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Growth variability of farm grown teak in response to climatic and soil factors across three agroclimatic zones of Tamil Nadu, India

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Teak (*Tectona grandis*, Linn. f) is a prized hardwood species with remarkable properties that make it a favored material in various industries. In current trend, the cultivation of teak in farmlands is considered as a promising option. But the documentation and research on growth attributes and the studies on influence of climatic and edaphic factors on growth of teak raised in farmland condition is lacking. In this regard, the present investigation on farm grown teak was perpetrated in three agroclimatic zones viz., High Rainfall Zone, Southern Zone and Cauvery Delta Zone of Tamil Nadu in four different age classes (0–5, 5–10, 10–15 and 15–20 years). The study was carried forward with the prime motive of determining growth attributes and analyzing the impact of climatic and edaphic parameters on growth biometry of farm raised teak, both in block and boundary plantations. The soil physico-chemical parameters were analyzed both in surface (0–15 cm) and subsurface (15–30 cm) of plantations and the outcomes were presented in the form of cluster heat map, the results revealed that maximum organic carbon (0.62%), available nitrogen (197 kg ha^{-1}), available phosphorous (22 kg ha^{-1}), available potassium (340 kg ha^{-1}), bulk density (1.34 g/cm^3) and porosity (51.10%) were observed in surface soils of high rainfall zone. The follow-up of correlation studies between growth and climatic variables using R-software brought to light that tree volume positively correlated with climatic parameters viz., annual rainfall, mean minimum temperature and mean relative humidity, but showed negative correlation with respect to mean maximum temperature in both boundary and block plantations. Harmoniously, the correlation analysis between growth and edaphic parameters showed positive correlation with edaphic variables viz., organic carbon, available nitrogen, available phosphorous and available potassium, whereas growth depicted negative correlation with pH and electrical conductivity in both boundary and block plantations. In addition, principal component analysis was carried out to determine the most contributing factor among all and also to portray the highly suitable zone for teak cultivation. The overall study results portray that among climatic parameters, annual rainfall has significant impact on growth of teak and with respect to edaphic variables organic carbon play a crucial role in improving the growth of teak raised in farm settings. In regard to various zones surveyed, High Rainfall Zone exhibit favorable climatic and soil conditions, which in turn reflect better growth performance when compared to other zones taken into consideration.

Keywords Teak, Climatic, Edaphic, Correlation, Cluster heat map, Principal component analysis

Teak (*Tectona grandis* Linn. f.) is regarded as king of timbers is known for its remarkable durability, resilience and improved aesthetic qualities[1,2]. Based on the 2014 FAO report, i.e. "State of the World's Forest Genetic Resources", among the tree species prioritized by countries for conserving and managing forest genetic resources, teak ranks highest in over 20 countries primarily due to its economic value, including timber, pulp, food, wood energy, and non-wood forest products[3].Teak is among the first species to be cultivated in pure plantations for commercial use[4]. Teak is widely cultivated in plantations across various regions, with India serving as the center of its genetic

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diversity[5]. Globally, teak plantations have expanded significantly over the years, and Indisa now accounts for 44 percent of the world's teak plantations, covering an area of 4.35 million hectares[6]. Within India, Tamil Nadu stands out as a prominent state for teak cultivation, with numerous plantations contributing significantly to both the local economy and the broader timber market[7]. Traditionally teak was managed on 80–100-year rotations whereas nowadays the rotation periods for commercial wood production have been reduced to 20 or 30 years, ensuring adequate heartwood grain patterns[4]. Teak though treated as a paragon among timber species, raises several questions on quality parameters when raised under farmland conditions[8]. Teak when raised under farm settings are influenced by a wide range of climatic and edaphic parameters[9]. Edaphic factors viz., soil type, pH levels, nutrient status and organic matter content along with climatic factors viz., rainfall, temperature and relative humidity all combine together and play a crucial role in shaping the growth and development of farm-grown teak trees[10]. Teak being a light demander, has its growth fairly influenced by sunlight as well[11]. Hence, understanding these influences is essential for carrying out successful tree farming.

Generally, teak exhibit better growth in regions with rainfall in the range of 900–2500 mm and temperature ranging between 17 and 43 °C[12]. Optimum rainfall is considered to be of greater importance as it has direct impacts on growth and productivity of teak[13]. Climate factors such as temperature, rainfall, and humidity directly affect the physiological processes of the trees, including photosynthesis, transpiration, and nutrient uptake, which ultimately shape the growth patterns and overall health of teak plantations[14]. Seasonal variations in temperature and precipitation can cause fluctuations in growth rates, influencing both the quality and quantity of the timber produced[15]. Hence it becomes a necessity to understand these climatic impacts which are crucial for optimizing teak plantation management, especially in the face of climate change and increasing weather variability.

With respect to edaphic parameters, teak as a calcicolous species requires soils rich in calcium to thrive and develop properly[16]. High silica-sesquioxide (SiO_2/R_2O_3) ratio in the soil, alluvial site, adequate Ca and Mg in the soil, good moisture availability, sandy loam texture and good drainage are all important edaphic factors that reflect better growth in teak plantations[17,18]. Quantitative information on the relationships between edaphic factors and plantation productivity is required to achieve goals for sustainable forest[19]. Soil quality is a key component of site quality. The growth of farm grown teak is recorded to be extraordinary in deep, well-drained alluvial soils with the range of pH being 6.5 to 7.5[20]. Meanwhile poor growth and form was observed in teak raised on dry sandy soil, shallow or hard pan soil, acidic, laterite, black cotton and waterlogged soils[21]. Soil texture and structure influence root development, water retention, and nutrient absorption, all of which are critical for the optimal growth of teak[22]. Thus, the overall variations in soil properties across different plantations can lead to significant differences in growth rates and wood quality[23]. Therefore, it is essential to tailor soil management practices based on the site conditions of each plantation site to obtain increased productivity. Based on the climatic factors, irrigation and pattern of cropping, Tamil Nadu has been grouped into seven agro-climatic zones[24]. With respect to the seven agro climatic zones, five zones are considered suitable for cultivation of teak under farmland conditions[25]. With this background, the present investigation was carried out in 200 different farmlands across three different agroclimatic zones of Tamil Nadu, i.e. High Rainfall Zone, Southern Zone and Cauvery Delta Zone, with the objective of (i) Documenting the growth biometry of teak in different zones, (ii) Assessing the impact of climatic and edaphic factors on teak growth and (iii) Determining the most suitable zone for cultivation of teak. Overall, this study focuses on establishment of scientific evidences for teak performance in farmlands in relation to climatic and edaphic factors.

Materials and methods

Field survey

Teak plantations raised in farmlands comprised the materials for the study and were perambulated in three agroclimatic zones of Tamil Nadu viz., High Rainfall Zone (HRZ), Southern Zone (SZ) and Cauvery Delta Zone (CDZ) (Fig. 1). A total of about 200 different teak fields were surveyed across the above-mentioned zones. In High Rainfall Zone, teak grown in farm lands of Kadayal, Kaliyakkavillai, Kilathoor, Pinanthode, Unnamalaikadai, Melpuram, Marthandam, Mankuzhy, Udayarpallam, Puthuvilai and Thingalnagar in both block and boundary plantions were perambulated. In Southern Zone assessment was carried out in farmlands of Kadayanallur, Kambaneri Pudukudi, Vadakarai, Panboli, Thenpothai, V.M. Pidagai, Tenkasi, Puliyangudi, Singammalpuram, Venkateswarapuram, Shenbagathoppu, Srivilliputhur, Vijayamangalam, Urseri, Kovilpatti, Madurai, Palamedu, Palaiyurpatty and Kottanathampatty. The evaluation of teak trees was carried out in farm lands of Pudhukottai, Kurumbur, Chettikkadu, Alanchirankadu, Avanthankottai, Puvattakudi, Periyaloor, Poovatrakkudi and Karunthirakkottai in Cauvery Delta Zone of Tamil Nadu. The identification of fields was carried out based on information obtained from native village people and extensive travel across the above mentioned zones.

Field sampling

Teak plantations in four age classes (0–5, 5–10, 10–15, 15–20) were considered for study in three agroclimatic zones of Tamil Nadu and biometric analysis was done. The study was carried out in both boundary and block plantations. Estimation of growth attributes viz., diameter at breast height and total height was done using tree telescope and the volume was determined. Simple random sampling method was employed for selection of trees with a sampling intensity of 10 percent. Higher sampling intensity was preferred, as land holdings varied from 1 to 20 hectares in different farmer fields and also 10% sampling intensity helps capture growth trends accurately.

