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Research paper

Integrating Allometric Modeling and Diameter Distribution Analysis to Predict Stand Volume and Carbon Storage of *Taiwania cryptomerioides* Hay. Plantations in Eastern Taiwan

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ABSTRACT

Forest carbon sinks are a fundamental component of Natural Climate Solutions (NCS). While plantations comprise only approximately 20% of Taiwan's forested area, their annual growth and carbon sequestration rates are three times those of natural forests. Thus, effective plantation management is crucial for supporting the development of forest carbon sinks in Taiwan. *Taiwania cryptomerioides* Hay., commonly known as Taiwania, is a highly suitable native afforestation tree species. However, past research has primarily focused on central and southern Taiwan. Establishing growth models for *T. cryptomerioides* plantations in eastern Taiwan can effectively fill this geographical data gap. This study focused on a 40-year-old *T. cryptomerioides* plantation at the Taiwan Forestry Research Institute's Experimental Forest. The diameter distribution method (DDM) was employed, integrating height-diameter relationships and volume equations based on allometric models to estimate total stand volume and carbon storage. The findings indicate that the developed models provided highly accurate estimates. The root mean square error (RMSE) for tree height and volume estimations were approximately 1.6147 m and 0.0293 m^3, respectively. The Weibull probability density function effectively modeled the stand diameter distribution. Estimated stand volume was 418.43 m^3 ha^{-1}, corresponding to carbon storage of 469.87 t CO_2 ha^{-1}. This relatively low carbon storage is likely attributable to low stand density. Ultimately, the findings of this study provide a reliable basis for the growth, yield, and management planning of *T. cryptomerioides* plantations in eastern Taiwan, clarifying their potential contribution to forest carbon sinks. As significant variations in form factors, stand diameter distributions, and carbon storage exist across regions, future research should focus on developing regional allometric models to further enhance the accuracy of carbon storage estimations.

Keywords: *Taiwania cryptomerioides* Hay., allometric model, diameter distribution method, Weibull probability density function, carbon storage

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INTRODUCTION

Forest carbon sinks are a common approach to Natural Climate Solutions (NCS) that can be enhanced through strengthened forest carbon sequestration. Primary strategies to reduce greenhouse gas (GHG) emissions include afforestation (AF), reforestation (RF), avoided forest conversion/avoided deforestation (AFC/AD), and improved forest management (IFM) (Griscom et al. 2017, Kaarakka et al. 2021, Seddon et al. 2021, Seddon 2022). These strategies can be effectively implemented through sound plantation management. In Taiwan however, most natural forests are old-growth forests located in remote mountainous areas. Following implementation of the nationwide logging ban in 1990, these forests have retained substantial carbon conservation value but provide only limited carbon sequestration benefits. Although plantations comprise only approximately 20% of Taiwan's forest area, their annual growth rates and carbon sequestration per unit area are approximately three times those of natural forests. Thus, they can deliver carbon sink benefits while simultaneously providing multiple ecological, economic, and social co-benefits, including biodiversity conservation, soil and water protection, environmental education, and local revitalization (Gilroy et al. 2014, Buotte et al. 2020, Hussain et al. 2021, Mikoláš et al. 2021, Abildtrup et al. 2024). As such, the effectiveness of plantation management is essential for developing forest carbon sinks in Taiwan.

Based on the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (2006), forest carbon storage, sequestration, and emissions are calculated from forest stand volume, growth, and mortality or harvest volume using relevant conversion factors. In forest management, assessment of forest carbon sinks ultimately depends on the fundamental principles of forest growth and yield. The development of forest growth and yield models based on statistical relationships has been widely applied both domestically and internationally (e.g., Lee and Yen 1995a, 1995b, 1996, Lin et al. 2003, Yen et al. 2008, Li and Yen 2012, Hussain et al. 2021, Li et al. 2021). In particular, allometric models and the Diameter Distribution Method (DDM) are commonly used to estimate individual tree and stand attributes, including tree height, stand volume, and carbon storage. These methods serve as practical statistical tools for quantifying forest characteristics and provide reliable basis for forest management decision making.

