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Provenance analysis of teak (*Tectona grandis* L.f.) in Myanmar: growth, heritability and trait-trait correlations at different ages

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ABSTRACT: Teak (*Tectona grandis* L. f.) is a species with considerable economic and ecological significance in Myanmar. Provenance analysis of teak was conducted to examine its growth performance, genetic gain, heritability, and trait correlations and elucidate the species' critical facets. Diameter at breast height (DBH) and total tree height (H) were measured and assessed for trees from eight teak provenances aged 11, 14, 15, and 16 years. Analyses were conducted exclusively on trees that remained at age 16, enabling fair comparisons across different age groups. Significant differences in the growth traits of teaks were observed across provenances and ages. Nattalin, the local provenance to the study region, exhibited the highest growth, with tree heights ranging from 16.03 m to 20.42 m and DBH from 20.06 cm to 24.57 cm over the four years. Conversely, Thabeikkyin, a non-local provenance, consistently demonstrated the lowest growth and limited adaptability, with tree heights ranging from 13.68 m to 17.88 m and DBH from 15.19 cm to 20.10 cm. The investigation revealed that most local teak provenances show better growth performance than non-local provenances and growth in teak provenances is genetically controlled. Higher heritability was observed with increasing height and decreasing DBH in the teak provenances of the study site. These findings represent an essential step towards developing significantly improved planting materials, providing valuable scientific insights that could shape future tree improvement programs in Myanmar, and contributing to the sustainable development and preservation of teak species in the study region.

KEY WORDS: Correlations, genetic gain, growth variation, mortality, provenance heritability.

INTRODUCTION

Myanmar is the third most deforested country in the world (FRA, 2015) reported by the Global Forest Resource Assessment (FRA), with a significant loss of forests of approximately 155,000 km^2 of forests between 1990 and 2020 (FAO, 2016), causing a decline in both the quantity and quality of forest resources. However, Myanmar remains one of the top ten hot-spot countries for conservation and restoration efforts (Brancalion *et al*., 2019). Therefore, it is crucial to prioritize efforts toward reforestation, forest resource management, and conservation in Myanmar.

Teak (*Tectona grandis* L. f.) is a deciduous tropical tree species of the family Lamiaceae (The Angiosperm Phylogeny Group, 2009) that occurs naturally over a large geographic area in Myanmar, Thailand, India, and Laos PDR (Kaosa-ard, 1989). Myanmar had approximately 16.5 million ha of natural teak forest areas, and 3.95 million ha of established plantations from 1981 to 2018 (FD, 2020). The Bago Yoma region in south-central Myanmar is renowned for its high-density, high-quality teak forests (Maung and Yamamoto, 2008; Su Mon *et al*., 2012), which account for 11.3% of all the teak-bearing forests in the country (Zin, 2000). According to a recent study, the Bago Yoma area has significantly diminished forest area (Kyaw *et al*., 2020). Thus, reforestation with high-quality teak varieties is required for the genetic improvement of trees, and tree breeding programs for teak species are the main determinants of successful reforestation in Myanmar. However, it is necessary to emphasize the significance of these determinants in Myanmar. Establishing plantations requires qualified planting materials from multiple sources to increase productivity and genetic diversity (Wanders *et al*., 2021). Therefore, selecting superior tree varieties that are locally adapted, physically sound, and genetically sound is imperative to ensure successful reforestation in this region.

Phenotypic variation within a species is determined by a combination of genetic variation within the species, environmental heterogeneity, and their interactions. Under unfavorable environmental conditions, even tree species with superior genotypes may exhibit undesirable phenotypes (Frampton, 1996). Teak is an outcrossing species with a prolonged life span and is subject to local adaptation and genetic variation (Balakrishnan *et al*., 2023). Furthermore, productivity (a trait of interest) is influenced primarily by both genetic and environmental factors (Keiding *et al*., 1986; Wellendorf *et al*., 1988). Hence, it is possible to measure and assess the interactions between the genotype and phenotype of tree species, thereby inferring how well they adapt to their environments over time, by comparing the phenotypic performance of different populations within and among various environments (Raddad, 2007; Stöcklin *et al*., 2009). The growth performance for teak, as developed by the Forest Research Institute Malaysia (FRIM), suggests that teak can reach a diameter at breast height (DBH) of 25–35 cm and a height of 22–25 m at age 15. In optimal plantation sites in Myanmar, teak can achieve heights of 30 m and a DBH of 60 cm by age 50 (Krishnapillay, 2000).

Obtaining accurate information on genetic parameters and variation patterns is essential for developing successful breeding strategies (Namkoong, 1979). The efficiency of early selection depends directly on the magnitude of the correlation between the growth traits of tree species (Lambeth, 1980), and broad-sense heritability can be used to estimate the genetic effects of provenance selection on the target traits in the first generation (Nanson, 1958). Teak trees are traditionally grown with a rotation period of 120–150 years and a thinning interval of 30 years (Pandey and Brown, 2000). The rotation age of plantation teak in its natural range varies between 50 and 90 years, whereas, outside its natural range, it varies between 40 and 60 years (Ball *et al*., 1999). Currently, depending on the site conditions, management intensity, and provenance of the teak, a shorter rotation period of 50–60 years (Pandey and Brown, 2000), 40–80 years (Prasetyo *et al*., 2020), or 15–30 years (Moya *et al*., 2014) is commonly applied. The reported broad-sense heritability values in some studies were as follows: a dynamic modulus of 0.34 for 10-year-old teak trees in Costa Rica (Moya and Marín, 2011); 0.50, –0.76, 0.39, –0.44, 0.51–0.77 in volume for 12-year-old teak trees in Indonesia (Hidayati *et al*., 2013a); and 0.27, 0.27, and 0.20 in volume for 24-year-old teak trees in Indonesia (Hidayati *et al*., 2013b). Collecting estimates of growth parameters from teak provenances is crucial for making informed decisions regarding trial site location, age selection, breeding strategies, and their implications. Additionally, understanding age-age and trait-trait correlations is necessary to achieve these goals. Regarding growth performance, DBH (stem diameter at breast height) is a crucial growth trait affecting tree species' productivity and fitness. Height (H) is also a key factor determining growth and dieback resistance (Rweyongeza *et al*., 2003). Hence, DBH and height growth were primarily used in this study to estimate growth variation and genetic control at different ages.