Tree volume estimation

The volume of tree from the base up to the highest green branch is termed as tree volume. In the present investigation, biometric attributes viz., the diameter at breast height and tree height were measured initially and then the volume of main bole up to the topmost height was calculated using the data collected from Laser

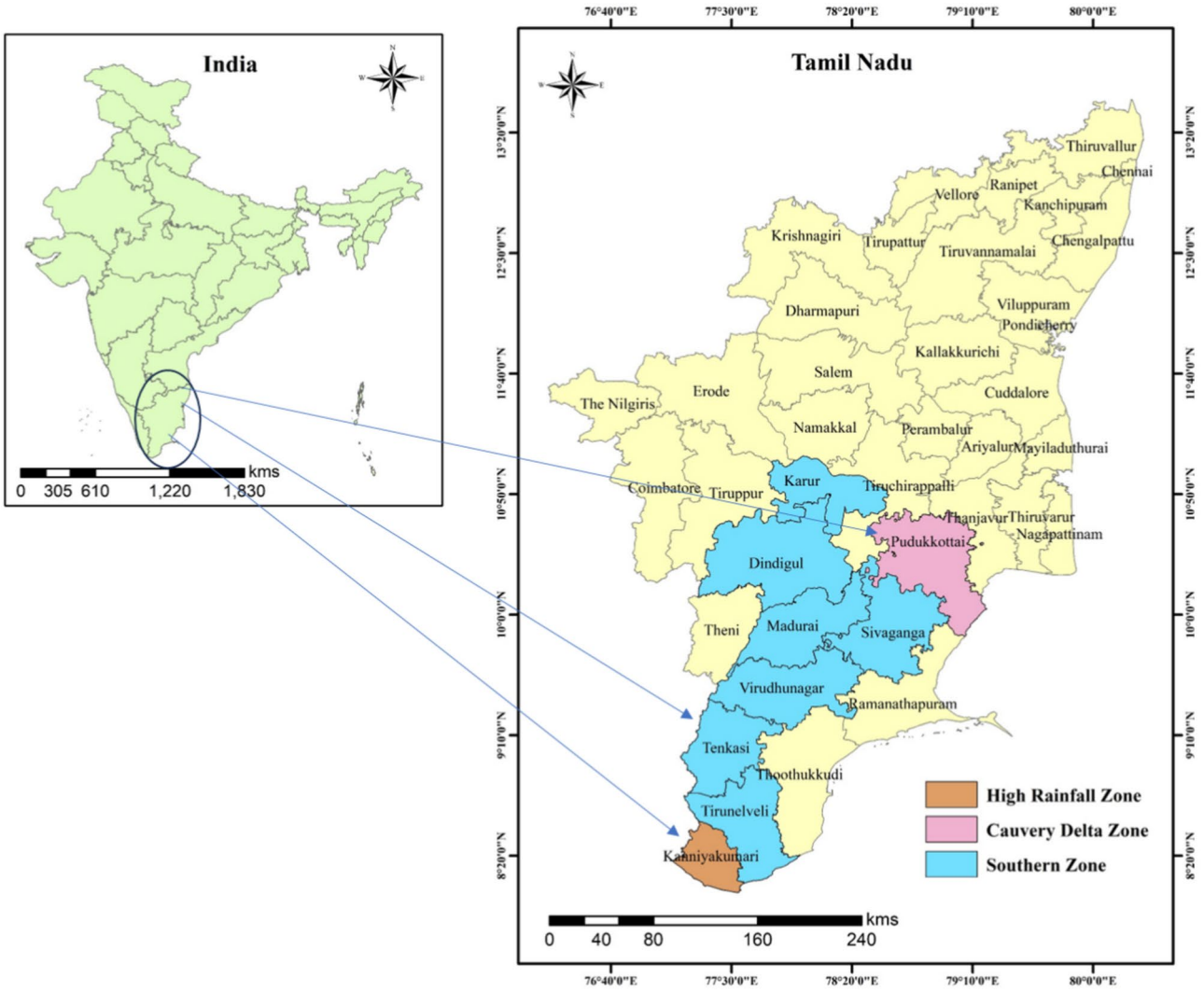

Fig. 1. Study Area of teak plantations in three agroclimatic zones of Tamil Nadu.

Distance Meter in all the sample trees selected for the study. The volume of every 2 m section was determined based on the formula given by Chaturvedi and Khanna (1982). The volume was expressed in Cubic meter per tree (m^3/tree)

$$V = \pi(d/2)^2 h$$

where V, volume; d, diameter at breast height; h, tree height.

Climatic and Edaphic variables

The climatic variables were obtained for a period of 20 years (2001–2021) from the database of scientific institutes. The climatic data for Kanyakumari, Tirunelveli, Tenkasi, Virudhunagar, Madurai, Dindigul and Pudhukottai districts were obtained from Agroclimatic Research Center (ACRC), Tamilnadu Agricultural University, Coimbatore. The climatic parameters viz., Rainfall (mm), maximum temperature (°C), minimum temperature (°C) and relative humidity (%) for a period of twenty years were collected for study.

Random Sampling method was employed for soil sampling, with a sampling intensity of 5%. The soil samples were collected randomly at 10–12 sites (sub samples) within each field at two depths viz., 0–15 cm (Surface) and 15–30 cm (Sub-surface). The collected sub samples were mixed thoroughly to form a composite sample, which act as a representation of the entire field. The composite sample was prepared separately for both surface and sub surface soils. Thus, approximately about two composite samples were obtained from each field for carrying out analysis. The soil physico-chemical properties viz., Soil bulk density, Porosity, Texture, Soil pH, EC, Available Nitrogen, Available Phosphorous, Available Potassium and Soil organic carbon were analysed from the composite soil samples collected from three agro climatic zones of Tamil Nadu. Soil bulk density was determined following the procedure described by Grossman & Reinsch[26] i.e. by dividing the mass of oven-dried soil (g), with the volume of bulk soil (cm^3). Soil porosity was calculated using the method of Flint and Flint[27], i.e. the ratio

of volume of water (cm^3) to volume of bulk soil (cm^3) and it is expressed in percentage (%). Soil texture was determined based on the methodology stated by Hobbs[28].

Soil pH was determined using the potentiometric method, as described by Jackson[29]. Meanwhile, soil electrical conductivity (EC) was calculated following the conductometric method[29]. Available nitrogen in the soil was estimated using the alkaline permanganate method as described by Subbiah and Asija[30]. Available phosphorus was determined using either Olsen's method or Bray's method[31], depending on the soil type. Olsen's method was carried out for alkaline soils whereas Bray's method was followed for acidic soil. Available potassium in the soil was measured using emission spectroscopy as described by Stanford and English[32], whereas soil organic carbon was determined using the wet chromic acid digestion method as outlined by Walkley and Black[33].

Statistical analysis

Statistical analysis was carried out using R-software. For correlation studies, ggpairs() function from GGally library was used. Whereas, for visualization of various soil properties cluster heat map was developed using pheatmap package in R. Principal component analysis was performed using prcomp function from ggpubr, ggplot2, factoextra and extrafont packages, for determining the most contributing climatic and edaphic factor and also to decide the most suitable zone for teak cultivation.

Results and discussion

The biometric data viz., diameter at breast height, tree height and tree volume was evaluated and were correlated with climatic and edaphic factors to assess the influence of edapho climatic factors towards productivity of farm grown teak.

Biometric attributes in block plantations of farm grown teak

The different biometric attributes of block plantations observed in four age classes of the three different agroclimatic zones are presented in Tables 1, 2, 3 and 4.

The diameter at breast height in block plantations of high rainfall zone in all four age classes considered for study ranged between 0.024 and 0.314 m, whereas for southern zone the range of values were 0.041 m to 0.264 m. In case of cauvery delta zone the variation in diameter at breast height was between 0.049 and 0.277 m (Fig. 2). These results strongly suggest that with the increase in age the diameter at breast height also increases progressively. This study was in line with[34], whose study proved that the mean diameter at breast height increased linearly with increase in age. Further Shahapurmath et al.[35], revealed that tree age plays a crucial role in determining the growth of teak trees raised in farmlands. Similarly, the studies of Sabastin et al.[36], revealed that increase in diameter growth occurs with increase in tree age for teak raised in farmlands.

In terms of tree height, among all four age classes maximum tree height was recorded in the age class 15–20 years, with value of 12.50 m, 11.50 m, 11.50 m for high rainfall zone, southern zone and cauvery delta zone respectively (Fig. 2) the increased tree height growth in high rainfall zone is mainly due to the influence of favourable climatic variables and optimum edaphic properties. Similar study carried out by Arunkumar[37] revealed that better growth in terms of tree height was depicted by trees growing in high rainfall areas and deep fertile soils. The results were also in accordance with the findings of Thompson and Nagabhushanam[38], that teak height growth was influenced to a certain extent by edaphic factors. Climatic factors had a strong impact on height growth of scots pine in Finland[39].

Tree volume in block plantations of three agroclimatic zones in four age classes shown a range from 0.002 to 0.927 m^3 in high rainfall zone, 0.004 to 0.623 m^3 in southern zone and 0.005 to 0.693 m^3 in cauvery delta zone (Fig. 2). The results agree with the findings of Ravi et al.[40], in *Ailanthus excelsa*, that tree volume varied with respect to age classes and growth conditions. Comparably, Sureshkrishnan et al.[41], studied and determined the volumes of *Tectona grandis*, *Melia dubia, Gmelina arborea* and *Ailanthus excelsa* in cauvery delta zone of Tamil Nadu for nine age classes in farmlands.

Biometric attributes in boundary plantations of farm grown teak

The different biometric attributes of block plantations observed in four age classes of the three different agroclimatic zones are presented in Tables 5, 6, 7 and 8.

The results of the present investigation portrayed that the growth biometry of boundary plantations for the age class of 15–20 years was maximum in all three agroclimatic zones when compared to block plantations. The maximum values recorded in terms of diameter at breast height, tree height and tree volume in boundary plantations of high rainfall zone (0.366 m, 13.00 m and 1.369 m^3) where higher when compared to block plantations (0.314 m, 12.50 m and 0.927 m^3) of the same age class. Similar trend was observed by Krishnan et al.[42], in cauvery delta zone of Tamil Nadu, where growth attributes viz., diameter at breast height, tree height and tree volume of boundary plantations in age class of 15–20 years showed better growth performance than block plantations in teak.

