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RESEARCH ARTICLE

Yield model and yield table construction in farm grown teak (*Tectona grandis* Linn. F) under different agroclimatic zones of Tamil Nadu, India

S Navaneetha Krishnan[1], A Balasubramanian[1*], M Sivaprakash[1], R Ravi[2], B Sivakumar[1], C N Hari Prasath[1], G Swathiga[1], V Manimaran[1] & K S Anjali[1]

[1]Department of Silviculture & NRM, Forest College and Research Institute, Mettupalayam 641 301, Coimbatore, India

[2]Department of Forest Products and Wildlife, Forest College and Research Institute, Mettupalayam 641 301, Coimbatore, India

*Email: balasubramanian.a@tnau.ac.in

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Abstract

The market value of *Tectona grandis* has significantly increased due to the growing demand for its high quality wood. Known for its versatile applications, *Tectona grandis* is commonly cultivated in block and boundary formations across communal lands. A field study was conducted across four agro-climatic zones of Tamil Nadu, namely the North Eastern Zone (NEZ), North Western Zone (NWZ), Cauvery Delta Zone (CDZ) and Western Zone (WZ), covering three different age classes across 120 farm-grown plantations. Biometric parameters of the trees, including height and diameter at 2-m intervals, were recorded using a tree telescope. The collected data was processed and Multiple Linear Regression (MLR) analysis was applied to develop a yield model, enabling the construction of accurate yield tables for *Tectona grandis* without relying on a form factor. The following yield models were developed for the respective zones: NEZ as Y_1= -0.291 + (0.002*Age) + (0.026**Mid diameter) + (0.010**Height), NWZ as Y_2= -0.163 - (0.012** Age) + (0.028** Mid diameter) + (0.009** Height), CDZ as Y_3= -0.343 - (0.001 Age) + (0.023** Mid diameter) + (0.024** Height) and WZ as Y_4= -0.187 - (0.002 Age) + (0.051** Mid diameter) - (0.036** Height). The key finding of this study is that the growth of *Tectona grandis* varies significantly across different agro-climatic zones. This variation can be effectively monitored using statistically constructed yield tables, which provides a valuable tool for the sustainable management of *Tectona grandis* plantations.

Keywords

age class; agroclimatic zones; farmland; *Tectona grandis*; volume; yield model

Introduction

Teak (*Tectona grandis* Linn. F), a member of the family Lamiaceae, is often referred to as the "King of Timber" (1) and is recognised as one of the most prominent and highly sought-after hardwood species worldwide (2-4). Due to its superior timber quality, high market demand and ease of domestication and cultivation, extensive *Tectona grandis* plantations have been established across tropical regions since the 1850s. The natural range of *Tectona grandis* is predominantly distributed across South and South-east Asia, which contributes for more than 90 percent of the world's *Tectona grandis* resources (5).

India, in particular, harbors approximately 1.68 M ha *Tectona grandis* plantation and 6.8 M ha of natural *Tectona grandis* forests (6), contributing around 45 % of the global *Tectona grandis* resources. But ironically, India remains a net importer of *Tectona grandis,* with an annual domestic production of only about 0.25 M cu.m (7), far below the annual demand of 100 cu.m (8, 9). Globally, India ranks first in *Tectona grandis* consumption, with 70 to 100 % of its requirements being met through imports from Africa and Latin America (7, 10).

To address the increasing global demand for teakwood, achieving higher production outputs within shorter rotation period has become essential. However, the growth biometry and volume production of *Tectona grandis* under varying edapho-climatic conditions remain poorly understood. This lack of comprehensive information hinders the development of yield tables for identifying suitable regions to support the successful cultivation of *Tectona grandis*.

