis.

We also referred to the data obtained by Yatagai (1937) at the old Xueshan cabin; accordingly, we inputted the values of *D*, *H*, and the number of stems into Model-a and Model-d. We compared the volumes estimated by Model-a and Model-d for the four forest types with the volume measured by Yatagai (1937) (Table 4 and Figure 4). The result showed that the volume bias of Model-a was higher than Model-d for the statistical method at the semi-mature stage; however, Model-d underestimated juvenile's volume and would be

Table 4. Total volume estimation comparison with the data of Yatagai (1937) between the Schumacher equation (Model-a) and generalized combined-variable equation (Model-d).

Age class	Type	Samples	DBH range	Model-a (total volume)	Difference	Model-d (total volume)	Difference	V- Yatagai (total volume)
Juvenile	III	404	2–19	3.141	1.423	1.001	3.563	4.564
	IV	248	2–27	3.357	1.638	0.672	4.323	4.995
Semi – mature	II	135	11–30	28.872	3.382	32.568	0.314	32.254
Mature	I	87	18–99	117.528	10.372	117.853	10.047	127.900
	II	10	35–80	17.507	4.070	17.908	3.669	21.577
	III	24	30–66	51.321	8.970	51.101	9.190	60.291
	IV	10	40–65	17.880	1.934	17.749	2.065	19.814
Total difference					31.790		33.172	

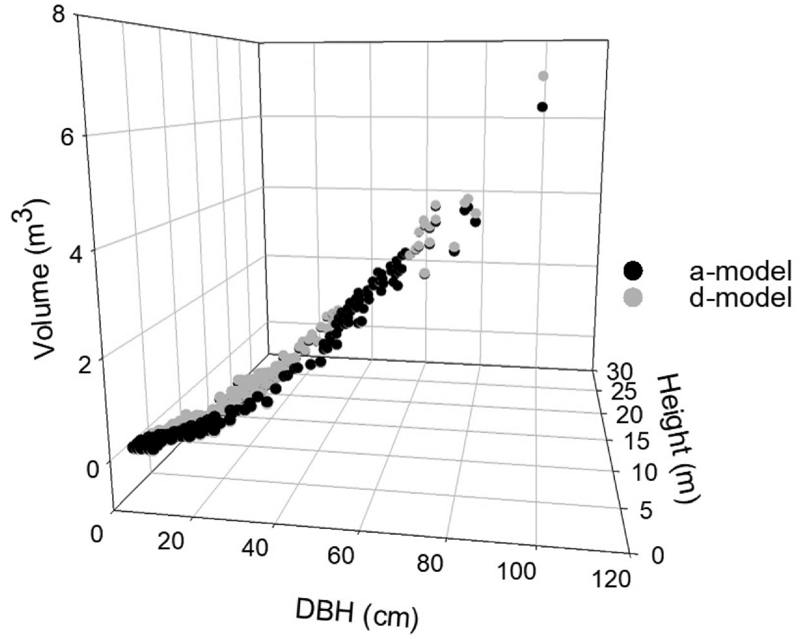

Figure 4. The distribution of the volume measured values on model-a and model-d by the data obtained for .Yatagai (1937)

calculated the negative volume when the *D* and *H* were small. Overall, the volume estimated by Model-a was closer to the measured volume. Therefore, Model-a had a superior predictive performance to Model-d.

Accordingly, Model-a exhibited superior fit performance for small trees. Although Model-d had a better predictive performance for medium-sized trees, its estimation was inaccurate when the *D* and *H* was too small. Overall, we determined that the difference between the measured values and estimated values was lower for Model-a than for Model-d. The volume equation of *A. kawakamii* is presented as follows:

$$V = 0.00003663 \times D^{1.6693} \times H^{1.4003} \quad (7)$$

Discussion

In the past, Liao et al. (1973) considered *A. kawakamii* and *P. morrisonicola* when deriving the volume estimation equation; however, we could not confirm the details regarding their samples, such as the collection locations, the number of samples, and sample size. In Taiwan, the altitudinal vegetation zone of *A. kawakamii* and *P. morrisonicola* were different, although all of them were defined as subalpine forest species. *Abies* forest usually forms a pure stand at 3,100–3,600 m, while *P. morrisonicola* was mixed with *Tsuga chinensis* var. *formosana* at 2,500–3,100 m and usually distributed lower than *Tsuga* forest (Su 1984). Therefore, the habitat of the two species were quite divided in Taiwan, and the vegetation distribution was different from the coniferous forests at high latitude sites (Akiko 1994; Li et al. 2013). The growth pattern of the two were also not alike because the different growth environment including temperature, precipitation, moisture, soil and the intraspecific and interspecies competition. Hence, we thought it is necessary to distinguish the two-volume equations.