The diameter at breast height, with reference to boundary plantations of four different age classes under three agroclimatic zones brought to light that, the maximum of value of diameter at breast height for high rainfall zone, southern zone and cauvery delta zone were 0.366 m, 0.293 m and 0.314 m respectively (Fig. 3). The study outcomes expose that diameter at breast height increases with increase in age. The study results are in accordance with the findings of Vijayabhama et al.[43], in casuarina plantations of different age classes of cauvery delta zone revealed that diameter at breast height increases with the increase in age of trees.

In terms of tree volume, the mean values of boundary plantations of high rainfall zone (1.369 m^3), southern zone (0.838 m^3) and cauvery delta zone (1.004 m^3) were comparatively higher than that of block plantations (Fig. 3). The increase in tree volume of boundary plantations was mainly due to wider spacing and less competition for light, space, nutrients and other resources used by the individual trees when compared to block

Zone	High Rainfall Zone				Southern Zone				Cauvery Delta Zone			
Tree No	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)
1	4	0.070	6.00	0.023	4	0.070	4.50	0.017	5	0.076	4.50	0.021
2	4	0.065	6.00	0.020	4	0.065	4.00	0.013	5	0.065	4.00	0.013
3	4	0.061	6.50	0.019	4	0.067	4.00	0.014	5	0.070	4.00	0.015
4	4	0.057	5.50	0.014	4	0.076	4.50	0.021	5	0.057	3.50	0.009
5	4	0.059	5.00	0.014	4	0.083	5.50	0.030	5	0.061	3.75	0.011
6	3	0.056	5.50	0.013	4	0.072	4.00	0.016	5	0.049	3.00	0.006
7	3	0.053	5.00	0.011	4	0.076	5.00	0.023	5	0.068	4.00	0.015
8	3	0.067	6.00	0.021	4	0.075	4.50	0.020	5	0.073	4.50	0.019
9	3	0.065	5.50	0.018	4	0.084	5.25	0.029	4	0.068	4.00	0.015
10	3	0.053	4.50	0.010	4	0.067	3.75	0.013	4	0.064	3.75	0.012
11	2	0.041	4.30	0.006	2	0.057	4.00	0.010	4	0.061	3.50	0.010
12	2	0.037	4.00	0.004	2	0.049	3.50	0.007	4	0.067	4.00	0.014
13	2	0.053	4.50	0.010	2	0.041	3.00	0.004	4	0.053	3.00	0.007
14	2	0.049	4.00	0.007	2	0.051	4.00	0.008	4	0.049	2.75	0.005
15	2	0.033	3.50	0.003	2	0.046	3.50	0.006	4	0.062	3.75	0.011
16	1	0.029	2.50	0.002	2	0.051	4.50	0.009	4	0.059	3.50	0.010
17	1	0.032	4.00	0.003	2	0.049	4.50	0.009	3	0.057	3.00	0.007
18	1	0.024	3.50	0.002	2	0.041	4.00	0.005	3	0.051	2.75	0.006
19	1	0.025	3.00	0.002	2	0.056	5.00	0.012	3	0.049	2.75	0.005
20	1	0.032	3.50	0.003	2	0.038	3.50	0.004	3	0.059	3.00	0.008
Mean		0.048	4.62	0.010	Mean	0.070	4.50	0.017	Mean	0.061	3.55	0.011
SEd		0.003	0.251	0.002	SEd	0.065	4.00	0.013	SEd	0.002	0.126	0.001
CD (0.05)		0.032	2.361	0.015	CD(0.05)	0.067	4.00	0.0140	CD(0.05)	0.017	1.187	0.009

Table 1. Biometric attributes of 0–5 years old age class farm grown teak (Block plantations) in three agroclimatic zones of Tamil Nadu.

plantations. The wider spacing in boundary plantation promotes better increment of tree volume in comparison to closer spacing of block plantation. Supporting the present study Zahabu et al.[44], inferred wider spacing favoured better growth for teak, that was raised in plantations of Tanzania. The variation in tree volume of three agroclimatic zones was attributed to heterogeneity of climatic variables and edaphic influences in different agroclimatic zones. The results agree with the findings of Reddy et al.[45], that the assessment of teak tree volume in three different agroclimatic zones of Karnataka, the northern transition zone had an optimum mean annual rainfall of 749 mm and the presence of favourable medium black soil has shown better volume and productivity as compared to other zones taken for productivity studies in Teak.

The overall investigation of biometric attributes of farm grown teak in both block and boundary plantations for four age classes viz., 0–5, 5–10, 10–15 and 15–20 years in three agroclimatic zones of Tamil Nadu brought to light that 15–20 years age class is the most favourable age class for obtaining maximum yield in terms of tree volume. Thus, with respect to boundary and block plantations of different agroclimatic zones, better growth performance was evident in boundary plantations due to several factors like climatic variables, edaphic influences, lesser competition for resources, wider spacing and better silvicultural and management interventions adopted by the tree growing farmers. Hence conclusions can be drawn that irrespective of the agroclimatic zones, the plantations of age class 15–20 years are recommended for commercial exploitation of teak grown in farmlands.

Correlation of climatic and edaphic influence on growth of farm grown teak

Climatic variables in three agro climatic zone of Tamil Nadu

The climatic variables of High Rainfall Zone, Southern Zone and Cauvery Delta Zone were collected for a period of 20 years (2001–2021) and presented in Table 9. The mean annual rainfall for 20 years was documented as 1248.83 mm in high rainfall zone, 908.15 mm in southern zone and 803.34 mm in cauvery delta zone. The maximum temperature during this period ranged between 35.90 to 39.75 °C for high rainfall zone, whereas for southern zone and cauvery delta zone the maximum temperature range was recorded between 38.83 to 43.33 °C and 40.08 to 43.60 °C respectively. The minimum range of temperature was observed between 14.64 to 17.29 °C in high rainfall zone, 13.64 to 16.80 °C in southern zone and 15.08 17.05 °C in cauvery delta zone. The mean relative humidity during this period was registered as 79.65% in high rainfall zone, 69.25% in southern zone and 68.90% in cauvery delta zone.

Correlation analysis

Correlation was carried out using R-software to correlate the climatic parameters viz., mean annual rainfall (mm), mean maximum temperature (°C), mean minimum temperature (°C) and mean relative humidity (%) with biometric attributes viz., diameter at breast height, tree height and tree volume in both block and boundary plantations of farm grown teak in High Rainfall Zone, Southern Zone and Cauvery Delta Zone of Tamil Nadu (Figs. 4, 5, 6, 7, 8, 9).

Correlation of climatic influence with growth of teak raised in block plantations

The results of correlation studies for tree volume of block plantations in high rainfall zone showed positive correlation with mean annual rainfall (r = 0.311) and mean minimum temperature (r = − 0.316), whereas negative correlation was observed with mean maximum temperature (r = − 0.250) (Fig. 4). Since high rainfall zone possess a mean annual rainfall of 1248.83 mm, the result suggests that teak grows well in regions with optimum rainfall. This result was supported by the findings of Seth and Khan[46], in which conclusions were drawn that teak exhibit better growth in areas with annual rainfall range of 800–2500 mm in tropics. Further the studies of Yeh and Wensel[47] expressed that, climatic variables in terms of annual precipitation had direct impact in growth of coniferous trees in temperate regions. In addition, the research outcomes of Flumignan et al.[48] on growth of Eucalyptus also conclude that rainfall plays an important role in shaping growth patterns in trees.

With reference to block plantations of southern zone tree volume showed positive correlation with mean annual rainfall (r = 0.283) and mean minimum temperature (r = 0.139) meanwhile, negative correlation was observed with respect to mean maximum temperature (r = − 0.113) (Fig. 5).Similarly, with respect to cauvery delta zone less significant positive correlation was observed for both annual rainfall (r = 0.055) and maximum temperature (r = 0.080), whereas less significant negative correlation (r = − 0.048) was observed for minimum temperature (Fig. 6). These results are in accordance with the findings of Raviperumal et al.[49], for *Azadirachta indica* and *Albizia lebbeck* plantations in Western agro climatic zone of Tamil Nadu which also inferred that positive correlation was observed between growth attributes and climatic variables namely mean annual rainfall, minimum temperature and relative humidity, whereas negative correlation was noticed in case of maximum temperatute. The research outcomes of Ravi et al.[40], in *Ailanthus excelsa* also proved that positive correlation was observed between annual rainfall and humidity with tree volume in Cauvery delta zone and Western agroclimatic zone of Tamil Nadu.