Provenance trials have been conducted to determine which planted tree species or genotypes are best suited to specific locations (Mátyás, 1994; Rweyongeza, 2011; Lobo *et al*., 2018). In Myanmar, the tree improvement programs began in the 1980s with the establishment of teak provenance trials using phenotypically superior trees from natural forests. Unfortunately, there is limited information on the assessment of growth parameters of teak provenance trials conducted in Myanmar, despite the urgent need for extensive efforts toward the reforestation and conservation of teak species. Therefore, investigations on provenance trials of tree species are vital for selecting economically profitable, genetically sound, and environmentally adaptable qualities of tree species for their utilization and sustainable conservation.

The limited access to information from provenance trials in Myanmar underscores the importance of this study. Accordingly, we hypothesized the following: First, local teak provenances originating from the study area would exhibit higher growth performance than non-local provenances. Second, teak provenances in the study area are expected to exhibit a strong selection effect on the growth traits. Third, even when a test site suitable for teak growth is found in the Bago Yoma region, a good growth performance requires genetic management.

Understanding teak provenance growth traits and genetic parameters is essential for improving the selection, production, and conservation of valuable teak genetic resources. Therefore, this study aimed to quantify the growth variation in teak provenances, investigate the degree and pattern of genetic control based on the DBH and height of teak provenances, and examine the correlations between growth traits and possibilities for early selection of superior teak provenances.

Table 1: Geographic information for the origin of teak provenances in Myanmar (2010–2019)

Provenance	Coordinates	Altitude (m)	Average annual rainfall (mm)	Average annual temperature (°C)
Bago	18° 07´N; 96° 04´E	134	3405.70	27.56
Kanbalu	23° 30´N; 95° 52´E	274	1157.00	28.48
Nattalin	18° 29´N; 95° 54´E	288	1435.10	28.13
Oaktwin	18° 55´N; 96° 01´E	245	2078.70	26.52
Paukkhaung	19° 07´N; 95° 46´E	293	1046.10	27.46
Phyu	18° 28´N; 96° 20´E	399	2389.60	26.68
Taungoo	19° 04´N; 96° 33´E	126	2020.00	26.68
Thabeikkyin	22° 51´N; 96° 07´E	437	1066.70	26.18

MATERIALS AND METHODS

Location and trial site description

The provenance trial was established in 2007 in compartment 9 of the Ngalaik Reserved Forest, located at a latitude of 19° 56' 16–21’ N and longitude of 95° 56' 30–35’ E (Figure 1). The trial area encompassed mixed deciduous forests in the Bago Yoma region. The topography is generally flat, the area is well-drained, gently flows from east to west, and is surrounded by cultivated and plowed areas. The area comprises yellow-brown forest soil dominated by sandy clay loam texture (Win, 2006). Seeds from selected superior trees of each provenance in the natural stands were collected, germinated in the nursery, and transplanted to the trial site. The design of the established trial was a randomized complete block with five blocks. Each block contained eight plots representing different origins: Bago, Kanbalu, Nattalin, Oaktwin, Paukkhaung, Phyu, Taungoo, and Thabeikkyin. The non-local provenances were Kanbalu and Thabeikkyin (Table 1). Each plot had 25 trees with a spacing of 2.7 m × 2.7 m, representing 125 trees for each provenance, i.e., 1000 trees. The study site covers an area of 1.143 ha. After thinning in 2022, only 498 trees remained at 16 years of age and assessed.