Taiwania cryptomerioides Hay., commonly known as Taiwania is a member of the genus *Taiwania* in the family Cupressaceae and is an excellent native plantation tree species in Taiwan. This species is characterized by fast growth, wide adaptability, high-quality timber, and significant economic value (Chiu et al. 2010). Previous studies have investigated the growth, yield, management, and carbon sink benefits of plantations of this conifer (Chen et al. 1997, Lin et al. 2003, 2004, Lin et al. 2008, Liu et al. 2009, 2012, Wang et al. 2010, 2012a, Cheng et al. 2014, Li et al. 2021, Lin and Yen 2022). However, most research sites are situated in central and southern Taiwan, and few studies have focused on eastern Taiwan. Establishing growth models for *T. cryptomerioides* plantations in Taiwan's eastern region could fill this geographical data gap, enhancing our understanding of the characteristics of this species across Taiwan. The present study focuses on the *T. cryptomerioides* plantation at the Taimalee

Experimental Forest of the Taiwan Forestry Research Institute. The research objectives are to: (1) develop individual-tree height-diameter relationships and volume equations using allometric models; (2) analyze stand structure and carbon storage across diameter classes using the diameter distribution model; and (3) explore the carbon sink potential of *T. cryptomerioides* plantations in the Taimalee area.

MATERIALS AND METHODS

Study area

The experimental site is a *T. cryptomerioides* plantation stand (22˚37' N, 120˚56' E, Figure 1) in Forest Area 2 of the Taimalee Experimental Forest (Taiwan Forestry Research Institute). Administratively, the site lies within Jinfeng Township of Taitung County. The stand is at an elevation of approximately 1,300 m, with a mean annual temperature of approximately 24℃, and annual rainfall of 2,500–3,000 mm, concentrated in summer. The slope of the terrain ranges from 5° to 25°. The region's soils are of the Sandimen series, and are classified as yellow soils formed from the weathering of argillite and slate of the Miocene Lushan Formation. Soil depth ranges from 50 cm to 90 cm, with stone fragments comprising approximately 10% of the profile. Organic matter content is moderate to high, providing favorable conditions for tree growth (Taiwan Forestry Research Institute 2002). The area was originally covered by a natural broadleaf forest dominated by tree species such as *Cinnamomum kanehirae* (Hay.), *Castanopsis cuspidata* (Thunb.) Schottky var. *carlesii* (Hemsl.) T. Yamaz., and *Pasania hancei* (Benth.) Schottky var. *ternaticupula* (Hay.) Liao. Following clear-cutting in 1981, however, a pure *T. cryptomerioides* plantation was established over an area of 20.8 ha with a planting density of 2,500 trees ha^{-1}. The stand was pruned at age 17, and in 2021 was designated as a mid-to-late stage silvicultural treatments experimental site for long-term research, thereby becoming one of the Taiwan Forestry Research Institute's long-term experimental sites.

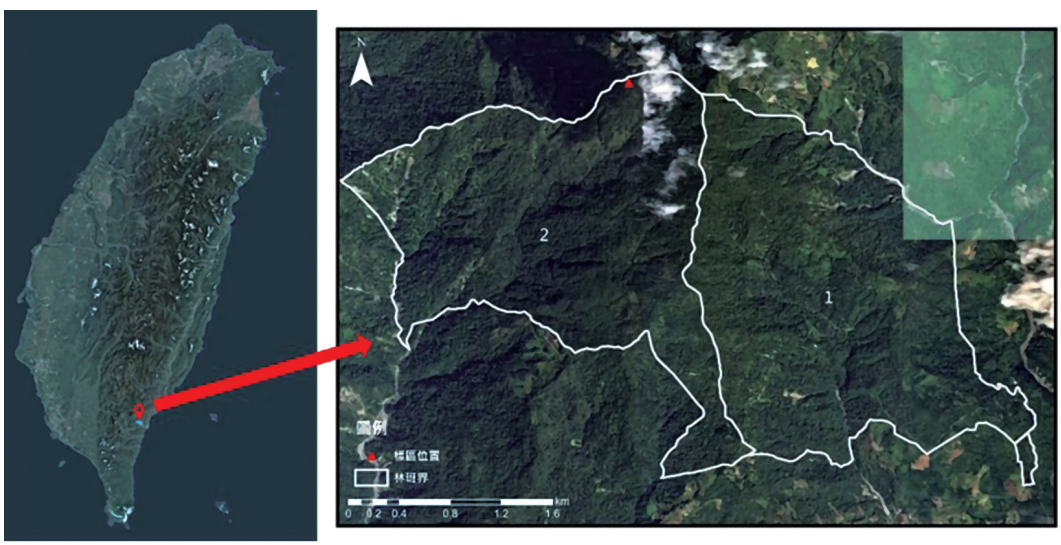

Figure 1. Location of the study area

Data collection

In this study, 30 sample trees with intact tops were selected from the stand using stratified sampling across three diameter classes. Before felling the sample trees, Diameter at Ground Level (DGL) and Diameter at Breast Height (DBH) were measured with diameter tape, and breast height position was marked. Total tree height was measured after felling. Diameters were measured at 2 m intervals, starting from a stump height of 0.3 m. Individual tree volume was calculated using the sectional measurement method (Smalian's formula, Li et al. 2021).