Correlation of climatic influence with growth of teak raised in boundary plantations

The findings in relation to correlation studies of growth attributes with climatic parameters in boundary plantations of high rainfall zone, southern zone and cauvery delta zone detailed that tree volume showed positive correlation with average annual rainfall (r = 0.418), (r = 0.372), (r = 0.185), relative humidity (r = 0.395), (r = 0.471), (r = 0.176) and minimum temperature (r = 0.132), (r = 0.253), (r = 0.119) whereas, negative correlation was expressed with maximum temperature (r = − 0.112), (r = − 0.333) and (r = − 0.301) for high rainfall zone, southern zone and cauvery delta zone respectively (Figs. 7, 8, 9). These results suggest that extremes of temperature have negative impact on volume increment. The findings of Gong et al.[50], also prove that high temperature rise has adverse effects on tree growth. Comparably, the findings of Haq et al.[51], also infer those extremes of temperature had a negative impact on the growth of *Dalbergia sisoo*. The results of Yang et al.[52], in

Zone	High Rainfall Zone				Southern Zone				Cauvery Delta Zone			
Tree No	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)
1	10	0.132	8.50	0.117	8	0.091	7.50	0.049	8	0.086	8.00	0.046
2	10	0.140	8.75	0.135	8	0.096	8.00	0.057	8	0.076	6.50	0.030
3	10	0.137	9.00	0.133	8	0.102	8.00	0.065	8	0.089	8.00	0.050
4	10	0.113	8.00	0.080	8	0.084	7.50	0.042	8	0.078	6.50	0.031
5	10	0.124	8.75	0.106	8	0.076	7.00	0.032	8	0.078	7.00	0.034
6	8	0.102	8.50	0.069	8	0.097	8.00	0.059	8	0.088	7.50	0.045
7	8	0.085	7.50	0.042	8	0.092	7.50	0.050	8	0.081	7.00	0.036
8	8	0.108	9.00	0.083	8	0.088	7.00	0.042	8	0.089	8.00	0.050
9	8	0.100	8.50	0.067	8	0.105	8.25	0.072	8	0.092	8.00	0.054
10	8	0.089	8.00	0.050	8	0.081	7.00	0.036	8	0.078	7.00	0.034
11	7	0.108	8.00	0.074	8	0.094	8.00	0.055	8	0.086	7.50	0.044
12	7	0.097	7.50	0.055	8	0.099	8.50	0.065	8	0.091	8.00	0.052
13	7	0.092	6.50	0.044	8	0.091	7.50	0.049	7	0.076	7.00	0.032
14	7	0.096	7.00	0.050	8	0.088	7.00	0.042	7	0.067	6.50	0.023
15	7	0.104	7.50	0.063	8	0.080	6.50	0.032	7	0.073	6.75	0.028
16	6	0.070	6.75	0.026	8	0.075	6.00	0.026	7	0.086	8.00	0.046
17	6	0.070	6.50	0.025	8	0.076	7.25	0.033	6	0.083	6.50	0.035
18	6	0.075	7.00	0.031	8	0.059	6.00	0.016	6	0.076	6.00	0.028
19	6	0.083	7.50	0.040	8	0.083	7.50	0.040	6	0.075	5.75	0.025
20	6	0.067	6.50	0.023	8	0.097	8.00	0.059	6	0.086	6.50	0.038
Mean		0.100	7.76	0.065	Mean	0.088	7.40	0.046	Mean	0.082	7.10	0.038
SEd		0.005	0.192	0.008	SEd	0.002	0.155	0.003	SEd	0.002	0.164	0.002
CD(0.05)		0.046	1.806	0.072	CD(0.05)	0.023	1.459	0.030	CD(0.05)	0.014	1.537	0.020

Table 2. Biometric attributes of 5–10 years old age class farm grown teak (Block plantations) in three agroclimatic zones of Tamil Nadu.

Pinus radiata demonstrated the negative correlation existed between tree volume and maximum temperature. Thus, conclusions can be drawn that fluctuations in temperature has significant negative impact on growth of trees. Interestingly, the study of Apurva et al.[53] on *Terminalia arjuna*, was incompatible with the present result, suggesting that increase in temperature is directly proportional to the growth attributes at juvenile stage. This may hold true as, *Terminalia arjuna* is a very strong light demander and also generally at juvenile or initial stage of growth higher temperature may be more adequate for better growth.

Thus, overall conclusions can be drawn that among all climatic parameters, mean annual rainfall has a very high significant role in promoting tree volume increment in all the three agroclimatic zones taken into consideration. Contradictorily, mean maximum temperature has negative impacts on tree growth, limiting the growth of teak mainly in southern zone and cauvery delta zone, which shows high maximum temperature when compared to high rainfall zone, which has resulted in comparatively less growth in the above two zones.

Edaphic variables in selected agroclimatic zones of Tamil Nadu

The soil physico-chemical properties viz., Soil bulk density (g/cm^3), Total porosity (%), Soil texture, Soil pH and Electrical conductivity (dSm^{-1}) along with, Organic carbon (%), Available nitrogen ($kg\ ha^{-1}$), Available phosphorus ($kg\ ha^{-1}$) and Available potassium ($kg\ ha^{-1}$) were investigated from the soil samples collected from High Rainfall Zone, Southern Zone and Cauvery Delta Zone of Tamil Nadu and the results are presented in Table 10.

Soil physico-chemical properties in surface soils of three agroclimatic zones of Tamil Nadu

With reference to surface soils, the minimum and maximum soil bulk density was recorded between 1.34 and 1.47 g/cm^3 for high rainfall zone, 1.38 and 1.51 g/cm^3 for southern zone, 1.39 and 1.53 g/cm^3 for cauvery delta zone respectively. The soil porosity was found to be between 44.86 to 51.10% for high rainfall zone, 43.65 to 48.24% for southern zone, 42.78 to 48.21% for cauvery delta zone. The soil texture in all zones were predominantly of sandy loam. The soil pH ranged between 7.2 to 7.74 for high rainfall zone, 7.43 to 8.23 for southern zone and 7.56 to 8.03 for cauvery delta zone. Electrical conductivity varied in the range of 0.12 dS/m to 0.17 dS/m, 0.16 dS/m to 0.23 dS/m and 0.14 dS/m to 0.21 dS/m for high rainfall zone, southern zone and cauvery delta zone respectively. In regard to organic carbon, the maximum and minimum values were recorded as 0.46% and 0.62% for high rainfall zone, 0.44% and 0.54% for southern zone and 0.45% to 0.60% for cauvery delta zone.

The range of values for available nitrogen, available phosphorous and available potassium were recorded as 181 $kg\ ha^{-1}$ to 197 $kg\ ha^{-1}$, 17 $kg\ ha^{-1}$ to 22 $kg\ ha^{-1}$ and 265 $kg\ ha^{-1}$ to 340 $kg\ ha^{-1}$ for high rainfall zone, followed by 171 $kg\ ha^{-1}$ to 192 $kg\ ha^{-1}$, 15.5 $kg\ ha^{-1}$ to 21.5 $kg\ ha^{-1}$ and 255 $kg\ ha^{-1}$ to 295 $kg\ ha^{-1}$ for southern zone. In cauvery delta zone, the values were tabulated between 174 to 189 $kg\ ha^{-1}$, 15 to 19 $kg\ ha^{-1}$ and 260 to 290 $kg\ ha^{-1}$ respectively.

Soil physico-chemical properties in sub surface soils of three agroclimatic zones of Tamil Nadu

For sub surface soils (15–30 cm), the soil bulk density ranged between 1.36 and 1.52 g/cm^3 for high rainfall zone, 1.43 g/cm^3 and 1.57 g/cm^3 for southern zone, 1.44 g/cm^3 and 1.59 g/cm^3 for cauvery delta zone. Soil porosity varied from 43.41% to 48.85% for high rainfall zone, 40.61% to 44.90% for southern zone and 40.02% to 45.90% for cauvery delta zone. The soil texture was found to be sandy clay loam across different zones. Further, the range of pH value was recorded between 7.34 to 7.89 for high rainfall zone, 7.54 to 8.30 for southern zone and 7.67 to 8.19 for cauvery delta zone. The variations in electrical conductivity were noted in the range of 0.13 dS/m and 0.16 dS/m for high rainfall zone, 0.18 dS/m and 0.24 dS/m for southern zone, 0.14 dS/m and 0.19 dS/m for cauvery delta zone. The maximum values of organic carbon for high rainfall zone, southern zone and cauvery delta zone were 0.56%, 0.48% and 0.51% respectively.

The available nitrogen varied between 177 to 193 $kg\ ha^{-1}$ in high rainfall zone, 165 to 189 $kg\ ha^{-1}$ in southern zone and 172 to 185 $kg\ ha^{-1}$ in cauvery delta zone. The values of available phosphorous was recorded between 15 to 20.5 $kg\ ha^{-1}$, 15.5 to 18.5 $kg\ ha^{-1}$ and 14.5 to 17 $kg\ ha^{-1}$ for high rainfall zone, southern zone and cauvery delta zone respectively. With reference to available phosphorous the values documented were between 258 to 328 $kg\ ha^{-1}$ for high rainfall zone, 240 to 289 $kg\ ha^{-1}$ for southern zone and 245 to 281 $kg\ ha^{-1}$ for cauvery delta zone.

Correlation analysis

The correlation studies with respect to growth and soil parameters in block and boundary plantations have been listed in Figs. 10 and 11.

Correlation of edaphic influence with growth parameters in block plantations of farm grown teak

The correlation of biometric attributes with soil properties in block plantations brought to light that, tree volume witnessed positive correlation with soil organic carbon ($r = 0.264$) available nitrogen ($r = 0.166$), available phosphorous ($r = 0.255$) and available potassium ($r = 0.426$). The findings of Olivares et al.[54], also revealed that soil parameters like available nitrogen, phosphorous and potassium had significant positive impacts on growth of banana plants. The results were also in line with the findings of Boonkird et al.[55], which inferred that available nitrogen had positive correlation with growth of teak. The strong correlation between available potassium and tree volume ($r = 0.426$), may be due to the fact that potassium is directly involved in the production and movement of carbohydrates, which are the building blocks for wood. Trees with ample potassium are more likely to have thicker trunks and more wood volume, explaining the strong positive correlation. These conclusions are harmonious with the findings of Sardans & Penuelas[56], Oosterhuis et al.[57] and Epron et al.[58], which also suggest that available pottasium has beneficial impacts on volume increment of trees. The findings of Aparanji[59] in teak