Yield prediction models in tree plantations are crucial for sustainable management, enabling tree growers to make informed decisions regarding timber harvest planning, inventory management and ecosystem conservation (11, 12). These models estimate the future growth and yield of plantation stands based on various factors such as species composition, site characteristics, management practices and environmental conditions (13, 14). Several approaches and techniques are used to develop yield prediction models in farm grown tree plantations, including statistical models, process-based models and machine learning methods (15).

In both even-aged and uneven-aged plantations, yield models typically consist of equations that relate tree yield to factors such as age, diameter, volume, as well as climatic, soil (edaphic) and topographical parameters (16). By using suitable inventory and other resource data, managers and scholars can predict future yields through the construction of species-specific yield prediction models and recommend optimal silvicultural strategies for managing plantations (17). Among these methods, MLR analysis is extensively used in tree crops to estimate growth production, rate of tree taperness, biomass estimation, yield prediction and other factors (18).

Yield tables are traditionally created through the process of form factor construction, which involves destructive analysis (11). In this study, tree diameters at different heights were measured non-destructively using a laser distance meter, commonly called to as a tree telescope. This method allows for the computation of volume in 2-m billets, offering a significant advantage in the development of yield tables for tree crops, though it remains underutilized.

Yield prediction models for farm-grown trees have been explored for species such as *Azadirachta indica*, *Albizia lebbeck*, *Ailanthus excelsa*, *Melia dubia* and *Casuarina equisetifolia* (19-22). However, the validation of these established yield models has generally been under prioritized in forestry species. Moreover, systematic studies to understand the growth biometry, yield variations and yield prediction models of farm-grown *Tectona grandis* under different agroclimatic zones are clearly missing.

The present study, therefore, focused to address this gap by providing scientific information into the growth patterns and yield variations of *Tectona grandis* across different agroclimatic zones of Tamil Nadu, with a focus on three distinct age classes. The analysis emphasizes parameters such as height, mid-diameter, clear bole and total volume to develop robust yield prediction models for sustainable management.

Materials and Methods

Study area

Tectona grandis plantations established on farmland were surveyed across four agro-climatic zones in Tamil Nadu (Fig. 1): the North Eastern Zone (NEZ), North Western Zone (NWZ), Cauvery Delta Zone (CDZ) and Western Zone (WZ) (Table 1).

Data consolidation, analysis and computation were performed using IBM SPSS (Statistical Package for the Social Sciences) and the Agricolae package in the R environment (23) at the Forest College and Research Institute, Mettupalayam, Tamil Nadu.

Volume estimation

The growth of *Tectona grandis* tree was evaluated by measuring biometric attributes, including tree height (m), clear bole height (m) and the diameter of 2-m segments of the main bole from ground level up to the clear bole height. These measurements were taken using a Leica DISTO™ D810 laser distance meter and categorized across three age classes: 5-10 years, 10-15 years and 15-20 years.

Table 1. Study zones and district wise *Tectona grandis* resources

S.No	Zone	District covered
Zone 1	North eastern zone (NEZ)	Thiruvannamalai, Vellore, Ranipet, Thiruvallur
Zone 2	North western zone (NWZ)	Kallakurichi, Krishnagiri, Salem, Namakkal
Zone 3	Cauvery delta zone (CDZ)	Trichy, Thanjavur, Perambalur
Zone 4	Western Zone (WZ)	Coimbatore, Erode