Allometric models for individual-tree height and volume

Allometric models are practical tools for predicting biomass and carbon storage and have long been used to construct height-diameter relationships and volume equations. These models typically use metrics such as DBH, tree height, and wood density as explanatory variables (Mahmood et al. 2019, Li et al. 2024). Based on data collected from the 30 sample trees in this study, individual-tree height and volume allometric models were developed for the *T. cryptomerioides* plantation in the Taimalee region. These models are expressed in Eqs. (1) and (2).

$$H = a \times DBH^{b} \quad \cdots\cdots(1)$$

$$V = a \times DBH^{b} \times H^{c} \quad \cdots\cdots(2)$$

where V represents the individual-tree volume (m^3) for the sampled *T. cryptomerioides*; H denotes tree height (m); DBH is the diameter at breast height (cm); and a, b, and c are the model parameters.

Diameter distribution models for stand volume and carbon storage

The diameter distribution method proposed by Hyink and Moser (1983) was employed to estimate stand volume and carbon storage in CO_2 equivalents. For the individual tree survey, nine 0.05-ha sample plots were established within the stand. Data collected from these plots were aggregated, and the Weibull Probability Density Function (PDF) was used to model the distribution of stand diameters. Probability density and cumulative distribution functions are presented in Eqs. (3) and (4). The maximum likelihood method was used to estimate function parameters, describing the distribution of trees across diameter classes. By integrating the allometric models developed in this study, stand volume and carbon storage (in CO_2 equivalents) for each diameter class were calculated. Additionally, the biomass expansion factor (BEF) method was used in accordance with the AR-TMS0001 Methodology for Afforestation and Reforestation Carbon Sink Project Activities of the Ministry of Environment; Climate Change Administration (2025a). Individual-tree volume was converted to total tree carbon storage in CO_2 equivalents using relevant conversion factors (Eq. 5).

$$f(x) = (c / b)[(x - a) / b]^{c-1} \exp\{-[(x - a) / b]^{c}\} \quad \cdots\cdots(3)$$

$$F(x) = 1 - \exp\{-[(x - a) / b]^{c}\} \quad \cdots\cdots(4)$$

$$C = V \times D \times BEF \times (1 + R) \times CF \times 44 / 12 \quad \cdots\cdots(5)$$

where x represents DBH (cm); a, b, and c are model parameters; and $f(x)$ and $F(x)$ denote the probability density function and cumulative distribution function, respectively.

C represents individual-tree carbon storage (in CO_2 equivalents) for the sampled *T. cryptomerioides*; V is the tree volume (m^3); D is the wood density (tonnes dry matter m^{-3}); BEF is the aboveground biomass expansion factor; R is the root-to-shoot ratio; and CF is the carbon fraction conversion factor. Since conversion factors were not measured in this study, values for coniferous plantations from the Republic of China National Greenhouse Gas Inventory Report (Climate Change Administration 2025b) were applied (D = 0.41, BEF = 1.27, R = 0.22, and CF = 0.4821).

Error analysis

Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) were used as reference metrics to test the allometric model fitness performance, as shown in Eqs. (6) and (7). RMSE is in the same units as the response variables; its value depends on the size and range of the response variables. While there is no standard threshold value, it provides a practical reference for error. RMSE is widely used to compare the fitness-for-use of different models for the same attribute (Colbert et al. 2004). MAPE is calculated by taking the observed values as the denominator and computing the absolute percentage of the error between the estimated values and the observed values. Following Lewis (1982), MAPE < 10% designates excellent estimation performance, 10 < MAPE < 20% signifies good estimation performance, 20 < MAPE <50% indicates reasonable estimation performance, and MAPE > 50% signifies inaccurate estimation performance. This metric enables comparison of model fit results across different attributes.

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

$$\mathrm{MAPE}(\%) = (1/n) \times \sum_{i=1}^{n}(|y_i - \hat{y}_i|/y_i) \times 100\% \quad \cdots(7)$$

where n represents the sample size; y_i is the observed value of height or volume; $\hat{y}_i$ indicates the model-predicted value of height or volume; and p is the number of model parameters.

The Kolmogorov–Smirnov test (K–S test) was used to assess the goodness-of-fit of the diameter distribution model. Following Law (2014), the K–S test statistic ($\sqrt{N} \times D_n$) was calculated using the number of sample trees (N) and maximum model discrepancy (D_n). This statistic was compared to the critical value $C_{1\text{-}a}$ to evaluate the model's performance (Li and Yen 2010, Huang et al. 2015).

RESULTS

Statistics of sample tree attributes

The 30 felled sample trees of *T. cryptomerioides* had DBH values ranging from 15.5 to 53.2 cm; height was 15.0 to 27.2 m; volume was 0.11 to 2.48 m^3; carbon storage in CO_2 equivalents was 0.12 to 2.79 t CO_2. Statistical information regarding the attributes for each diameter class is provided in Table 1.