Zone	High Rainfall Zone				Southern Zone				Cauvery Delta Zone			
Tree No	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)
1	15	0.183	9.50	0.250	15	0.135	10.50	0.151	15	0.140	10.00	0.154
2	15	0.196	10.00	0.301	15	0.124	9.00	0.109	15	0.119	9.00	0.101
3	15	0.210	10.50	0.364	15	0.131	10.00	0.134	15	0.137	10.00	0.147
4	15	0.189	9.00	0.254	15	0.123	9.00	0.106	15	0.148	10.00	0.172
5	15	0.156	8.50	0.163	13	0.105	8.50	0.074	15	0.175	10.50	0.253
6	15	0.197	9.50	0.291	13	0.116	9.00	0.096	15	0.164	10.50	0.222
7	15	0.188	9.00	0.249	13	0.108	8.50	0.078	15	0.134	9.50	0.133
8	15	0.175	10.00	0.241	13	0.102	8.50	0.069	15	0.145	10.00	0.165
9	15	0.172	10.50	0.244	13	0.134	10.25	0.144	15	0.118	9.00	0.098
10	15	0.156	9.50	0.182	13	0.119	9.50	0.106	15	0.129	9.50	0.124
11	15	0.158	10.00	0.196	13	0.121	9.50	0.109	12	0.132	9.50	0.130
12	15	0.194	10.50	0.311	13	0.113	9.00	0.090	12	0.115	8.50	0.088
13	15	0.154	9.50	0.178	13	0.127	10.00	0.127	12	0.102	8.00	0.065
14	15	0.185	10.00	0.268	13	0.104	8.50	0.072	12	0.113	8.50	0.085
15	14	0.161	9.00	0.183	12	0.097	8.25	0.061	12	0.137	9.50	0.140
16	14	0.167	9.00	0.198	12	0.116	9.50	0.101	12	0.127	9.00	0.115
17	14	0.158	8.50	0.167	12	0.108	9.00	0.083	12	0.119	9.00	0.101
18	14	0.169	9.50	0.213	12	0.127	10.00	0.127	12	0.129	10.00	0.131
19	14	0.177	9.50	0.233	12	0.129	10.00	0.131	12	0.134	10.50	0.148
20	14	0.163	9.00	0.188	12	0.111	9.00	0.088	12	0.115	8.50	0.088
Mean		0.175	9.53	0.234	Mean	0.118	9.28	0.103	Mean	0.132	9.45	0.133
SEd		0.004	0.138	0.012	SEd	0.003	0.151	0.006	SEd	0.004	0.166	0.010
CD(0.05)		0.035	1.296	0.114	CD(0.05)	0.024	1.414	0.055	CD(0.05)	0.037	1.557	0.097

Table 3. Biometric attributes of 10–15 years old age class farm grown teak (Block plantations) in three agroclimatic zones of Tamil Nadu.

Zone	High Rainfall Zone				Southern Zone				Cauvery Delta Zone			
Tree No	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)
1	20	0.288	12.50	0.815	18	0.256	11.25	0.580	18	0.266	11.00	0.611
2	20	0.282	11.00	0.686	18	0.242	10.50	0.483	18	0.248	10.75	0.521
3	20	0.288	11.00	0.717	18	0.248	11.00	0.533	18	0.255	10.75	0.548
4	20	0.282	11.50	0.717	18	0.240	10.50	0.477	18	0.232	10.50	0.446
5	20	0.287	12.00	0.774	18	0.245	10.75	0.508	18	0.275	11.50	0.685
6	20	0.298	12.00	0.835	18	0.258	11.25	0.588	18	0.240	10.75	0.488
7	20	0.266	11.00	0.611	20	0.242	10.50	0.483	18	0.226	10.00	0.401
8	20	0.314	12.00	0.927	20	0.248	10.50	0.509	18	0.264	11.50	0.631
9	20	0.296	12.50	0.861	20	0.256	11.00	0.568	18	0.275	11.50	0.685
10	20	0.283	11.00	0.694	20	0.247	10.50	0.502	18	0.268	11.50	0.646
11	20	0.247	10.50	0.502	20	0.244	10.50	0.489	18	0.232	10.50	0.446
12	20	0.266	11.00	0.611	20	0.258	11.00	0.575	18	0.258	11.00	0.575
13	20	0.307	12.00	0.900	20	0.250	10.50	0.515	18	0.256	11.00	0.568
14	20	0.282	12.50	0.717	20	0.256	11.00	0.568	18	0.247	10.75	0.514
15	18	0.250	11.00	0.538	20	0.242	10.50	0.483	18	0.261	11.00	0.590
16	18	0.218	10.50	0.393	20	0.263	11.50	0.623	18	0.268	11.50	0.646
17	18	0.224	11.00	0.434	20	0.234	10.50	0.452	18	0.237	10.50	0.464
18	18	0.196	10.00	0.301	20	0.264	11.25	0.617	18	0.274	11.50	0.677
19	18	0.213	10.00	0.357	20	0.225	10.00	0.396	18	0.229	10.00	0.413
20	18	0.229	10.50	0.433	20	0.236	10.50	0.458	18	0.277	11.50	0.693
Mean		0.266	11.28	0.641	Mean	0.248	10.75	0.520	Mean	0.255	10.95	0.562
SEd		0.008	0.179	0.042	SEd	0.002	0.085	0.013	SEd	0.004	0.111	0.022
CD(0.05)		0.072	1.685	0.396	CD(0.05)	0.021	0.799	0.125	CD(0.05)	0.035	1.044	0.203

Table 4. Biometric attributes of 15–20 years old age class farm grown teak (Block plantations) in three agroclimatic zones of Tamil Nadu.

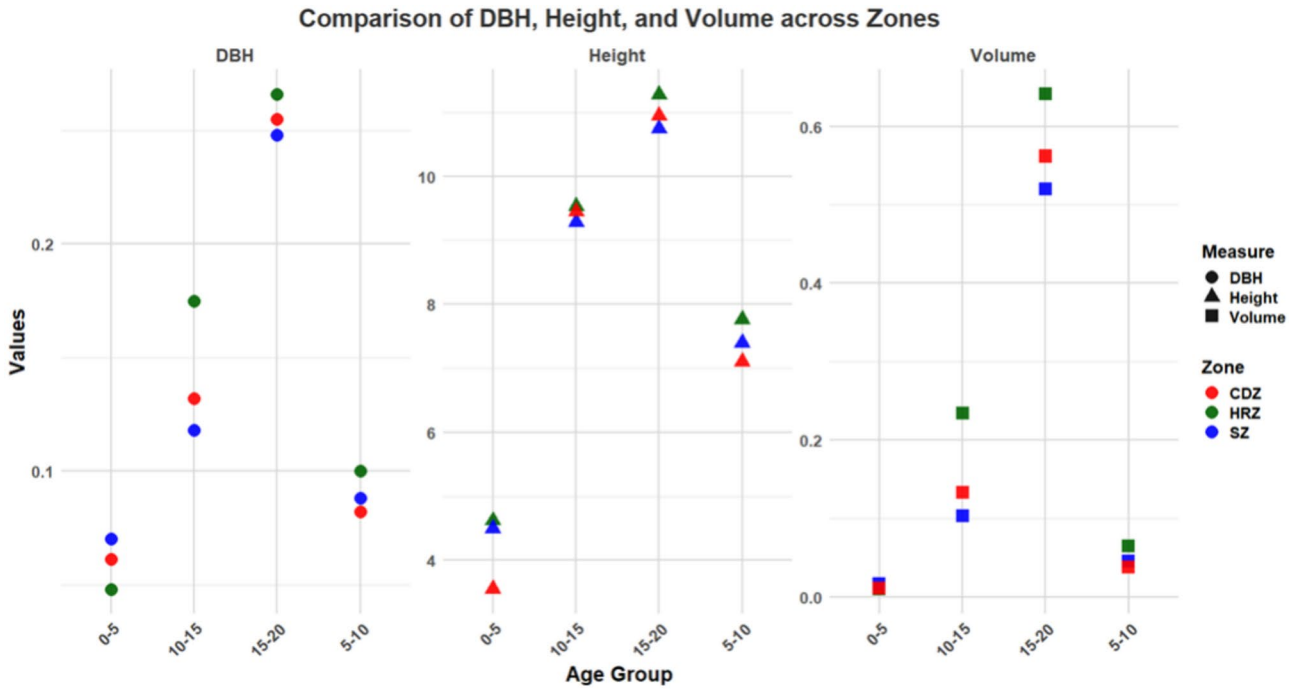

Fig. 2. Comparison of growth attributes of farm grown teak in block plantations of different zones.

plantations, Rajasugunasekar et al.[60] in *Ailanthus excelsa* also revealed similar positive correlation with volume and edaphic influences. Further, increase in growth biometry of *Eucalyptus grandis* plantations was directly proportional to the increase in available nitrogen and available phosphorous[61]. In addition, the tree volume reflected negative correlation with pH and electrical conductivity in block plantations, indicating that when there is an increase in pH and electrical conductivity the growth is affected adversely. The findings of Kumi et al.[62], revealed that the soil electrical conductivity had increasingly negative impact on tree volume.

Correlation of edaphic influence with growth parameters in boundary plantations of farm grown teak

With reference to boundary plantations, the results highlighted that tree volume positively correlated with available nitrogen (r = 0.127), and available potassium (r = 0.189), whereas a very high significant positive correlation (r = 0.756**) was observed with respect to soil organic carbon. The results thus conclude that, soil organic carbon is one among the most important parameter that has greater impact on growth of teak. As organic carbon increases, so does soil fertility, leading to improved root health, better nutrient uptake, and ultimately greater tree biomass and volume[63,64]. The results were harmonious with the findings of Watanabe et al.[65], that soils rich in organic matter with good water holding capacity is amenable for increased growth in teak, making it the most important factor for tree growth. Similarly, Gupta et al.[66], observed positive correlation between soil organic matter and growth biometry in poplar and inferred that soil organic matter is highly crucial for better growth performance of poplar. Boonkird et al.[55], also suggested that growth attributes of teak were positively correlated and influenced by soil organic carbon.