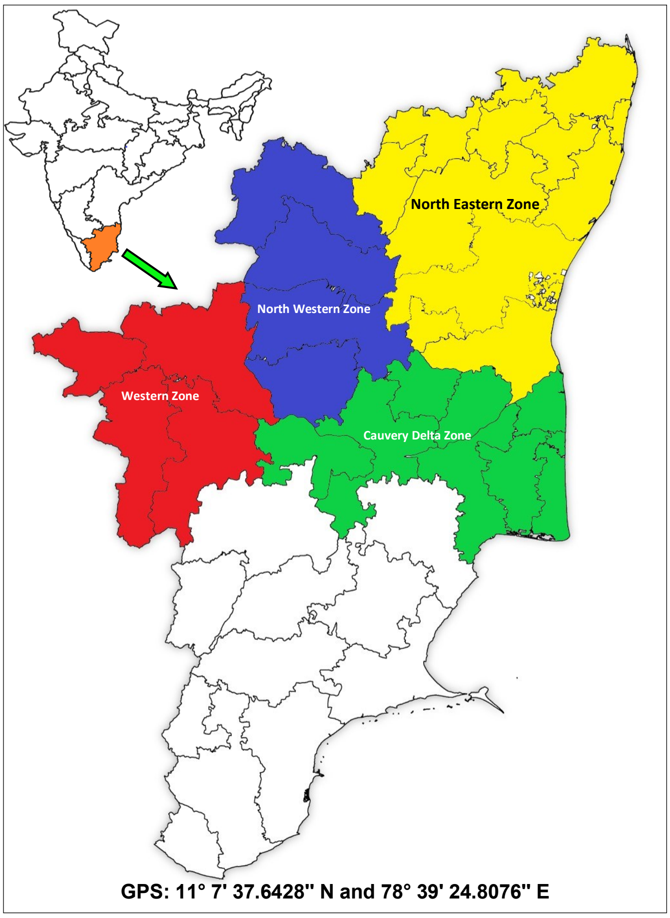

Fig. 1. Location of study area.

The volume of each 2-m section was calculated using the formula provided by Chaturvedi and Khanna (1982) (Eqn. 1) and is expressed in cubic meters per tree (m^3/tree).

$$V = \pi r^2 h \quad \text{........(Eqn.1)}$$

Where, V = Volume, r = Radius at mid-point (m) and h = bole height (m)

Estimation of total volume

The total volume of the tree was determined by summing the volumes of all 2-m segments from the base to the tip of the crown (Eqn. 2). This approach minimizes errors commonly associated with volume estimation using form factors by accurately accounting for the tapering of the standing tree.

$$V = V1 + V2 + V3 + \ldots + Vn \quad \text{........(Eqn.2)}$$

Where, V = Total tree volume (m^3), V1, V2, V3, Vn = Volume at each 2-m segments (m3)

Yield model and yield table construction

The linear multiple regression method was employed to model the relationship between the dependent and independent variables (24). In the present study, the independent variables included the age of the tree, total height and mid-diameter, while the total volume served as the dependent variable. The general equation (Eqn. 3) developed through linear multiple regression is as follows:

$$Y = a + b_1x_1 + b_2x_2 + b_3x_3 \ldots\ldots + b_nx_n \quad \text{........(Eqn.3)}$$

Where, Y - Yield (m^3), a - intercept, x_1- age of the tree (years), x_2 - Mid Diameter (m), x_3 - Height of trees (m) and b_1, b_2, b_3- Coefficients of b_1 and b_2

Validation of yield models

The developed yield models were validated using residual plot analysis (25). A separate set of biometric data, collected from the study area, was used for validation. These validation data were not included in the development of the yield model. The actual volume for the selected biometric data was calculated using the total volume estimation methodology, while the predicted volume was computed using the developed model. A regression analysis was performed between the actual and predicted volumes to validate the model. The closer the residual sum of squares is to zero, the better the model fits the original data. Additionally, a chi-square test for goodness of fit was conducted to assess the consistency of the developed yield model. If the p-value from this test was greater than the significance level (0.01), the model was considered valid for all independent data.

Results and Discussion

Yield model and yield table for Tectona grandis

Yield models are mathematical functions that establish relationship between yield and factors such as stand age, site index and stand density. The developed yield model for *Tectona grandis* has proven to be effective, reliable and widely applicable to farm plantations. These models and the accompanying yield table were formulated using biometric attributes, including age, total height and mid-diameter of the trees. The multiple linear regression method was employed to develop both the yield model and the yield table for *Tectona grandis* (22).