Allometric models for individual-tree height, and volume

Applying data from the 30 sample trees, the allometric models (Eqs. 1, 2) were fitted for height and volume. Parameters and test results are provided in Table 2.

Table 2 shows that MAPE values for all allometric models were less than 10%. Based on Lewis's (1982) criteria, these results reflect high-accuracy estimation performance. In the present study, the root mean square

Table 1. Characteristics of sampled trees in each diameter class for *Taiwania cryptomerioides*

Diameter class	DBH range (cm)	Number of sample trees	DBH (cm)	Height (m)	Volume (m^3)	Carbon storage (t CO_2)
1	15≦DBH<28	9	21.56±3.97	18.97±3.29	0.32±0.17	0.36±0.19
2	28≦DBH<41	12	34.93±4.21	23.26±1.72	0.95±0.26	1.07±0.30
3	41≦DBH<54	9	46.52±4.14	26.06±0.69	1.85±0.33	2.08±0.38
Total		30	34.39±10.62	22.81±3.49	1.03±0.66	1.16±0.74

Note: Values are presented as mean ± standard deviation (SD); DBH = Diameter at Breast Height.

Table 2. Tree height, volume equations and errors

Characteristics	Equations	RMSE	MAPE
Height (m)	$5.3572 \times DBH^{0.413}$	1.6147 (m)	5.40%
Stand volume (m^3)	$0.000029 \times DBH^{1.8891} \times H^{1.165}$	0.0293 (m^3)	2.62%

Note. DBH = Diameter at Breast Height; RMSE = Root Mean Square Error; MAPE = Mean Absolute Percentage Error.

error (RMSE) for height was 1.6147 m and 0.0293 m^3 for volume. Although RMSE is a practical error metric, its acceptable threshold varies by attribute. Therefore, it is best suited for relative comparisons—such as evaluating different methods or tree species—for the same attribute.

Diameter distribution models for stand volume and carbon storage

A three-parameter Weibull probability density function was used to model the diameter distribution of the *T. cryptomerioides* plantation stand in Forest Area 2 of the Taimalee Experimental Forest, Taiwan Forestry Research Institute. Function parameters were computed using the maximum likelihood method implemented in SAS statistical software (Figure 2). The calculated parameters for the Weibull distribution were as follows: location parameter a = 3.62, scale parameter b = 31.77, and shape parameter c = 2.11. The K–S test statistic ($\sqrt{N} \times D_n$) proposed by Law (2014) was used to test simulation results. The calculated test statistic was 0.523, lower than the critical value of 0.874, indicating that the model passed the goodness-of-fit test. In other words, no significant difference between the simulated and actual stand survey-based diameter distribution was detected. The findings confirm the model's suitability in representing the stand's diameter distribution. Based on the satisfactory simulation performance of the diameter distribution model, the distribution of trees in each diameter class in the parent stand established through this method was used. This diameter distribution was combined with the average diameter of each diameter class, the height-diameter curve equation, and the volume equation established in the previous section to estimate the volume and carbon storage (in CO_2 equivalent) for each diameter class and the entire stand (Table 3).

DISCUSSION

Although Taiwan is situated in a tropical-subtropical zone, its complex mountainous topography creates diverse ecosystem environments across varying climatic zones. This fosters a rich plant diversity, resulting in a broader variety of plantation tree species than

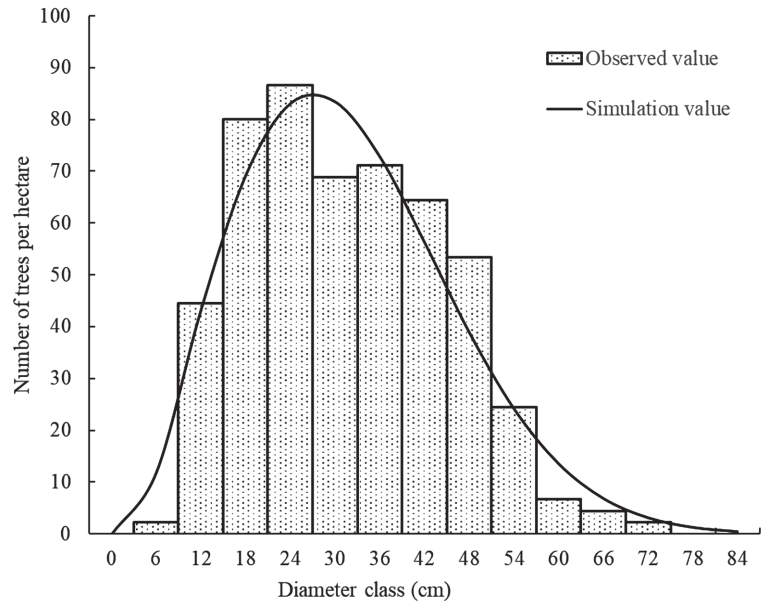

Figure 2. Comparing observed and simulated values of the diameter distribution method for *Taiwania cryptomerioides* in the Taimalee region; the parameters a, b, and c of the Weibull model were 3.62, 31.77, and 2.11, respectively.