At the same time, the results revealed that tree volume exhibited significant negative correlation with pH (r = − 0.635*) and electrical conductivity (r = − 0.671*). pH of soil affects nutrient availability in the soil. Most trees prefer slightly acidic to neutral soils i.e. pH between 6 and 7[67]. The significant negative correlation may be due to the fact that when the pH is too high (alkaline) or too low (acidic), it can reduce the availability of essential nutrients, leading to nutrient deficiencies which result in poor growth performance[68]. The studies of Rahman et al.[69] also detail that too low or too high pH badly affect growth of trees. However, the study outcomes of Ezenwa[70] on teak were contradictory to the present investigation, suggesting that positive correlation was exhibited between the tree volume and soil pH. This could be due to the fact that, the soils in the study area might have had a lower initial pH (more acidic) and in this juncture, the increase in pH would have brought the soil closer to the optimal range (near neutral, 6–7) and thus would have improved nutrient availability for teak trees and would have promoted growth.

The present investigation results also showed that tree volume showed slight negative correlation with available phosphorous (r = − 0.054). These results may also have direct relation with too low pH or too high pH. In alkaline soils with higher pH, phosphorus tends to bind with calcium and forms insoluble calcium phosphates, which are less available to plants[71]. This reduced availability may limit tree growth, leading to a negative correlation. Likewise, in acidic soils with lower pH, phosphorus binds to iron and aluminium oxides, and may reduce its availability for plant uptake. Complementing the present study results, Adekunle et al.[72] revealed that available phosphorous had negative correlation with growth attributes of teak. Harmoniously,

Zone	High Rainfall Zone				Southern Zone				Cauvery Delta Zone			
Tree No	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)
1	4	0.108	9.00	0.083	5	0.091	7.50	0.049	4	0.064	4.00	0.013
2	4	0.088	8.00	0.048	5	0.083	7.00	0.038	4	0.075	5.00	0.022
3	4	0.107	8.50	0.076	5	0.081	7.00	0.036	4	0.062	4.00	0.012
4	4	0.083	7.50	0.040	5	0.096	8.00	0.057	4	0.070	4.50	0.017
5	4	0.080	7.50	0.037	5	0.088	7.50	0.045	4	0.068	4.50	0.017
6	4	0.119	8.00	0.090	5	0.078	6.50	0.031	4	0.048	3.00	0.005
7	4	0.099	7.00	0.054	4	0.089	6.00	0.038	4	0.067	4.25	0.015
8	3	0.088	7.00	0.042	4	0.062	4.50	0.014	4	0.054	3.50	0.008
9	3	0.068	6.50	0.024	4	0.083	6.00	0.032	4	0.076	5.00	0.023
10	3	0.075	6.50	0.029	4	0.081	5.50	0.029	4	0.059	3.75	0.010
11	3	0.086	6.50	0.038	4	0.076	5.50	0.025	4	0.078	5.00	0.024
12	3	0.065	7.00	0.023	4	0.065	4.50	0.015	3	0.067	4.50	0.016
13	3	0.072	6.50	0.026	3	0.059	4.50	0.012	3	0.054	3.50	0.008
14	3	0.089	7.50	0.047	3	0.054	4.00	0.009	3	0.062	3.50	0.011
15	2	0.064	4.50	0.014	3	0.056	4.50	0.011	3	0.065	4.00	0.013
16	2	0.070	4.50	0.017	3	0.053	4.00	0.009	3	0.068	4.50	0.017
17	2	0.061	4.25	0.012	3	0.067	4.50	0.016	3	0.064	4.00	0.013
18	2	0.056	4.00	0.010	3	0.065	4.50	0.015	3	0.072	5.00	0.020
19	2	0.051	3.75	0.008	3	0.073	5.50	0.023	3	0.057	3.50	0.009
20	2	0.065	4.50	0.015	3	0.072	5.50	0.022	3	0.072	5.00	0.020
Mean		0.080	6.43	0.037	Mean	0.074	5.63	0.026	Mean	0.065	4.20	0.015
SEd		0.004	0.360	0.005	SEd	0.003	0.283	0.003	SEd	0.002	0.139	0.001
CD(0.05)		0.039	3.381	0.051	CD(0.05)	0.027	2.658	0.030	CD(0.05)	0.017	1.304	0.011

Table 5. Biometric attributes of 0–5 years old age class farm grown teak (Boundary plantations) in three agroclimatic zones of Tamil Nadu.

Zone	High Rainfall Zone				Southern Zone				Cauvery Delta Zone			
Tree No	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)
1	8	0.121	10.00	0.115	10	0.119	9.00	0.101	10	0.124	10.00	0.121
2	8	0.111	9.75	0.095	10	0.092	7.50	0.050	10	0.123	10.00	0.118
3	8	0.099	9.00	0.069	10	0.121	9.50	0.109	10	0.104	9.00	0.076
4	8	0.102	9.25	0.075	10	0.110	8.50	0.081	10	0.115	9.50	0.098
5	8	0.089	8.75	0.055	10	0.105	8.50	0.074	10	0.118	9.75	0.106
6	8	0.092	8.50	0.057	10	0.115	9.00	0.093	10	0.108	9.00	0.083
7	8	0.107	9.00	0.080	8	0.089	8.00	0.050	10	0.121	10.00	0.115
8	8	0.116	9.75	0.103	8	0.097	8.50	0.063	10	0.099	9.00	0.069
9	8	0.127	10.00	0.127	8	0.094	8.50	0.059	8	0.121	9.50	0.109
10	8	0.110	9.00	0.085	8	0.086	7.50	0.044	8	0.113	9.00	0.090
11	8	0.118	9.00	0.098	8	0.083	7.50	0.040	8	0.105	8.50	0.074
12	8	0.124	9.75	0.118	8	0.096	8.00	0.057	8	0.118	9.50	0.104
13	8	0.092	8.00	0.054	6	0.073	6.00	0.025	6	0.081	7.50	0.039
14	8	0.099	8.50	0.065	6	0.091	7.50	0.049	6	0.113	9.00	0.090
15	8	0.104	8.75	0.074	6	0.086	7.00	0.041	6	0.086	7.50	0.044
16	8	0.131	10.00	0.134	6	0.083	7.00	0.038	6	0.105	8.50	0.074
17	8	0.096	8.00	0.057	6	0.084	7.50	0.042	6	0.097	8.00	0.059
18	8	0.083	7.50	0.040	6	0.092	8.00	0.054	6	0.084	7.50	0.042
19	8	0.109	9.00	0.084	6	0.097	7.50	0.056	6	0.083	7.00	0.038
20	8	0.099	8.00	0.061	6	0.102	8.50	0.069	6	0.094	8.00	0.055
Mean		0.106	8.98	0.082	Mean	0.096	7.95	0.060	Mean	0.106	8.79	0.080
SEd		0.003	0.167	0.006	SEd	0.003	0.185	0.005	SEd	0.003	0.209	0.006
CD(0.05)		0.028	1.569	0.056	CD(0.05)	0.027	1.734	0.047	CD(0.05)	0.030	1.966	0.058

Table 6. Biometric attributes of 5–10 years old age class farm grown teak (Boundary plantations) in three agroclimatic zones of Tamil Nadu.

Zone	High Rainfall Zone				Southern Zone				Cauvery Delta Zone			
Tree No	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)
1	15	0.191	11.25	0.323	15	0.180	10.50	0.267	12	0.169	11.25	0.252
2	15	0.183	10.75	0.283	15	0.185	10.50	0.281	12	0.161	11.00	0.223
3	15	0.185	11.00	0.295	15	0.202	11.00	0.353	12	0.159	11.00	0.219
4	15	0.172	10.50	0.244	15	0.204	11.25	0.367	12	0.172	11.50	0.267
5	15	0.188	11.00	0.305	15	0.197	10.75	0.329	12	0.156	10.75	0.206
6	15	0.169	10.75	0.240	15	0.210	11.50	0.399	12	0.153	10.75	0.197
7	15	0.177	11.00	0.270	15	0.188	10.50	0.291	12	0.162	11.00	0.228
8	15	0.158	10.50	0.205	15	0.201	11.00	0.348	12	0.158	10.75	0.210
9	15	0.178	11.00	0.275	13	0.129	10.50	0.137	12	0.166	11.25	0.242
10	15	0.186	11.00	0.300	13	0.131	10.50	0.141	12	0.159	10.75	0.214
11	15	0.156	10.50	0.200	13	0.143	11.00	0.177	12	0.172	11.50	0.267
12	15	0.166	10.75	0.231	13	0.126	10.00	0.124	12	0.151	10.75	0.193
13	15	0.153	10.00	0.183	12	0.154	11.00	0.206	12	0.143	10.50	0.169
14	15	0.175	10.75	0.259	12	0.143	10.50	0.169	12	0.150	10.75	0.189
15	15	0.193	11.25	0.328	12	0.134	10.00	0.140	12	0.167	11.00	0.241
16	15	0.197	11.50	0.352	12	0.126	9.50	0.118	12	0.164	11.00	0.232
17	15	0.194	11.25	0.333	12	0.140	10.50	0.162	12	0.169	11.00	0.246
18	15	0.180	11.00	0.280	12	0.123	9.50	0.112	12	0.156	10.75	0.206
19	15	0.150	10.00	0.176	12	0.151	11.50	0.207	12	0.154	10.50	0.197
20	15	0.161	10.50	0.213	12	0.134	10.75	0.151	12	0.159	11.00	0.219
Mean		0.176	10.81	0.265	Mean	0.160	10.61	0.224	Mean	0.160	10.94	0.221
SEd		0.003	0.089	0.012	SEd	0.007	0.125	0.021	SEd	0.002	0.063	0.006
CD(0.05)		0.031	0.832	0.109	CD(0.05)	0.067	1.174	0.201	CD(0.05)	0.016	0.587	0.055

Table 7. Biometric attributes of 10–15 years old age class farm grown teak (Boundary plantations) in three agroclimatic zones of Tamil Nadu.