The yield model for *Tectona grandis* was created using volume data from three distinct age classes (5-10 years, 10-15 years and 15-20 years) across four agro-climatic zones in Tamil Nadu. The model for farm-grown *Tectona grandis* was constructed using multiple linear regression analysis, a methodology similar to that used by Sefidi to estimate forest stand volume and tree density in northern Iran (26).

Yield models for farm grown *Tectona grandis*:

1) NEZ: Y_1= -0.291 + (0.002*Age) + (0.026**Mid diameter) + (0.010**Height)
2) NWZ: Y_2= -0.163 - (0.012** Age) + (0.028** Mid diameter) + (0.009** Height)
3) CDZ: Y_3= -0.343 - (0.001 Age) + (0.023** Mid diameter) + (0.024** Height)
4) WZ: Y_4= -0.187 - (0.002 Age) + (0.051** Mid diameter) - (0.036** Height)

The predicted yield model for *Tectona grandis*, based on these equations, is presented in Table 2 and compared with the actual measured volume. The yield table for *Tectona grandis* was developed for three age classes: 5-10 years, 10-15 years and 15-20 years. By segmenting the age into 5-year intervals, farmers can effectively monitor growth and implement timely management interventions to optimize both productivity and economic returns.

Validation of yield model for Tectona grandis

The yield model developed for *Tectona grandis* was utilized to predict tree yield across different age classes. Pooled data were used to construct the yield model through the multiple linear regression methodology. For any predictive model, accuracy must be verified using field data to ensure reliability.

In the present study, the yield model for *Tectona*

Table 2. Multiple linear regression analysis for the prediction of volume of *Tectona grandis*

Variables	Regression coefficient			
	NEZ (Y_1)	NWZ (Y_2)	CDZ (Y_3)	WZ (Y_4)
Intercept (a)	-0.291	-0.163	-0.343	-0.187
Age (Years) (X_1)	0.002	-0.012**	-0.001	-0.002
Mid diameter (m) (X_2)	0.026**	0.028**	0.023**	0.051**
Height (m) (X_3)	0.010**	0.009**	0.024**	-0.036**
R^2	0.883	0.894	0.909	0.936

NEZ - North eastern zone; **NWZ** - North western zone; **CDZ** - Cauvery delta zone; **WZ** - Western zone.

Regression equations: **1**) Y_1= -0.291 + 0.002X_1 + 0.026**X_2 + 0.010**X_3, **2**) Y_2= -0.163 - 0.012**X_1 + 0.028**X_2 + 0.009**X_3, **3**) Y_3= -0.343 - 0.001X_1 + 0.023**X_2 + 0.024**X_3, **4**) Y_4= -0.187 - 0.002X_1 + 0.051**X_2 - 0.036**X_3, **Regression coefficient is significant at 1% level.

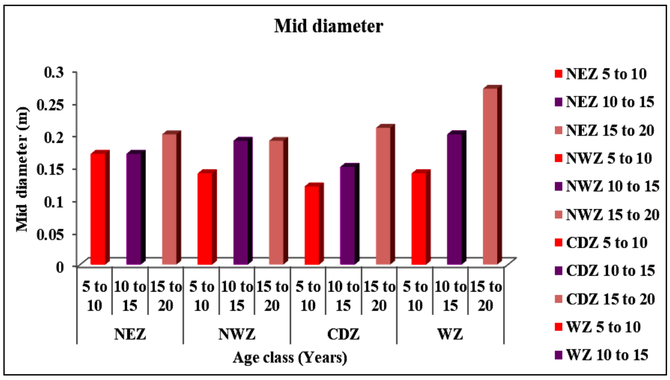

Fig. 2. Diameter increment in *Tectona grandis* with the relation of age-class. **NEZ** - North Eastern Zone, **NWZ** - North Western Zone, **CDZ** - Cauvery Delta Zone, **WZ** – Western Zone.