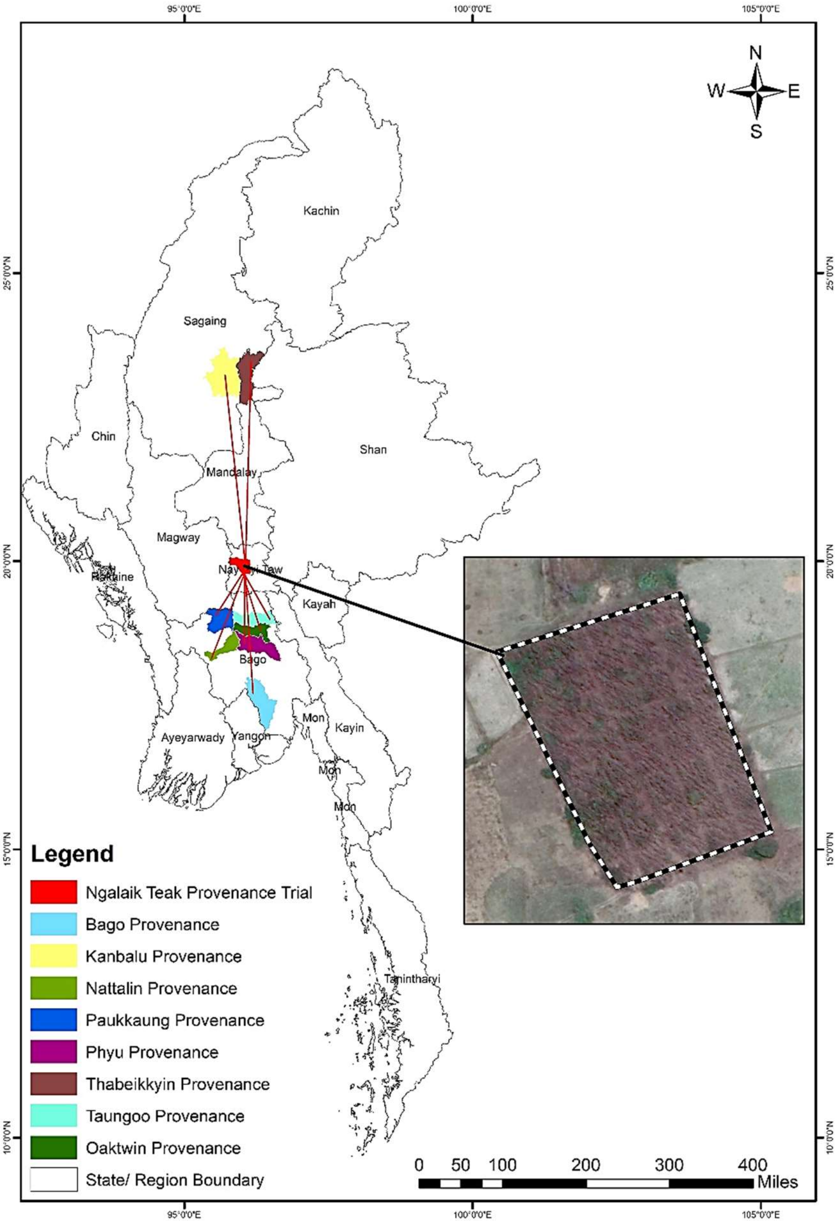

Fig. 1. A map showing the location of the teak provenance trial with eight provenances in Myanmar.

Measurement and estimation of growth and genetic parameters

We measured the phenotypic traits of each tree, such as diameter at breast height (DBH) over the bark and total tree height (H), at the ages of 11, 14, 15, and 16 years. These measurements were identified as DBH_11, DBH_14, DBH_15, and DBH_16 for DBH and H_11, H_14, H_15, and H_16 for heights of different ages, respectively. A diameter tape was used to measure the individual DBH 1.3 m above the ground. Individual height was measured using a graduated pole and a clinometer for taller trees. This study evaluated the mortality of trees in various provenances by comparing the number of dead trees to the total number of trees planted initially.

For the analyses, only (498) trees that survived at age 16 was included, to ensure a balanced number of observations across different ages. Before conducting any analyses, we carefully checked the data to meet the assumptions of normality and homogeneity and removed any outliers. To estimate the individual tree volume (V), we used height and DBH measurements, along with an equation developed by (Cordero and Kanninen, 2003): $V = \frac{\pi}{4} h d^2 f$, where h is the height in meters, d is the DBH in centimeters, and f is the form factor of breast height ($f = 0.45$). The broad-sense heritability, which reflects the total genotypic effects of the provenances, was estimated

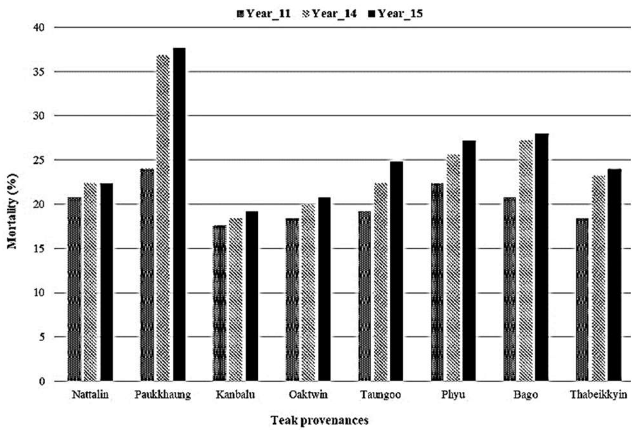

Fig. 2. Mortality (%) of teak provenances at different ages before thinning. Year_11, Year_14, and Year_15 were at age 11, 14, and 15, respectively.

Table 2: Analysis of variance for total tree height, diameter at breast height (DBH), and volume of teak provenances at the trial site in different years.

Source of variation	Df	SS	MS	*F*-value	*P*-value
Height					
Provenance	7	78.597	11.228	8.333	<0.001
Year	3	462.078	154.026	114.309	<0.001
Provenance × year	21	2.104	0.100	0.074	1.000
DBH					
Provenance	7	319.465	45.638	18.355	<0.001
Year	3	560.939	186.980	75.202	<0.001
Provenance × year	21	4.530	0.216	0.087	1.000
Volume					
Provenance	7	0.375	0.054	22.732	<0.001
Year	3	0.939	0.313	132.770	<0.001
Provenance × year	21	0.017	0.001	0.349	0.996

Df, Degree of freedom; SS, Sum of squares; MS, Mean squares. Non-significant at P>0.05, Significant at P<0.001.

as follows: $H_p^2 = \frac{\sigma_p^2}{\sigma_p^2+\sigma_c^2+\sigma_e^2}$, as proposed by (Holland *et al.*, 2010), where σ^2_p is the among provenance variance, σ^2_c is the plot variance, and σ^2_e is the residual variance.

Statistical analysis

For the four years, the growth traits of the different teak provenances were compared using an ANOVA. The linear model was applied to examine variations and interactions of each growth trait among provenances within site: $Y_{ij} = \mu + B_i + P_j + BP_{ij} + \varepsilon_{ij}$, where Y_{ij} is the plot average of the trait in block i of provenance j, μ is the grand mean, B_i is the random effect of block i, P_j is the fixed effect of provenance j, BP_{ij} is the random interaction of block i of provenance j, and ε_{ij} is the residual error. After conducting post-hoc tests, the Scheffe test was used to examine all possible linear combinations of group means and to determine which pair of means differed at the site. Pearson's correlation coefficient was used to test the relationships between all growth traits at different ages. SPSS version 25.0. software was used to analyze the data.