Zone	High Rainfall Zone				Southern Zone				Cauvery Delta Zone			
Tree No	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)	Age (years)	DBH (m)	Tree Height (m)	Tree Volume (m^3)
1	20	0.330	12.75	1.087	20	0.253	12.50	0.629	20	0.314	13.00	1.004
2	20	0.315	12.50	0.975	20	0.269	13.00	0.739	20	0.283	12.00	0.757
3	20	0.298	11.50	0.800	20	0.274	13.00	0.766	20	0.288	12.00	0.783
4	20	0.360	13.00	1.322	20	0.248	12.50	0.606	20	0.293	12.50	0.842
5	20	0.322	12.00	0.975	20	0.275	13.00	0.774	20	0.299	12.75	0.897
6	20	0.346	13.00	1.219	20	0.277	13.00	0.783	20	0.283	12.00	0.757
7	20	0.314	11.50	0.888	20	0.252	12.50	0.621	20	0.269	11.50	0.654
8	20	0.293	11.00	0.741	20	0.250	12.50	0.613	20	0.296	12.50	0.861
9	20	0.323	12.50	1.025	20	0.280	13.00	0.802	20	0.306	13.00	0.954
10	20	0.313	11.50	0.885	20	0.287	13.00	0.838	20	0.271	11.50	0.662
11	20	0.344	12.00	1.114	18	0.285	12.00	0.765	18	0.275	11.50	0.685
12	18	0.303	11.75	0.844	18	0.293	12.25	0.826	18	0.268	11.00	0.618
13	18	0.314	12.00	0.927	18	0.288	12.00	0.783	18	0.288	12.00	0.783
14	18	0.328	12.50	1.056	18	0.290	12.00	0.791	18	0.256	11.00	0.568
15	18	0.322	12.50	1.015	18	0.279	11.75	0.716	18	0.280	11.75	0.725
16	18	0.274	11.50	0.677	18	0.287	12.00	0.774	18	0.256	10.50	0.542
17	18	0.366	13.00	1.369	16	0.193	11.25	0.328	18	0.293	12.25	0.826
18	18	0.277	11.50	0.693	16	0.197	11.50	0.352	18	0.269	11.00	0.625
19	18	0.248	11.00	0.533	16	0.194	11.25	0.333	18	0.291	12.00	0.800
20	18	0.229	10.75	0.444	16	0.180	11.00	0.280	18	0.295	12.25	0.835
Mean		0.311	11.99	0.930	Mean	0.258	12.25	0.656	Mean	0.284	11.90	0.759
SEd		0.008	0.158	0.054	SEd	0.008	0.147	0.041	SEd	0.003	0.154	0.028
CD (0.05)		0.072	1.480	0.506	CD (0.05)	0.077	1.384	0.388	CD(0.05)	0.033	1.449	0.262

Table 8. Biometric attributes of 15–20 years old age class farm grown teak (Boundary plantations) in three agroclimatic zones of Tamil Nadu.

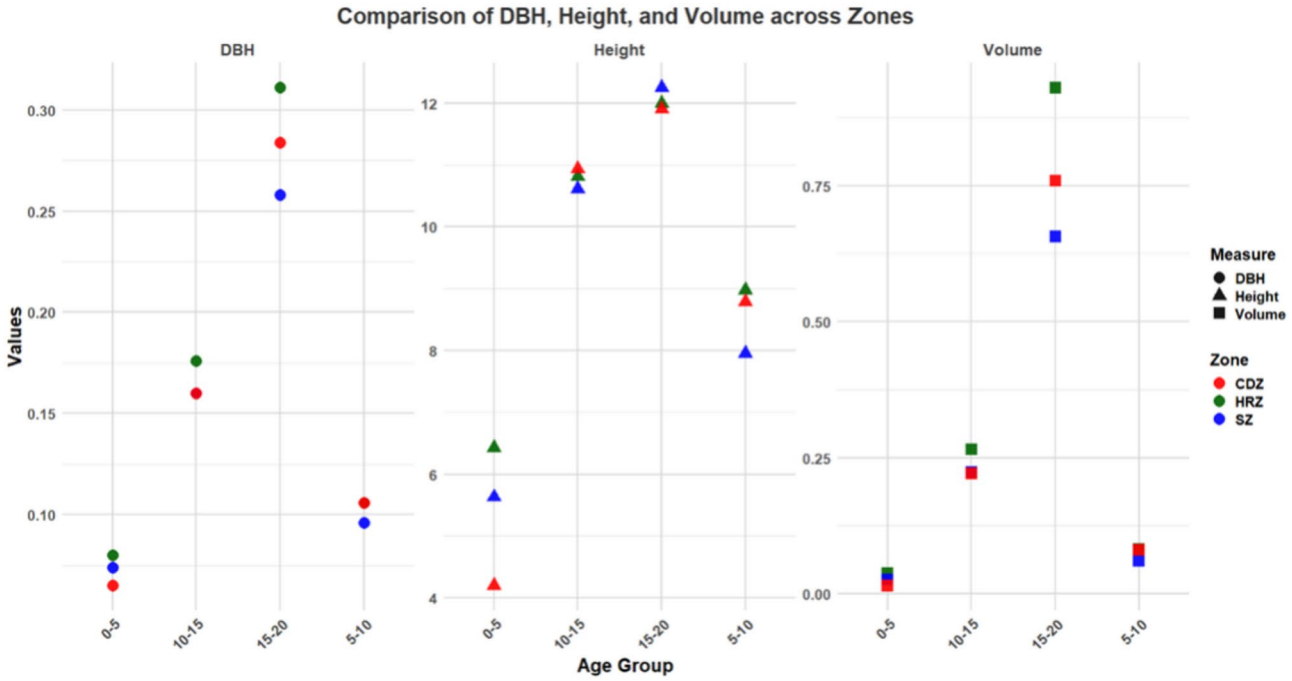

Fig. 3. Comparison of growth attributes of farm grown teak in boundary plantations of different zones.

Zone	High Rainfall Zone				Southern Zone				Cauvery Delta Zone			
Year	Average Annual Rainfall (mm)	Temperature		Relative Humidity (%)	Average Annual Rainfall (mm)	Temperature		Relative Humidity (%)	Average Annual Rainfall (mm)	Temperature		Relative Humidity (%)
		Max (°C)	Min (°C)			Max (°C)	Min (°C)			Max (°C)	Min (°C)	
2001	1977.54	39.32	15.98	82.75	1059.96	42.44	14.99	72.06	664.45	42.33	16.37	69.25
2002	1360.55	37.95	15.63	79.62	764.65	41.02	14.59	68.44	548.44	41.80	15.89	66.25
2003	1328.91	36.72	15.65	81.25	1012.50	40.83	15.15	70.62	785.74	41.17	16.42	68.94
2004	1829.88	39.07	15.46	81.88	1307.81	42.39	15.05	73.12	975.59	42.80	15.62	71.62
2005	1845.70	39.23	16.15	82.94	1402.73	40.81	14.81	73.44	1133.79	40.87	15.74	71.06
2006	2072.46	38.77	14.79	83.38	1128.52	41.60	14.09	73.81	748.83	42.08	14.51	71.44
2007	1265.62	39.56	14.64	80.88	780.47	41.25	14.38	68.12	696.09	41.48	14.38	67.56
2008	1302.54	35.90	15.10	81.81	980.86	39.92	13.64	71.38	991.41	40.54	14.94	71.69
2009	980.86	39.00	15.46	77.88	595.90	42.45	15.23	64.75	616.99	42.19	16.23	65.69
2010	1096.88	39.31	16.63	79.31	986.13	41.40	15.47	68.38	1001.95	41.67	16.28	69.94
2011	759.38	38.65	15.76	76.75	727.23	40.32	14.87	68.50	806.84	40.23	15.20	69.62
2012	727.73	38.45	15.48	76.50	553.71	40.66	14.35	65.19	622.27	41.04	15.08	67.31
2013	965.04	38.62	16.78	78.44	585.35	42.23	15.83	63.62	580.08	42.53	16.31	64.75
2014	1207.62	39.25	16.82	79.38	775.20	41.15	16.15	67.00	738.28	41.27	17.05	66.88
2015	1360.55	37.64	15.95	81.12	970.31	38.83	15.26	71.38	1065.23	40.13	15.78	71.25
2016	495.70	39.54	16.07	75.44	479.88	43.33	15.90	64.25	421.88	43.60	16.07	64.81
2017	912.30	39.15	16.48	76.38	896.48	42.74	15.73	68.69	738.28	43.08	15.87	67.81
2018	827.93	38.26	16.75	78.56	733.01	39.86	14.85	68.62	606.45	40.08	15.55	68.38
2019	1081.05	39.75	16.12	76.00	891.21	41.55	15.09	66.88	849.02	42.73	16.05	66.94
2020	928.12	38.71	17.29	78.62	1059.96	41.23	16.80	70.50	938.67	41.98	16.79	70.38
2021	1899.07	38.52	15.23	83.69	1379.36	40.86	14.16	75.56	1339.78	40.73	15.24	75.38
Mean	1248.83	38.64	15.92	79.65	908.15	41.28	15.07	69.25	803.34	41.63	15.78	68.90

Table 9. Climatic variables for three agroclimatic zones of Tamil Nadu.