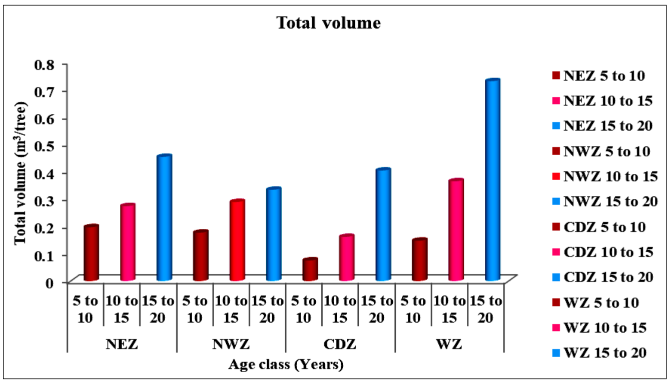

Fig. 3. Volume increment in *Tectona grandis* with the relation of age-class. NEZ - North Eastern Zone, **NWZ** - North Western Zone, **CDZ** - Cauvery Delta Zone, **WZ** – Western Zone.

grandis was validated using field data and appropriate statistical tools and techniques (Fig. 2 and 3). Yield models constructed for *Tectona grandis* were validated using the chi-square test and residual plots of the predicted volume. An independent data were collected and analysed to assess the efficiency of the predicted models (Fig. 4).

Validation of yield model for Tectona grandis in NEZ

Biometric data from *Tectona grandis* plantations aged 5-10 years were used to validate the yield model. Key biometric observations *viz.,* tree height and mid-diameter, were used to compute the actual volume of 5-10 years *Tectona grandis* trees (Table 3). The results of the current study revealed that the predicted volume from the yield model was 0.1849 m^3/tree, whereas the actual volume was 0.1318 m^3/tree, with residual mean sum of square of 0.003.

For the age class of 10-15 years, the actual volume of *Tectona grandis* was 0.2581 m^3/tree, while the predicted volume derived from the yield model was 0.2891 m^3/tree, resulting in a 3 % deviation. The residual mean sum of squares for the yield model was observed to be 0.003 (Table 4).

In the age class of 15-20 years, the actual volume was recorded as 0.5900 m^3/tree, compared to the predicted volume of 0.4911 m^3/tree, accounting for a 9 % deviation, with a residual mean sum of squares of 0.003 (Table 5).

Validation of yield model for Tectona grandis in NWZ

In the North Western Zone (NWZ), the actual volume observed for Tectona grandis in the age class of 5-10 years was 0.1990 m^3/tree, while the predicted volume from the yield model was 0.2483 m^3/tree, showing a 4 % deviation from the actual volume. The residual mean sum of squares for the yield model was calculated to be 0.003 (Table 3).

For the age class of 10-15 years, the actual volume determined using field data was 0.3530 m^3/tree, compared to the predicted volume of 0.2957 m^3/tree, resulting in a 5 % deviation from the actual volume. The residual mean sum of squares for the yield model was also 0.003, with the residuals distributed normally (Table 4).

In the age class of 15-20 years, the actual volume recorded was 0.3085 m^3/tree, while the predicted volume was 0.3279 m^3/tree, accounting for a 2 % deviation (Table 5).