We reconstruct the equation for *A. kawakamii* after nearly 50 years. Usually, sampling trees to stem analysis should consider the tree distribution of stands. However, the targeted stands were natural forests and cutting natural forests were prohibited in Taiwan. Besides, the remoteness and precipitous topography of our study area and restrictions against tree cutting and handling, obtaining study materials was rugged. Therefore, the sample trees used in this study were collected from windfall trees and this is also the limitations of the study and we only obtained nine samples and got their volumes through stem analysis. To ensure the accuracy of the volume equation established in this study, we verified other samples' historical data. Although the sample size was not enough, we could still choose appropriate results for subsequent testing.

As well-known, the volume equation is a powerful tool to predict tree volume based on *D* and *H* and has been widely employed in regional and large scales worldwide. We also found that numerous researches have established the volume equations for some important tree species in Taiwan, individually. However, the purpose of those volume equations was mainly focused on the economic benefits of forests, especially in plantations (Yen et al. 2008; Chiu et al. 2011). Rare addressed the economic benefits of forests. Based on the study results, our study results help in determining individual tree volume. The tree volume equation could provide fundamental information for estimating the stock and carbon storage of Taiwan fir under conditions of global climate change and could widely assess various ecosystem services for Taiwan fir to understand its contributions in the high mountain area.

Conclusions

This study is the first case in Taiwan. Due to obtaining samples are rare and need all the permissions from different administration of government in Taiwan. We used six models to test suitability for *A. kawakamii* tree volume estimation. Of these, the Schumacher equation ($V = aD^bH^c$) was observed to be the most suitable model for volume estimation, as demonstrated by the validation statistics. Evaluation of volume equations based on sample size revealed that the Schumacher equation was accurate for juvenile trees and that the generalized combined-variable equation was accurate for semi-mature trees. Nevertheless, the generalized combined-variable equation provided underestimations when juvenile trees were considered. In summary, our new tree volume equation was observed among the timber volume models to have higher accuracy. Thus, the volume estimation equation derived in this study is particularly suitable for the Taiwan fir forest in this area.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Akiko I. 1994. Late Cenozoic vegetational and climatic changes in Kyushu, Japan. Paleogeogr Paleoclimatol Paleoecol. 108:229–280. doi:10.1016/0031-0182(94)90236-4.

Akindele SO, LeMay VM. 2006. Development of tree volume equations for common timber species in the tropical rain forest area of Nigeria. For Ecol Manage. 226:41–48. doi:10.1016/j.foreco.2006.01.022.

Boufford DE, Ohashi H, Huang TC, Hsieh CF, Tsai JL, Yang KC, Peng CI, Kuoh CS, Hsiao A. 2003. Flora of Taiwan. Vol. Six, 2nd edn. Taipei: Department of Botany, National Taiwan University.

Bruce D. 1919. Alignment charts in forest mensuration. J For. 17:773–801.

Caccamo G, Iqbal IA, Osborn J, Bi H, Arkley K, Melville G, Aurik D, Stone C. 2018. Comparing yield estimates derived from LiDAR and aerial photogrammetric point-cloud data with cut-to-length harvester data in a *Pinus radiata* plantation in Tasmania. Austral For. 81:131–141. doi:10.1080/00049158.2018.1458582.

Chen CT, Chen CC. 2015. Forest management. Taipei: Cheng Chung Book Co. Chinese.

Chiu CA, Lin HC, Liao MC, Tseng YH, Ou CH, Lu KC, Tzeng HY. 2008. A physiognomic classification scheme of potential vegetation of Taiwan. Q J Chin For. 30:89–112. Chinese.

Chiu CM, Tang SL, Chung CH, Lin CJ. 2011. Effects of thinning strategies on carbon storage and biomass of Taiwan Red Cypress (*Chamaecyparis Formosensis*) plantations. Q J For Res. 44 (3):385–400. Chinese.

Chou SI. 1972. The study on forest soils and reforestation in Taiwan. J Agric For. 12:155–174. Chinese.

Cunia T. 1964. Weighted least squares method and construction of volume tables. For Sci. 10:180–191.

Furnival GM. 1961. An index for comparing equations used in constructing volume tables. For Sci. 7:337–341.

Grosenbaugh LR 1964. Some suggestions for better sample-tree-measurement. In: Proceedings of the Society of American Foresters Meeting; 1963 October 20–23; Boston, Mass. Bethesda (Md.): Society of American Foresters, p. 36–42

Ho CS. 1986. An introduction to the geology of Taiwan explanatory text of the geologic map of Taiwan. Taipei: Central Geological Survey, The Ministry of Economic Affairs Republic of China. Chinese.

Honer TG. 1965. A new total cubic foot volume function. For Chron. 41:476–493. doi:10.5558/tfc41476-4.

Jong ZX, Lin JS, Wu SY. 2006. Application of computerized image system on tree-ring measurement. Ilan Univ J Bioresour. 2:33–41. Chinese.