Table 3. Prediction of stand volume, and carbon storage for *Taiwania cryptomerioides* based on the diameter distribution model

Diameter class (cm)	Theoretical probability (%)	Estimated number of trees (trees ha^{-1})	Average DBH (cm)	Average height (m)	Average volume (m^3)	Stand volume (m^3 ha^{-1})	Carbon storage (t CO_2 ha^{-1})
3-9	2.3	12	3	8.43	0.00	0.03	0.04
9-15	8.5	43	9	13.28	0.04	1.61	1.81
15-21	13.6	69	15	16.39	0.13	8.67	9.74
21-27	16.3	83	21	18.84	0.28	23.16	26.00
27-33	16.4	83	27	20.90	0.51	42.01	47.18
33-39	14.3	73	33	22.70	0.81	59.45	66.76
39-45	11.1	56	39	24.32	1.21	67.77	76.10
45-51	7.6	39	45	25.81	1.70	66.25	74.40
51-57	4.8	24	51	27.17	2.29	54.85	61.59
57-63	2.7	14	57	28.45	2.97	41.65	46.77
63-69	1.4	7	63	29.65	3.77	26.40	29.64
69-75	0.6	3	69	30.79	4.68	14.04	15.76
75-81	0.3	1	75	31.87	5.70	5.70	6.40
81-87	0.1	1	81	32.90	6.84	6.84	7.68
Sum	100.0	508				418.43	469.87

typically found in temperate regions. Owing to a lack of specific carbon sink and biomass estimation models for many regions and tree species, the biomass expansion factor method (Eq. 1) has been frequently used to estimate tree carbon stocks in past research. Thus, the accuracy of individual-tree volume estimation is particularly crucial. Based on the conventional calculation method used by forestry authorities in Taiwan, individual tree volume equations only exist for selected tree species, including *Cunninghamia lanceolata* (Lamb.) Hook., *Cryptomeria japonica* (Thunb. ex Lf) D. Don, *Pinus luchuensis* Mayr., *Pinus taiwanensis* Hay., *Acacia confusa* Merr., and particular species of Lauraceae and *Quercus*. For other tree species, volume is commonly calculated using an average form factor of 0.45, i.e., sten vikyn $e = (DBH/2)^2 \times \pi \times$ height $\times$ 0.45. In the present study, the measured form factor of the 30 sample trees ranged from 0.378 to 0.458, with an average of 0.420. Using the average form factor of 0.45 would lead to an overestimation of approximately 7%. Since the form factor is influenced by tree species, age, stand density, and site conditions, significant variations may exist among different stands. For example, the average form factor for the *T. cryptomerioides* plantation in Compartment 12 of the Lioukuei Experimental Forest of Taiwan Forestry Research Institute (Li et al. 2021) was about 0.38. Furthermore, the average form factors for the *Chamaecyparis formosensis* plantations in Compartments 121 and 123 of the Daan River Working Circle, and the *Cryptomeria japonica* plantation in Compartment 74 of the Luanda Working Circle (Yen et al. 2008), were approximately 0.40 and 0.33, respectively. Moreover, the average form factor for the *Cunninghamia lanceolata* plantation in Compartment 111 of the Basianshan Working Circle (Yen et al. 2004) was the highest at precisely 0.45. The results from these studies, with estimation error ranges from 0% to 26% underscores the need to develop region-specific volume equations.

The height-diameter curve equation developed in this study had an RMSE value of approximately 1.6 m; which was lower than those reported for the *Cunninghamia lanceolata* plantation in the Basianshan region (RMSE value: 2.7 m, Yen et al. 2004), the *Chamaecyparis formosensis* plantation in the Xitou region (RMSE value of approximately 2.2 m, Wang et al. 2012b), the *Chamaecyparis formosensis* and *Cryptomeria japonica* plantations in central Taiwan (RMSE values of approximately 4.2 and 2.7 m, Yen et al. 2008), and the *T. cryptomerioides* plantation in the Lioukuei region (RMSE values of approximately 4.2 and 2.7 m, Li et al. 2021). Regarding the volume equation, the RMSE value in this study (approximately 0.03 m^3) was lower than that reported for the *Cunninghamia lanceolata* equation in the Basianshan region (RMSE value of approximately 0.07 m^3, Yen et al. 2004) and *T. cryptomerioides* in the Lioukuei region (RMSE value of approximately 0.08 m^3, Li et al. 2021), though it was higher than those reported for *Chamaecyparis formosensis* and *Cryptomeria japonica* in central Taiwan (RMSE values of approximately 0.007 and 0.0006 m^3, Yen et al. 2008). Since the number of sample trees for model development in the studies mentioned above were quite similar, the primary factors influencing model error are likely not the sample size but differences in stand environment or genetic characteristics of the tree species.