Validation of yield model for Tectona grandis in CDZ

The actual volumes recorded were 0.0809 m^3/tree,

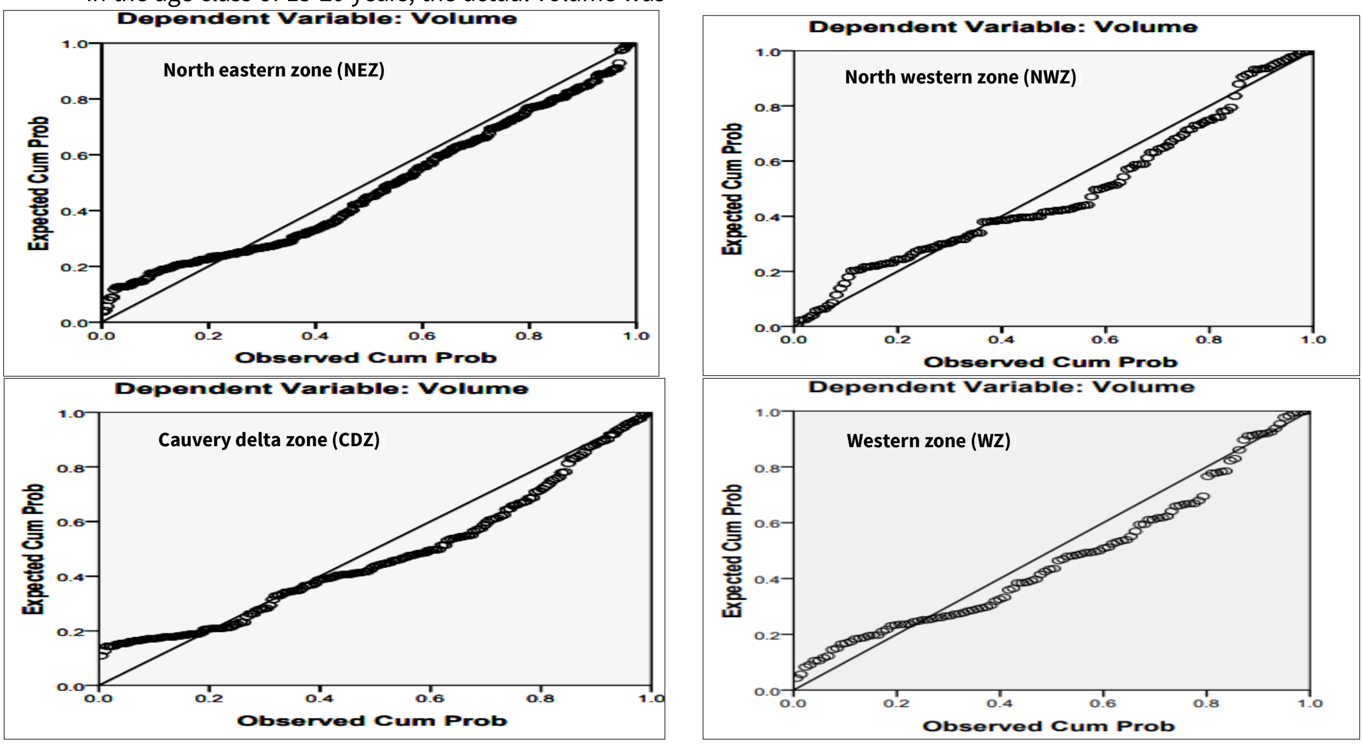

Fig. 4. Relationship between actual and predicted diameter in *Tectona grandis* plantations.

0.1583 m^3/tree and 0.3298 m^3/tree for the age classes of 5-10 years (Table 3), 10-15 years (Table 4) and 15-20 years (Table 5), respectively.

In contrast, the predicted volumes derived from the yield model for the respective age classes were 0.0976 m^3/tree, 0.2036 m^3/tree and 0.3364 m^3/tree. The residual mean sum of squares for the yield model was calculated to be 0.002 for the Cauvery Delta Zone (CDZ).

Validation of yield model for Tectona grandis in WZ

For *Tectona grandis*, the actual volume recorded in age class of 5-10 years was 0.0528 m^3/tree (Table 3), while the predicted volume was estimated to be 0.0553 m^3/tree, with residual mean sum of square of 0.005. In the age classes of 10-15 years (Table 4) and 15-20 years (Table 5), the actual volume were observed as 0.4229 m^3/tree and 0.8301 m^3/tree, respectively. In comparison, the predicted volumes for these age classes were 0.4711 m^3/tree and 0.8086 m^3/tree, respectively, with the residual mean sum of square also recorded as 0.005.