RESULTS

Mortality and growth variation of teak provenances at different ages

The trial began with the first thinning treatment in July 2022. Across the 16-year trial period, nuanced trends in mortality rates emerged, reflecting the interplay between thinning interventions and stand dynamics. Initially, mortality rates remained relatively stable, hovering within the 20–25% range over 11 to 15 years, notwithstanding the ongoing thinning activities (Figure 2). However, rates due to thinning were at age 16, ranging from 48.0% to 52.8% across teak provenances and overall mortality rate at age 16 was 50.2%.

Highly significant differences were found between provenances across years; however, there were no interactions between provenance and year for height (m), DBH (cm), or volume (m^3) (Table 2). The growth performance of teak provenances differed significantly, except at 11 years of age (Table 3). Nattalin (local provenance) showed the best growth performance in terms of DBH, height, and volume among the eight provenances, whereas Thabeikkyin (non-local provenance) consistently showed the poorest results over four years (Table 3, Figure 3). The height for each provenance showed significant differences between ages 11 and 16 years, whereas fewer differences were found between ages 14 and 15 (Figure 3). The mean DBHs for each provenance in different years were not likely to show significant differences between the ages of 14, 15, and 16 (Figure 3). There are likely to be significant differences in the mean volumes for each provenance between the ages of 11 and 16 (Figure 4).

Correlations for growth traits of teak provenances at different ages

Correlations between growth traits of teak provenances at different ages are shown in Table 4. A strong positive correlation exists between height (H) and diameter at breast height (DBH) of teak trees at different ages. The results showed that teak provenances with greater heights also had greater DBHs (Table 4).

Heritability estimates of teak provenances at different ages

The assessment of broad-sense heritability (H_p^2), the genetic variance of provenance means (σ_p^2), and phenotypic variance among provenance means for DBH and teak provenance height were conducted across different ages as outlined in Table 5. Over four consecutive years, the variance components attributed to height replication decreased from 6.44 to 3.85, indicating reduced variability over time. However, the variance components attributable to replication demonstrated an

Table 3: Least square means of total tree height, diameter at breast height (DBH), and volume for teak provenances at different ages.

Name of Provenance	No. of trees	Height (m) on ages				DBH (cm) on ages				Volume (m^3) on ages			
		11	14	15	16	11	14	15	16	11	14	15	16
Bago	59	14.91^{ns}	16.9^{ab}	18.46^{ab}	19.95 ^{ab}	19.38^{a}	23.01^{a}	24.11^{a}	24.62^{a}	0.21^{a}	0.33^{a}	0.40^{a}	0.45^{a}
Kanbalu	62	15.58^{ns}	17.50^{ab}	18.63^{ab}	20.16^{a}	19.05^{a}	22.12^{ab}	23.31^{ab}	23.81^{ab}	0.21^{a}	0.31^{ab}	0.37^{ab}	0.42^{a}
Nattalin	62	16.03^{ns}	18.12^{a}	19.36^{a}	20.42^{a}	20.06^{a}	23.18^{a}	24.16^{a}	24.57^{a}	0.25^{a}	0.37^{a}	0.42^{a}	0.47^{a}
Oaktwin	64	14.77^{ns}	16.62^{ab}	17.86^{ab}	19.23^{ab}	17.59^{ab}	20.79^{ab}	21.85^{ab}	22.36^{ab}	0.17^{ab}	0.27^{ab}	0.32^{ab}	0.36^{ab}
Paukkhaung	60	14.34^{ns}	16.36^{ab}	17.77^{ab}	19.15^{ab}	19.21^{a}	21.48^{ab}	22.86^{ab}	23.24^{ab}	0.20^{ab}	0.28^{ab}	0.35^{ab}	0.39^{ab}
Phyu	63	15.11^{ns}	17.00^{ab}	18.56^{ab}	19.94^{ab}	19.10^{a}	22.76^{a}	23.88^{a}	24.25^{ab}	0.20^{ab}	0.33^{a}	0.39^{a}	0.44^{a}
Taungoo	65	15.04^{ns}	17.00^{ab}	18.18^{ab}	19.56^{ab}	18.08^{ab}	21.59^{ab}	22.63^{ab}	23.05^{ab}	0.18^{ab}	0.29^{ab}	0.34^{ab}	0.38^{ab}
Thabeikkyin	63	13.68^{ns}	15.59^{b}	16.76^{b}	17.88^{b}	15.19^{b}	18.46^{b}	19.60^{b}	20.10^{b}	0.12^{b}	0.20^{b}	0.24^{b}	0.27^{b}
Mean		**14.93**	**16.90**	**18.20**	**19.54**	**18.46**	**21.67**	**22.8**	**23.25**	**0.19**	**0.30**	**0.35**	**0.40**
SD		**0.72**	**0.75**	**0.77**	**0.80**	**1.53**	**1.54**	**1.52**	**1.50**	**0.04**	**0.05**	**0.06**	**0.06**
P value		**ns**	**	**	**	**	**	**	**	***	***	***	***

Note: SD denotes the standard deviation. Significant difference at the 5% level by Scheffé's post-hoc test for teak provenances.
Significance levels: ns, non-significant; * P<0.05, ** P<0.01, *** P<0.001.