Taiwania cryptomerioides is an excellent native plantation tree species in Taiwan. The Taiwan Forestry Research Institute established large-scale plantations in the Taimalee and

Lioukuei Experimental Forests. At the time of this study, the stand was 40 years old, and similar in age to the 42-year-old *T. cryptomerioides* plantation examined by Li et al. (2021) in the Lioukuei Experimental Forest. The elevations of the two stands are also comparable. A horizontal comparison of stand diameter distributions can aid researchers in understanding the adaptability of *T. cryptomerioides* in these two prominent planting regions more comprehensively. In the present study, the weibull parameters a, b, and c were 3.62, 31.77, and 2.11, respectively. Compared to the simulation results for the *T. cryptomerioides* plantation in the Lioukuei Experimental Forest (a = 9.10, b = 25.02, c = 2.64; Li et al. 2021), the sum of parameters a and b is similar for both stands. Since this sum of a and b approximates the DBH at the 64th percentile of stand density, it can be inferred that the average DBH of the two stands is quite similar. However, the larger b parameter and smaller a and c parameters for the Taimalee stand indicate greater diameter variation (i.e., a wider distribution range) compared to the Lioukuei stand. In probabilistic terms, the Taimalee plantation contains a higher frequency of small-diameter trees and a wider spread of DBH values (Figure 3). Even though the number of small-diameter trees is larger, their individual carbon storage is lower. Thus, in terms of aggregate carbon storage per diameter class, the distribution pattern of stand carbon storage tends to approximate a bell-shaped distribution.

Estimating carbon storage across forest types is essential for addressing global climate issues (Yen and Lee 2011, Yen and Wang 2013). Most related studies have typically estimated per-unit-area carbon storage by directly scaling up carbon data from sample plots in proportion to area. In contrast, the present study employed the diameter

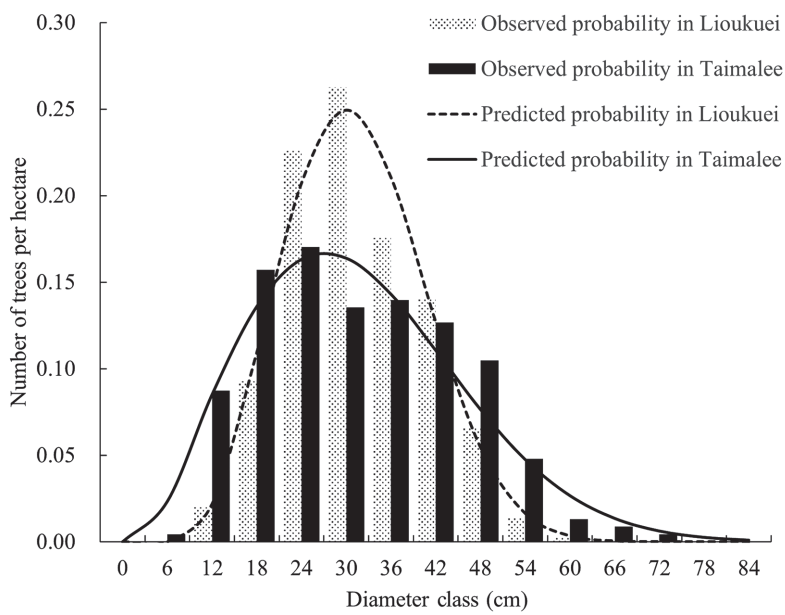

Figure 3. Comparing the diameter distribution of *Taiwania cryptomerioides* in the Taimalee and Lioukuei regions; the parameters a, b, and c of the Weibull function for the Lioukuei area were 9.10, 25.02, and 2.64, respectively.