A study on yield model construction for *Ailanthus excelsa* in the Cauvery delta zone of Tamil Nadu, incorporating tree age, height and mid-diameter as predictor variables (21). Similar studies on yield model development using branch

Table 3. Validation of yield model in *Tectona grandis* of 5-10 years

Zone	Age (Years)	Mid diameter (m)	Height (m)	Actual Volume (m^3/tree)	Predicted Volume (m^3/tree)
NEZ (Y_1)	7	0.16	8.6	0.1678	0.2189
	7	0.12	9.1	0.1030	0.1262
	7	0.14	8.7	0.1311	0.1702
	8	0.16	6.5	0.1351	0.2131
	8	0.16	6.3	0.1219	0.1962
Mean				0.1318	0.1849
NWZ (Y_2)	5.5	0.16	8.3	0.1600	0.2111
	5.5	0.13	8.7	0.1234	0.1694
	8	0.20	10.8	0.3252	0.3587
	8	0.15	10.7	0.1963	0.2574
	8	0.16	9.7	0.1900	0.2451
Mean				0.1990	0.2483
CDZ (Y_3)	7	0.11	7.6	0.0776	0.0946
	7	0.12	6.3	0.0747	0.0839
	8	0.15	5.4	0.0898	0.1133
	8	0.15	5.1	0.0867	0.1098
	8	0.14	5.2	0.0755	0.0866
Mean				0.0809	0.0976
WZ (Y_4)	5	0.11	7.5	0.0662	0.0741
	5	0.10	7.6	0.0585	0.0343
	5	0.09	6.8	0.0481	0.0422
	6	0.09	6.3	0.0434	0.0516
	6	0.10	6.3	0.0476	0.0745
Mean				0.0528	0.0553

NEZ - North eastern zone; **NWZ -** North western zone; **CDZ** - Cauvery delta zone; **WZ** - Western zone.

Table 4. Validation of yield model in *Tectona grandis* of 10-15 years

Zone	Age (Years)	Mid diameter (m)	Height (m)	Actual Volume (m^3/tree)	Predicted Volume (m^3/tree)
NEZ (Y_1)	11	0.15	7.7	0.1366	0.1988
	11	0.19	8.9	0.2534	0.3152
	11	0.14	7.4	0.1172	0.1743
	12	0.21	12.5	0.4205	0.3962
	12	0.19	12.2	0.3626	0.3609
Mean				**0.2581**	**0.2891**
NWZ (Y_2)	11	0.21	14.2	0.4718	0.4089
	11	0.23	14.6	0.6280	0.4918
	14	0.13	13.2	0.1715	0.1481
	14	0.14	13.4	0.1991	0.1748
	14	0.17	13.8	0.2948	0.2551
Mean				**0.3530**	**0.2957**
CDZ (Y_3)	12	0.14	9.7	0.1592	0.2103
	12	0.13	9.7	0.1305	0.1789
	12	0.17	9.8	0.2200	0.2691
	13	0.15	7.0	0.1311	0.1673
	13	0.16	7.2	0.1509	0.1926
Mean				**0.1583**	**0.2036**
WZ (Y_4)	11	0.26	12.4	0.6703	0.6808
	11	0.18	10.4	0.2587	0.3244
	11	0.17	9.8	0.2167	0.2940
	12	0.22	11.4	0.4284	0.4945
	12	0.24	12.2	0.5406	0.5616
Mean				**0.4229**	**0.4711**

NEZ - North eastern zone; **NWZ** - North western zone; **CDZ** - Cauvery delta zone; **WZ** - Western zone.