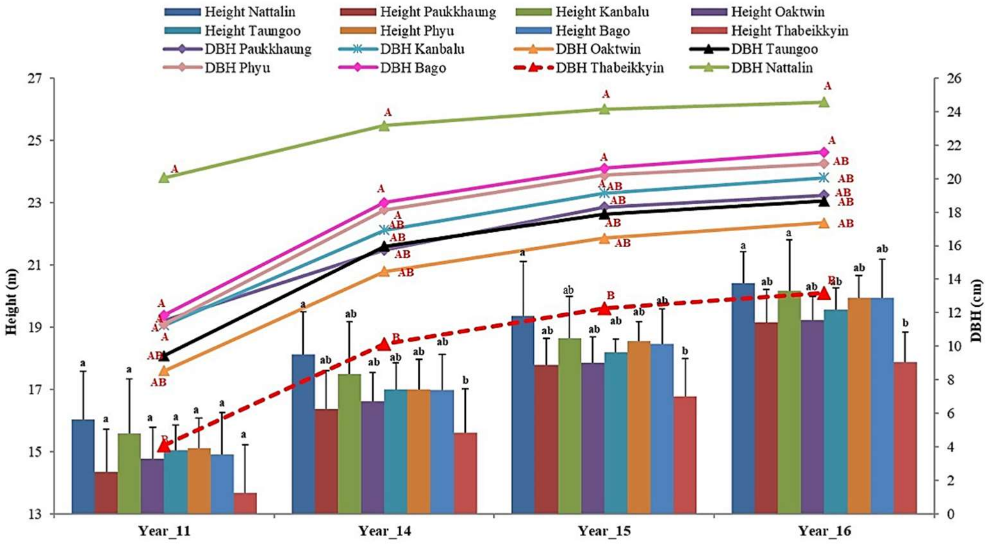

Fig.3. Performance of mean tree heights (H) in meters and diameters at breast height (DBH) in centimeters depending on the different ages and applied teak provenances. Year_11, Year_14, Year_15, and Year_16 were ages 11, 14, 15, and 16 years, respectively. The bars are standard errors. Data bearing identical letters (A & B for DBH, a & b for H) are not significantly different (P<0.05) by Scheffé's post-hoc test for teak provenances.

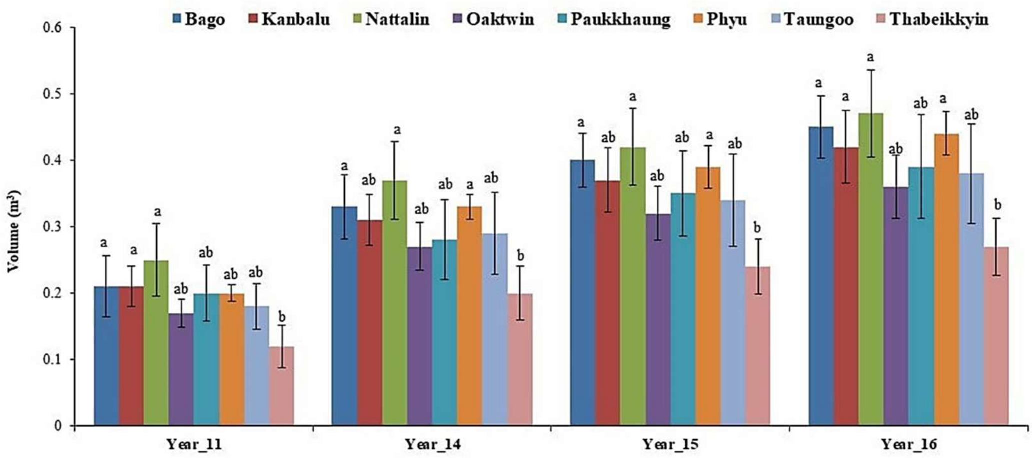

Fig. 4. Volume (m^3) performance for each teak provenance at different ages. Year_11, Year_14, Year_15, and Year_16 were ages 11, 14, 15, and 16 years, respectively. Data bearing identical letters (a & b) are not significantly different (P<0.05) by Scheffé's post-hoc test for teak provenances.

Table 4: Correlation coefficient between mean growth performances of traits measured at different ages of teak provenances.

	H_11	H_14	H_15	H_16	DBH_11	DBH_14	DBH_15	DBH_16	V_11	V_14	V_15	V_16
H_11	1	0.99**	0.93**	0.88**	0.35*	0.32*	0.27ns	0.26ns	0.65**	0.61**	0.51**	0.48**
H_14		1	0.95**	0.90**	0.36*	0.34*	0.29ns	0.28ns	0.64**	0.63**	0.54**	0.50**
H_15			1	0.93**	0.39*	0.36*	0.31*	0.30ns	0.63**	0.62**	0.56**	0.52**
H_16				1	0.46**	0.42**	0.37*	0.36*	0.67**	0.66**	0.60**	0.60**
DBH_11					1	0.95**	0.95**	0.95**	0.92**	0.90**	0.94**	0.94**
DBH_14						1	0.99**	0.99**	0.86**	0.93**	0.97**	0.97**
DBH_15							1	0.99**	0.84**	0.90**	0.95**	0.95**
DBH_16								1	0.83**	0.90**	0.95**	0.95**
V_11									1	0.95**	0.93**	0.93**
V_14										1	0.98**	0.98**
V_15											1	0.99**
V_16												1

0 0.5 1

Note: **. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed). ns. Correlation is not significant at 0.05 level (2-tailed) H_11- H_16: mean tree heights (H) at 11, 14, 15, and 16 years; DBH_11- DBH_16: mean diameter at breast height (DBH) at 11, 14, 15, and 16 years; V_11- V_16: mean volumes (V) at 11, 14, 15, and 16 years.

Table 5: Analysis of variance component and heritability estimates for tree height and DBH of eight teak provenances over age trends.