Li CF, Chytrý M, Zelený D, Chen MY, Chen TY, Chiou CR, Hsia YJ, Liu HY, Yang SZ, Yeh CL, et al. 2013. Classification of Taiwan forest vegetation. Appl Veg Sci. 16(4):698–719. doi:10.1111/avsc.12025

Liao DN, Zhang YS, Yen KH. 1973. Volume table of main tree species in Taiwan – fir tree volume table. Taipei: Taiwan Forestry Bureau; p. 78–103. Chinese

Liao MC, Chiu CA, Lin HC, Tseng YH, Tzeng HY, Lu KC. 2012. Understory vegetation diversity at *Abies kawakamii* (Hayata) Ito forest in Mt. Shei. Q J For Res. 34:129–179. Chinese.

Liao MC, Tsai ST, Wang W, Tzeng HY, Ou CH. 2013. Study on population structure of *Abies kawakamii* (Hayata) Ito in East Xue Trail of Xue Mountain. Q J For Res. 35:1–14. Chinese.

Lin JC, Chen SJ, Wu MS. 2015. An analysis of the timber harvest volume and production in Taiwan between 1991 and 2013. Taiwan J For Sci. 30:121–130. Chinese.

Liu SH. 1970. Comparative studies on the preparation of volume table. Q J Chin For. 4:1–14. Chinese.

Liu TS. 1971. A monograph of the genus *Abies*. Taipei: College of Agriculture National Taiwan University; p. 127–131.

Lu KC, Ou CH, Wang CM, Shao KT, Lin LK, Lin PH, Lin ZY, Sun YH, Tseng YH, Yeh WB, et al. 2010. The integrated research project of alpine ecosystem in Mt. Xue region. Miaoli: Shei-Pa National Park. Chinese.

Newnham RM. 1967. A modification to the combined-variable formula for computing tree volume. J For. 65:719–720.

Qiu LW, Huang QX, Wu CC, Hsieh HT. 2015. Summary of the fourth national forest resource inventory report. Taiwan For J. 41(4):3–13. Chinese.

Schumacher FX, Hall FS. 1933. Logarithmic expression of timber-tree volume. J Agric Res. 47:719–734.

Spurr SH. 1952. Forest inventory. New York: The Ronald Press Company.

Stoate TN. 1945. The use of a volume equation in pine stands. Austral For. 9:48–52. doi:10.1080/00049158.1945.10675220.

Su HJ. 1984. Studies on the climate and vegetation types of the natural forests in Taiwan (II): altitudinal vegetation zones in relation to temperature gradient. Q J Chin For. 17:1–14.

Taiwan Forestry Bureau. 1995. The third forest resources and land use inventory in Taiwan. Taipei: Taiwan Forestry Bureau.Chinese.

Tseng SH, Tzeng HY. 2016. Assessing the gap dynamics in a subalpine forest on Xue mountain through aerial orthophotos. Q J For Res. 38:227–240. Chinese.

Vasilescu MM, Tereşeu CC, Dinulică F, Borz SA, Popa B. 2017. A new stem volume equation for Norway Spruce (*Picea abies* (L.) Karst) trees in Romania. Baltic For. 23:626–635.

Wang W, Chiu CA, Tsai ST, Hsu CK, Tzeng HY, Lu KC. 2010. Vegetation research along the east trail of Mt. Shei. Q J For Res. 32:15–34. Chinese.

Yang BL, Dan ZC. 1963. Aerial stand volume tables for Taiwan Cypress and hardwood types (II). Taipei: Agricultural and Forestry Aerial Survey Journal NO.10. Chinese.

Yang BL, Lin YH. 1961. Aerial stand volume tables for Taiwan Cypress and hardwood types (I). Taipei: Agricultural and Forestry Aerial Survey Journal NO.4. Chinese.

Yang YC, Lin WL. 2003. Forest Measurement. Taipei: National Institute for Compilation and Translation. Chinese.

Yatagai M. 1937. Über die bestandsaufbauformen des naturwaldes der tannen (*Abies kawakamii* Ito) an "Tugitakayama". J Taihoku Soc Agric For. 2:119–139. Japanese.

Yen CH. 2009. The study of soil properties in alpine region. Miaoli: Shei-Pa National Park. Chinese.

Yen TM, Ai LM, Li CL, Lee JS, Huang KL. 2009. Aboveground carbon contents and storage of three major Taiwanese conifer species. Taiwan J For Sci. 24:91–102.

Yen TM, Huang KL, Li LE, Wang CH. 2020. Assessing carbon sequestration in plantation forests of important conifers based on the system of permanent sample plots across Taiwan. J Sustain For. 39:392–406. doi:10.1080/10549811.2019.1673181.

Yen TM, Ji YJ, Lee JS. 2010. Estimating biomass production and carbon storage for a fast-growing Makino Bamboo (*Phyllostachys makinoi*) plant based on the diameter distribution model. For Ecol Manage. 260:339–344. doi:10.1016/j.foreco.2010.04.021.

Yen TM, Lee JS, Huang KL. 2008. Growth and yield models for thinning demonstration zones of Taiwan Red Cypress (*Chamaecyparis formosensis* Matsum.) and Japanese Cedar (*Cryptomeria japonica* D. Don) plantations in central Taiwan. Q J For Res. 30:31–40. Chinese.