Table 4. Reported stand volume and carbon storage of coniferous plantations compiled from published studies

Location	Species	Age (year)	Density (trees ha^{-1})	Stand volume (m^3 ha^{-1})	Carbon storage[1] (t CO_2 ha^{-1})	Mean annual increment (t CO_2 ha^{-1} year^{-1})	Literature
Taimalee	*Taiwania cryptomerioides*	40	509	418	470	11.750	This study
Lioukuei	*Taiwania cryptomerioides*	42	982	680	764	18.190	Li et al. 2021
Xitou	*Taiwania cryptomerioides*	39	925	599	673	17.256	Cheng et al. 2014
Xitou	*Cryptomeria japonica*	37	1,358	520	584	15.784	Cheng et al. 2013
Xitou	*Cryptomeria japonica*	46	1,058	618	694	15.087	Lee 2020
Lioukuei	*Chamaecyparis formosensis*	44	700	309	347	7.886	Huang 1977
Xitou	*Chamaecyparis formosensis*	45	825	536	602	13.378	Huang 1977
Huisun	*Cunninghamia konishii*	53	460	538	604	11.396	Hussain et al. 2021

Note: To enhance data comparability, stand carbon storage values were estimated based on the accumulated storage described in each paper and the conversion coefficients used in Equation (1) of the current study.

distribution method to simulate stand structure and combined this with allometric equations for estimation. Past research suggests that this method generally yields results not significantly different from direct estimation. Moreover, this method reveals the distribution structure of stand carbon storage across diameter classes (Yen 2023), providing more informative and valuable stand data for forest management. Employing the method proposed in this study (Table 3), stand volume was estimated to be approximately 418.43 m^3 ha^{-1}, and carbon storage was estimated at approximately 469.87 t CO_2 ha^{-1}. Compared to data compiled from the literature (Table 4), carbon storage is relatively low, which is likely due to the low stand density of the study site.

CONCLUSIONS AND SUGGESTIONS

This study investigated a 40-year-old *T. cryptomerioides* plantation at the Taimalee Experimental Forest of the Taiwan Forestry Research Institute. Integrating height-diameter and volume equations derived from allometric models, the diameter distribution method was used to estimate the volume and carbon storage of the entire stand. Stand volume was 418.43 m^3 ha^{-1}, and carbon storage was 469.87 t CO_2 ha^{-1}. Model test results indicated good estimation performance. The diameter distribution method not only enables estimation of the overall stand carbon stock, but also characterizes carbon distribution structure across diameter classes, providing management units with additional stand information. Moreover, the findings compiled in this study illustrate significant variations in form factors, stand diameter distribution structure, and carbon storage among stands across regions. Future research should focus on developing regional allometric models to enhance the accuracy of carbon stock estimation.

To develop individual-tree height and volume allometric models, this study employed destructive sampling. This approach not only limited the sample size but also precluded the opportunity to continuously monitor long-term dynamic development. Furthermore, research conducted at a single point in time lacks the predictive capacity required for dynamic temporal scales. Given recent advancements in Light Detection and Ranging (LiDAR) technology, future studies could explore the use of terrestrial laser scanning (TLS) equipment to replace destructive surveys, thereby preserving the potential for long-term longitudinal research.

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研究報告

應用異速模式與直徑分布法模擬臺灣東部臺灣杉 (*Taiwania cryptomerioides* Hay.)人工林蓄積量及碳貯存量

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摘要

森林碳匯是自然氣候解決方案(NCS)的重要組成部分，雖然人工林僅佔臺灣森林面積的 20%，但其年生長量與碳吸存量卻是天然林的三倍。因此，有效的人工林經營管理對於臺灣森林碳匯的發展至關重要。臺灣杉(*Taiwania cryptomerioides* Hay.)是優良的本土造林樹種；然而，過去的研究主要集中在臺灣中南部，建立臺灣東部臺灣杉人工林的生長模式，將能有效彌補此地域研究上的缺口。本研究以林業試驗所太麻里試驗林中40年生的臺灣杉人工林為研究對象，研究採用直徑分布法，結合樹高及材積之異速模式，藉以推估總林分蓄積與碳儲存量。研究結果顯示，所建立的模式提供了高準確度的推估值，樹高與材積模式的均方根誤差(RMSE)分別約為1.6147公尺與 0.0293立方公尺。此外，Weibull 機率密度函數能有效地模擬林分直徑分布，估算之林分蓄積量為 418.43 m^3 ha^{-1}，而碳儲存量為469.87t CO_2 ha^{-1}。此林分之碳儲存量較低，可能歸因於較低的林分密度。最終，本研究結果為臺灣東部臺灣杉人工林的生長、收穫及經營管理規劃提供了基礎數據，並分析了其對森林碳匯的潛在貢獻。由於不同地區在形數、林分直徑分布及碳儲存量上存在著顯著差異，未來的研究應著重於發展區域性的異速模式，以進一步提升碳儲存量估算的準確性。