Source of variance	Height (m) on Ages				DBH (cm) on Ages			
	11	14	15	16	11	14	15	16
$σ^2_c$ (plot variance)	6.44	5.55	3.53	3.85	1.21	2.1	2.63	2.99
$σ^2_p$ (provenance variance)	2.58	2.81**	2.93**	3.21**	11.65**	11.86**	11.56**	11.20**
$σ^2_e$ (residual variance)	1.11	0.96	0.63	0.70	2.17	2.51	2.77	2.65
$σ^2_p / σ^2_e$	2.32	2.94	4.66	4.59	5.37	4.73	4.17	4.23
$σ^2_c + σ^2_e$ (environmental components of variance)	7.56	6.51	4.16	4.55	3.38	4.61	5.40	5.64
H^2 (heritability)	0.25	0.30	0.41	0.41	0.78	0.72	0.68	0.67
Mean value of the trait	14.93	16.90	18.20	19.54	18.46	21.67	22.8	23.25
$CV = \frac{\sqrt{\sigma_e^2}}{mean\ Ht}$, $CV = \frac{\sqrt{\sigma_e^2}}{mean\ DBH}$	0.07	0.06	0.04	0.04	0.08	0.07	0.07	0.07

**Significant at the 1% level of probability (*P*<0.01), CV: coefficient of variation. $σ^2c$ is the plot variance, $σ^2p$ is the among provenance variance, $σ^2e$ is the residual variance, H^2 is the broad-sense heritability, CV is the coefficient of variance, H is total tree height, and DBH is the diameter at breast height.

intriguingly contrasting trend for DBH from 1.21 to 2.99. Regarding genetic variance, height did not exhibit high significance among the different provenances in the 11th year, whereas DBH was highly significant in all ages. The absolute values of genetic variance for height increased from the 11th year to the 16th year, whereas the values of genetic variance for DBH decreased with age.

The environmental components of variance were 7.56, 6.51, 4.16, and 4.54 for height and 3.38, 4.61, 5.40, and 5.64 for DBH, indicating that they decreased with height but increased with DBH. The height of teak provenances showed a moderate genetic influence, with heritability ranging from 0.25 to 0.41, and increased with age. DBH also showed high genetic control, with values of 0.78, 0.72, 0.68, and 0.67, respectively, indicating that it decreased with age.

DISCUSSION

Ecological characteristics

Our study found that local teak provenances, specifically those from Bago, Phyu, and Paukkhaung, exhibited higher growth rates compared to other local provenances. Among these, Nattalin demonstrated the best growth performance, coupled with a relatively low mortality rate of approximately 20% prior to the thinning treatment. In contrast, Kanbalu, a non-local provenance, exhibited higher growth rates compared to the local provenances and consistently lower mortality rates across various ages, indicating strong adaptability to the study environment. This adaptability represents a critical characteristic of teak, contributing significantly to its survival and growth in various environments. Nevertheless, the growth rates observed in this study were lower than those reported for teak provenances of similar age in the Forest Research Institute Malaysia (FRIM). Teak, a species known for its preference for light-demanding, exhibits remarkable adaptability. This adaptability represents a critical characteristic of teak, contributing significantly to its survival and growth in various environments. Noteworthy is the consistent observation of mortality rates below 30% for trees aged 11 to 15 throughout the trial, showing the resilience of younger trees. A discernible inflection point was noted at the 16-year age, where rates experienced a pronounced increase to 50.2%, indicating the cumulative impact of thinning practice. The study suggested that most local provenances generally exhibit better growth rates than non-local provenances; however, non-local provenances show lower mortality rates. Furthermore, the findings indicated that while local provenances may have a higher growth rate, they also have a higher mortality rate, suggesting a potential trade-off between growth and survival. Notably, the Nattalin (local) provenance exhibited the most substantial growth across all measurement ages, followed by Bago (local), Phyu (local), and Kanbalu (non-local). In contrast, the Thabeikkyin (non-local) provenance demonstrated the most diminutive adaptation. Referring to the literature data, assessment ages from 11 to 16 could all be considered "young teak" in the context of the rotation of plantation teak species for commercial purposes between 50 and 60 years. Therefore, most teak provenances in this study with better growth performance and lower mortality would be assumed to have shorter rotations among all provenances. Specifically, after thinning treatment, it increases its sun foliage within the crown canopy, promoting its height growth (Lowe, 1976; Pokorný *et al*., 2008). Additionally, the findings revealed significant differences in the measured growth traits, such as DBH, height, and estimated volume among provenances and ages. Therefore, further assessments, including growth data from older ages, would be beneficial even after selective thinning for substantial measurements.

Age-age genetic correlations and time trends in heritability are meaningful results for applied tree improvement programs because they enable breeders to decide when selection can be undertaken most effectively and efficiently (Lambeth, 1980; Osorio *et al*., 2003; White *et al*., 2007). Our study found that broad-sense heritability for height increased during the study period, whereas that for DBH decreased. The broad-sense heritability was moderate to high, indicating the potential for improving teak growth through tree breeding programs for advanced generations. In addition, high heritability allows for greater dynamism in breeding programs, enabling the recombination of desirable individuals within a shorter period (Santos *et al*., 2014). Furthermore, other studies have reported that some tropical species show lower heritability for height than for DBH (Maid and Bhumibhamon, 2009; Nirsatmanto, 2012; Naiem and Purnomo, 2014); however, some studies have reported that individual heritability for height was higher than that for DBH (Hodge *et al*., 2002; Rochon *et al*., 2007; Sotelo *et al*., 2007). Our study revealed that as teak trees aged, the absolute values of error variance in DBH increased, whereas they decreased with height. As the trees aged, the relative sizes of the environmental components increased, whereas genetic variance among the provenances decreased. However, the opposite was true for height, as the relative size of the environmental components decreased and the genetic variance among provenances increased. The assessment of heritability estimates of teak provenances at different ages showed a progressive increase, suggesting a significant and increasing contribution to the overall variance as the study progressed. Therefore, selecting height at older ages of teak provenances at this trial site could result in significant genetic gain as it is under a substantial increase in genetic control.