Table 5. Validation of yield model in *Tectona grandis* of 15-20 years

Zone	Age (Years)	Mid diameter (m)	Height (m)	Actual Volume (m^3/tree)	Predicted Volume (m^3/tree)
NEZ (Y_1)	18	0.20	12.5	0.4000	0.3950
	18	0.27	12.8	0.7123	0.5652
	18	0.21	13.1	0.4724	0.4333
	19	0.28	13.8	0.8374	0.6079
	19	0.22	14.3	0.5280	0.4539
		Mean		0.5900	0.4911
NWZ (Y_2)	15	0.21	8.2	0.2725	0.3069
	15	0.22	8.7	0.3307	0.3515
	15	0.17	8.8	0.2035	0.2168
	15	0.24	8.7	0.3845	0.3996
	15	0.22	8.9	0.3512	0.3649
		Mean		0.3085	0.3279
CDZ (Y_3)	15	0.16	6.3	0.1717	0.2217
	15	0.19	6.2	0.1299	0.1666
	16	0.18	12.6	0.3079	0.3492
	16	0.23	13.4	0.5639	0.4951
	16	0.22	13	0.4758	0.4496
		Mean		0.3298	0.3364
WZ (Y_4)	16	0.23	11.5	0.4826	0.5461
	19	0.25	12.2	0.5804	0.5914
	19	0.30	11.7	0.8179	0.8756
	20	0.34	13.1	1.2053	1.0476
	20	0.33	12.7	1.0644	0.9825
		Mean		0.8301	0.8086

NEZ - North eastern zone; **NWZ** - North western zone; **CDZ** - Cauvery delta zone; **WZ** - Western zone.

wood for total volume calculation aligns closely with the findings of the present study (27, 28).

Supporting the present study, yield models for *Azadirachta indica* and *Albizia lebbeck* were developed in the Western Agro-climatic Zone of Tamil Nadu, covering seven different age classes (20). In contrast to these findings, a previous study utilized the diameter at breast height as the sole predictor variable to develop the commercial volume predictions for tree species such as *Tectona grandis* and Mango (29).

In *Tectona grandis* plantations located in Tamil Nadu and Costa Rica, yield models were constructed and optimized for specific plantation, with confirmation that the best-fit models developed for one plantation or zone cannot be used for other plantations or zones. Another study confirmed that power equations were significantly superior to other models. This superiority was evident from their higher coefficient of determination (COD = r^2) values and lower (SE) values, demonstrating their accuracy and reliability in yield estimation (30).

For example, in Ghana, a yield model developed for *Samanea saman* utilized the equations:

$$\ln(V) = 8.3023 + 2.1746 \ln(V) \text{ and}$$

$$\ln(D) = -9.1864 + 1.85502 \ln(H) + 0.8234 \ln(D)$$

These equations were identified as the best-fitted models for rain tree grown in forest plantations of Ghana. Biomass estimation studies conducted in Costa Rica highlighted that variables such as total height (TH) and diameter at breast height (DBH) alone were utilised for framing linear and logarithmic equations, resulting in robust, best-fit models for biomass and yield prediction (31-33).

Conclusion

The best-fitting prediction equation, selected from the developed set for *Tectona grandis*, was used to construct a localized yield table. This yield table was developed specifically for farm-grown *Tectona grandis* trees across four different agro-climatic zones of Tamil Nadu. Validation of the yield model yielded a minimum residual mean sum of squares (R^2) ranging from 0.002 to 0.005. The validation results indicate a deviation of only 2 to 5 % from the actual observed volume across the three age classes. Furthermore, the yield tables provide volume estimates based on age, mid-diameter and height specific to each yield models (Y_1, Y_2, Y_3 and Y_4) for the selected agro-climatic zones. These tables serve as valuable tools for tree growers, timber traders and buyers, enabling them to estimate the commercial volume of a tree efficiently without the need for felling, thus facilitating the calculation of its commercial value.

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Authors' contributions

All the authors have contributed to the conceptualization of research work and designing of experiments, execution of field/lab experiments and data collection, analysis of data and interpretation and preparation of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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