背景

面對全球氣候變遷的嚴峻挑戰，森林碳匯已被視為自然氣候解決方案的核心途徑。在臺灣，人工林僅佔全島森林面積的20%，但其單位面積的年生長量及碳吸存能力卻高達天然林的3倍。這顯示出在人工林的經營將是提升臺灣森林碳匯發展的關鍵因素。森林碳匯的量化基礎在於森林生長收穫的推估。其中，異速模式與直徑分布法被視為推估單木與林分性態值的有效統計工具。臺灣杉(*Taiwania cryptomerioides* Hay.)作為原生的優良造林樹種，

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具有生長快速、材質優良及適應性廣等特性。然而，過去關於臺灣杉人工林的生長模式研究多集中於臺灣中南部地區，東部地區的相關資料相對匱乏。為彌補此地域性資料缺口，本研究選定林業試驗所太麻里試驗林作為研究場域，旨在建立東部地區臺灣杉人工林的生長模式與碳匯推估基礎，以補充臺灣杉的生長特性資料庫。

材料與方法

本研究之試驗地設於臺東縣之林業試驗所太麻里試驗林第2林區。研究對象為1981年由天然闊葉林伐採後營造之臺灣杉純林，造林面積20.8公頃，現況為40年生之林分，且已劃設為長期試驗地。

在數據蒐集方面，本研究採用分層取樣法，選取30株不同徑級且梢端完整的樣木。伐倒前量測胸徑，伐倒後量測樹高，並採用區分求積法計算材積。

在模式建立與分析方法上，本研究分為2個層次：

1. 異速模式建立：利用30株樣木資料，建立單木樹高及立木材積之異速方程式。
2. 直徑分布模擬：設置9個0.05公頃樣區進行每木調查，採用直徑分布法以Weibull機率密度函數模擬林分結構，並利用最大概似法求解參數，藉此描述林分內各直徑級的株數分布。

結果與討論

本研究異速模式配適結果顯示，樹高及材積模式之MAPE值皆小於10%，顯示具有極高之推估準確度，證實本研究建立之模式適用於該地區之精確推估。其精確度優於部分過去於八仙山、溪頭及六龜地區針對不同針葉樹種之研究，顯示除樣本數外，林分環境與遺傳特性亦是影響模式誤差之主因。

在形數方面，本研究實測樣木之平均形數為0.420。若依通用方式以平均形數0.45進行估算，將導致約7%的高估誤差。與過去文獻相比，不同地區或樹種之形數差異顯著，此結果突顯了建立區域性專用材積式對於提升推估精度的必要性。

在林分結構模擬部分，Weibull分布函數之參數求解結果為a = 3.62、b = 31.77、c = 2.11。通過K-S統計檢定。透過橫向比較，本研究發現太麻里林分與六龜試驗林42年生臺灣杉林分雖平均胸徑相近，但太麻里林分具有較大的b參數與較小的a、c參數，顯示太麻里地區之臺灣杉直徑變異較大，小徑木數量較多且分布範圍更廣。儘管小徑木單株碳貯量低，但因數量較多，整體分布仍呈鐘型結構。

最終，本研究推估太麻里試驗林40年生臺灣杉人工林之每公頃蓄積量為418.43 m^3 ha^{-1}，每公頃碳貯存量為469.87 t CO_2 ha^{-1}。相較於其他文獻，本區碳貯存量偏低，推測主要原因歸咎於該林分密度較低所致。然而，透過直徑分布法之應用，本研究不僅獲得總量數據，更分析了碳匯在各直徑級的分布結構，提供了比平均值更具經營參考價值的資訊。

結論

本研究針對臺灣東部太麻里地區40年生臺灣杉人工林，建立了具高準確度的樹高、材積及碳貯存量異速模式，並證實 Weibull 機率密度函數能有效模擬該地林分之直徑分布結構。研究結果顯示，該林分每公頃蓄積量達418.43 m^3 ha^{-1}，碳貯存量達469.87 t CO_2 ha^{-1}。

本研究採用直徑分布法結合異速模型，不僅能精確推估全林分碳匯總量，更能細緻化地呈現各直徑級的碳貯存貢獻，為森林經營者提供更詳盡的決策依據。其次，研究數據證實了不同區域之林分在形數、直徑結構及碳貯存量上存在顯著的地域性差異。因此，為了提升碳匯估算的精確度，未來應持續致力於臺灣各區域主要造林樹種異速模式的建立，以確切掌握人工林在自然氣候解決方案中的潛在貢獻與實質效益。

關鍵詞：臺灣杉、異速模式、直徑分布法、Weibull機率密度函數、碳儲存

陳巧瑋、楊蒼叡、李志璇、劉冠廷、李隆恩。2026。應用異速模式與直徑分布法模擬臺灣東部臺灣杉(*Taiwania cryptomerioides* Hay.)人工林蓄積量及碳貯存量。台灣林業科學41(1): 43-58.