While studies on age-related changes in the quantitative and qualitative traits of teak species in Myanmar are scarce, this study provides data on quantitative growth traits from a single teak provenance trial in Myanmar over a period of 16 years. The results indicated that growth traits were genetically controlled and adaptive growth differences existed among teak provenances. Therefore, these traits can be improved by selection. Because the heritability index for height increases with plant age, selecting this trait in older plants may provide a stronger genetic correlation with desirable growth traits than selecting it in younger plants.The higher heritability of DBH at younger ages suggests that it may be a strong predictor of early selection. Thus, the findings may assist in selecting superior teak trees for the first generation of future tree improvement programs. Therefore, we recommend that selecting superior trees from high-performance provenances, except for Thabeikkyin (non-local), be effective in maintaining a broad genetic base of teak for future tree improvement programs in the Bago Yoma region of Myanmar.

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LITERATURE CITED

Balakrishnan, S., Ramasamy, Y., Dev, S.A. 2023 An overview of teak genetic improvement towards conservation of genetic resources in a changing climate with special emphasis on India. Tree Genet. Genomes. **19(3)**: 29.

Ball, J., Pandey, D., Hirai, S., Etners, T., Nair, C. 1999 *Global overview of teak plantations* Regional Seminar Site, Technology and Productivity of Teak Plantations Chiang Mai, Thailand.

Brancalion, P.H., Niamir, A., Broadbent, E., Crouzeilles, R., Barros, F.S., Almeyda Zambrano, A.M., Baccini, A., Aronson, J., Goetz, S., Reid, J.L., Strassburg, B.B.N., Wilson, S., Chazdon, R.L. 2019 Global restoration opportunities in tropical rainforest landscapes. Sci. Adv. **5(7):** eaav3223.

Cordero, L.D.P., Kanninen, M. 2003 Provisional equations for estimating total and merchantable volume of *Tectona Grandis* trees in Costa Rica. For. Trees Livelihoods. **13(14)**: 345–359.

FAO 2016 UN and Government Partners for the Protection of Myanmar's Forests, Critical for Reducing Climate Change. Food and Agriculture Organization (FAO).

FD 2020 Forestry in Myanmar. Myanmar: Forest Department, Ministry of Natural Resources and Environmental Conservation, Myanmar.

FRA, F. 2015 Global Forest Resources Assessment 2015 Desk reference. Food and agriculture organization of the United Nations, Rome.

Frampton, J. 1996 The tree improvement process. Limbs and Needles. **23**: 10–12.

Hidayati, F., Ishiguri, F., Iizuka, K., Makino, K., Tanabe, J., Marsoem, S.N., Na'iem, M., Yokota, S., Yoshizawa, N. 2013a Growth characteristics, stress-wave velocity, and Pilodyn penetration of 15 clones of 12-year-old *Tectona grandis* trees planted at two different sites in Indonesia. J. Wood Sci. **59(3)**: 249–254.

Hidayati, F., Ishiguri, F., Iizuka, K., Makino, K., Takashima, Y., Danarto, S., Winarni, W.W., Irawati, D., Na'iem, M., Yokota, S. 2013b Variation in tree growth characteristics, stress-wave velocity, and Pilodyn penetration of 24-year-old teak (*Tectona grandis*) trees originating in 21 seed provenances planted in Indonesia. J. Wood Sci. **59(6)**: 512–516.

Hodge, G., Dvorak, W., Urueña, H., Rosales, L. 2002 Growth, provenance effects and genetic variation of *Bombacopsis quinata* in field tests in Venezuela and Colombia. For. Ecol. Manag. **158(1-3)**: 273–289.

Holland, J.B., Nyquist, W.E., Cervantes-Martínez, C. 2010 Estimating and interpreting heritability for plant breeding: An Update. In Janick, J. (ed.) Plant Breeding Reviews. **Vol. 22,** pp. 9–112.

Kaosa-ard, A. 1989 Teak (*Tectona grandis* Linn. f.) - iits natural distribution and related factors. Nat. Hist. Bull. Siam Soc. **29**: 55–74.

Keiding, H., Wellendorf, H., Lauridsen, E.B. 1986 Evaluation of an International Series of Teak Provenance Trials. Danida Forest Seed Centre.

Krishnapillay, B. 2000 Silviculture and management of teak plantations. Unasylva **51**: 14–21.

Kyaw, T.Y., Germain, R.H., Stehman, S.V., Quackenbush, L.J. 2020 Quantifying forest loss and forest degradation in Myanmar's "home of teak". Can. J. For. Res. **50(2)**: 89–101.

Lambeth, C.C. 1980 Juvenile-Mature correlations in Pinaceae and implications for early selection. For. Sci. **26**: 571–580.

Lobo, A., Hansen, J. K., Hansen, L. N., Dahl Kjær, E. 2018 Differences among six woody perennials native to Northern Europe in their level of genetic differentiation and adaptive potential at fine local scale. Ecol. Evol. **8(4)**: 2231–2239.

Lowe, R. 1976 Teak (*Tectona grandis* Linn. f.) thinning experiment in Nigeria. Commonw. For. Rev. **55**: 189–202.

Maid, M., Bhumibhamon, S. 2009 Timor mountain gum improvement program in Eastern Thailand. J. Sustain. Dev. **2(1)**: 176–181.

Mátyás, C. 1994 Modeling climate change effects with provenance test data. Tree Physiol. **14(7-9)**: 797–804.

Maung, T.M., Yamamoto, M. 2008 Exploring the socio-economic situation of plantation villagers: a case study in Myanmar Bago Yoma. Small-Scale For. **7(1)**: 29–48.

Moya, R., Bond, B., Quesada, H. 2014 A review of heartwood properties of *Tectona grandis* trees from fast-growth plantations. Wood Sci. Technol. **48(2)**: 411–433.

Moya, R., Marín, J.D. 2011 Grouping of *Tectona grandis* (Lf) clones using wood color and stiffness. New For. **42(3)**: 329–345.

Naiem, M., Purnomo, S. 2014 Evaluation of four years old progeny test of *Shoreamacrophylla* in PT Sari Bumi Kusuma, Central Kalimantan. Procedia Environ. Sci. **20**: 809–815.

Namkoong, G. 1979 Introduction to Quantitative Genetics in Forestry. United States Department of Agriculture, Forest Service.

Nanson, A. 1958 Perspectives d'amélioration en première génération par sélection des provenances. J. For. **11**: 825.

Nirsatmanto, A. 2012 Genetic variation observed in composite seedling seed orchard of *Acacia mangium* Willd. at Central Java, Indonesia: implications for increasing genetic gain and seed production. Indones. J. For. Res. **9(2)**: 91–99.

Osorio, L., White, T., Huber, D. 2003 Age-age and trait-trait correlations for *Eucalyptus grandis* Hill ex Maiden and their implications for optimal selection age and design of clonal trials. Theor. Appl. Genet. **106(4)**: 735–743.

Pandey, D., Brown, C. 2000 Teak: a global overview. Unasylva **51**: 3–13.

Pokorný, R., Tomášková, I., Havránková, K. 2008 Temporal variation and efficiency of leaf area index in young mountain Norway spruce stand. Eur. J. For. Res. **127(5)**: 359–367.

Prasetyo, E., Widiyatno, Indrioko, S., Na'iem, M., Matsui, T., Matsuo, A., Suyama, Y., Tsumura, Y. 2020 Genetic diversity and the origin of commercial plantation of Indonesian teak on Java Island. Tree Genet. Genomes **16(2)**: 34.

Raddad, E.A.Y. 2007 Ecophysiological and genetic variation in seedling traits and in first-year field performance of eight *Acacia senegal* provenances in the Blue Nile, Sudan. New For. **34(3)**: 207–222.

Rochon, C., Margolis, H.A., Weber, J.C. 2007 Genetic variation in growth of *Guazuma crinita* (Mart.) trees at an early age in the Peruvian Amazon. For. Ecol. Manag. **243(2-3)**: 291–298.

Rweyongeza, D.M. 2011 Pattern of genotype–environment interaction in *Picea glauca* (Moench) Voss in Alberta, Canada. Ann. For. Sci. **68(2)**: 245–253.

Rweyongeza, D.M., Yeh, F.C., Dhir, N.K. 2003 Genetic variation in stem growth components in white spruce seedlings and its implications to retrospective early selection. For. Gen. **10(4)**: 299–308.

Santos, A.M., Rosado, S.C.D.S., Oliveira, A.N. 2014 Estimation of genetic parameters and verification of early selection efficiency in baru (*Dipteryx alata*). Crop Breed. Appl. Biotechnol. **14(4)**: 238–243.

Sotelo, C., Beaulieu, J., Hernandez, R. 2007 Genetic variation in wood shrinkage with tree growth and wood density of *Calycophyllum spruceanum* at an early age in the Peruvian Amazon. Can. J. For. Res. **37(5)**: 966–976.

Stöcklin, J., Kuss, P., Pluess, A. 2009 Genetic diversity, phenotypic variation and local adaptation in the alpine landscape: case studies with alpine plant species. Bot. Helv. **119(2)**: 125–133.

Su Mon, M., Mizoue, N., Htun, N. Z., Kajisa, T., Yoshida, S. 2012 Estimating forest canopy density of tropical mixed deciduous vegetation using Landsat data: a comparison of three classification approaches. Int. J. Remote Sens. **33(4)**: 1042–1057.

Suzuki, R., Takeda, S., Keh, S.K. 2004 The impact of forest fires on the long-term sustainability of taungya teak reforestation in Bago Yoma, Myanmar. Tropics **14(1)**: 87–102.

The Angiosperm Phylogeny Group 2009 An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants: APG III. Bot. J. Linn. Soc. **161(2)**: 105–121.

Wanders, T. H., Ofori, J. N., Amoako, A., Postuma, M., Wagemaker, C. A., Veenendaal, E. M., Vergeer, P. 2021 Teak genetic diversity in Ghana shows a narrow base for further breeding and a need for improved international collaboration for provenance exchange. J. Genet. Resour. **2(4)**: 44–54.

Wellendorf, H., Kaosa-ard, A., Arboretet, K.V.-o. L. 1988 Teak Improvement Strategy in Thailand. Teak Improvement Centre, Royal Forest Department Ngao.

White, T.L., Adams, W.T., Neale, D.B. 2007 Forest Genetics. Cabi.

Win, B.N. 2006 Surface Soil Wash due to Forest Degradation in Ngalaik Watershed Area. Myanmar: Forest Research Institute, Forest Department, Ministry of Natural Resources and Environmental Conservation.

Zin, A.T. 2000 Potentialities and constraints of teak bearing forest for sustainable forest management under current management system in Oattwin Township forest, Bago Yoma Region, Myanmar [M.Sc. Thesis, Dresden Technical University, Tharandt, Germany].