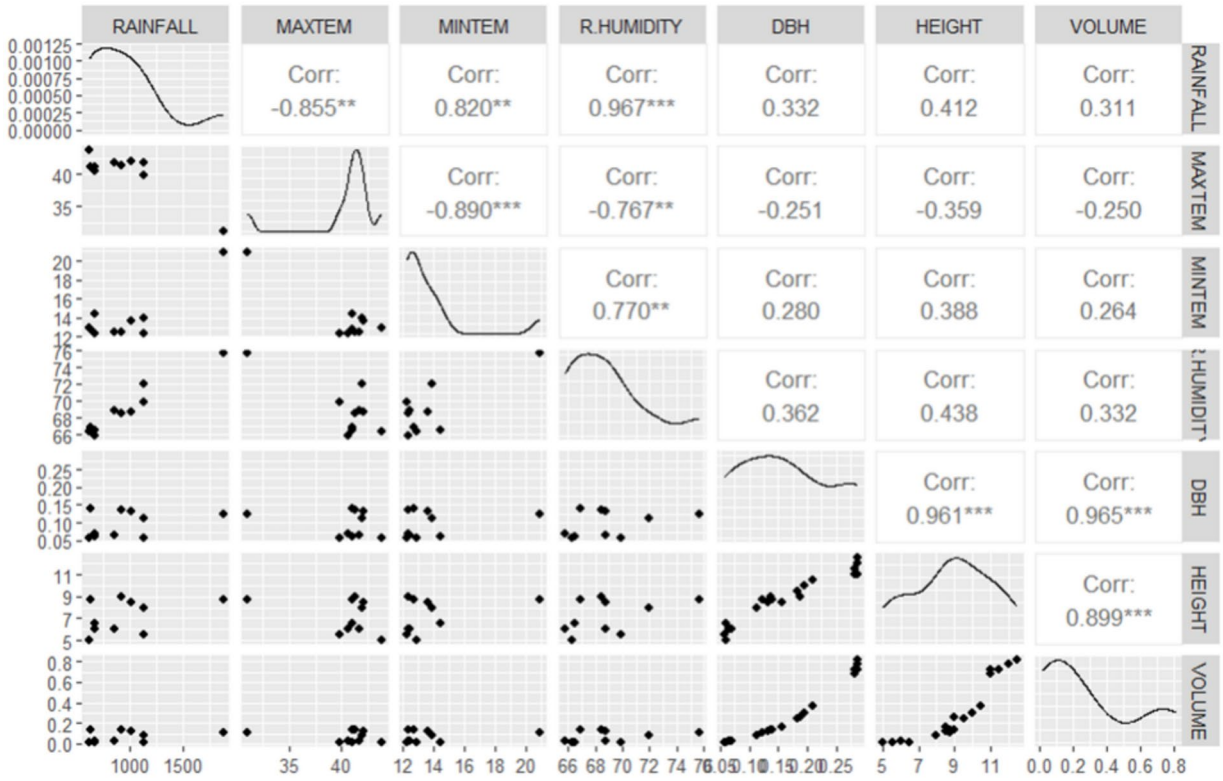

Fig. 4. Correlation for Tree biometrics versus Climatic factors in block plantations of High Rainfall Zone.

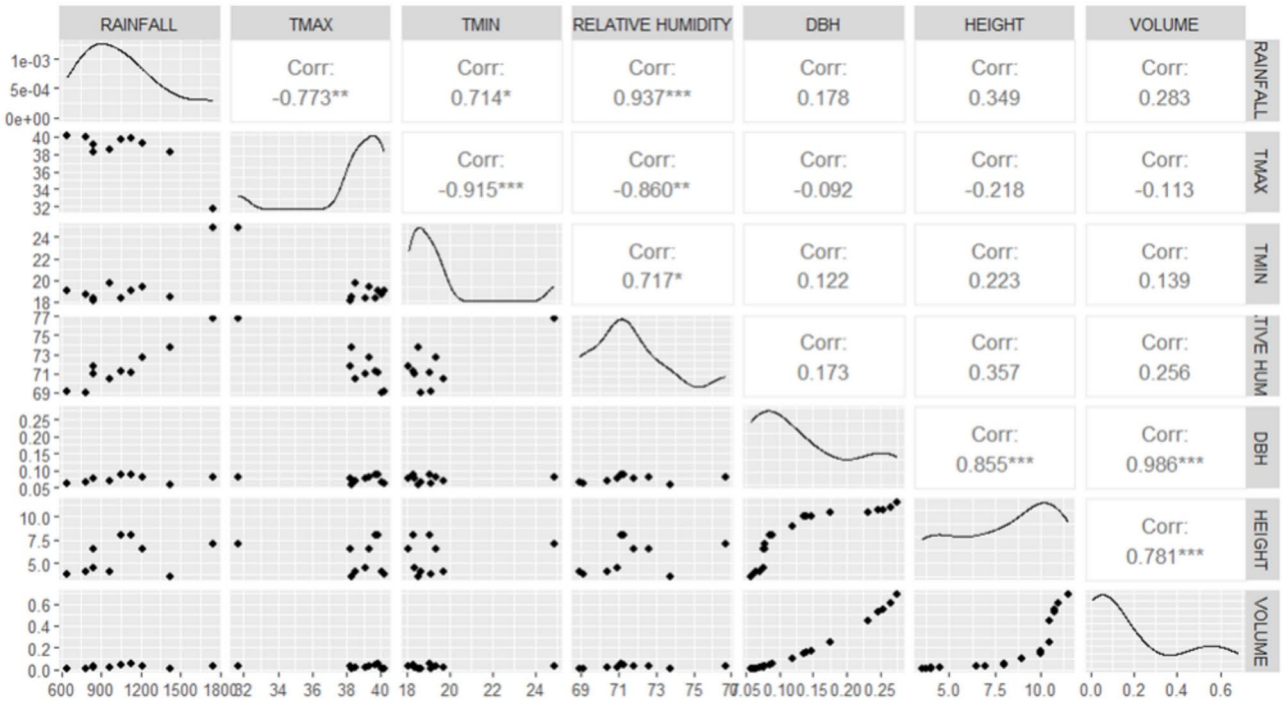

Fig. 5. Correlation for Tree biometrics versus Climatic factors in block plantations of Southern Zone.

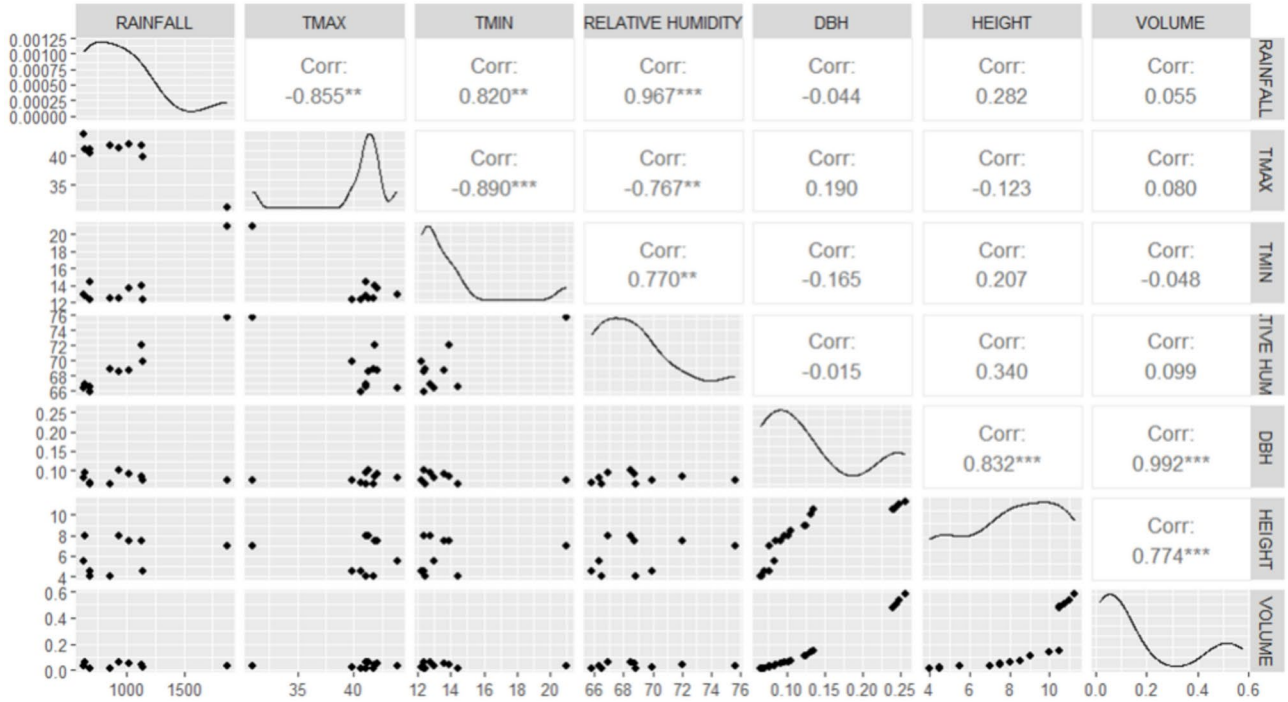

Fig. 6. Correlation for Tree biometrics versus Climatic factors in block plantations of Cauvery Delta Zone.

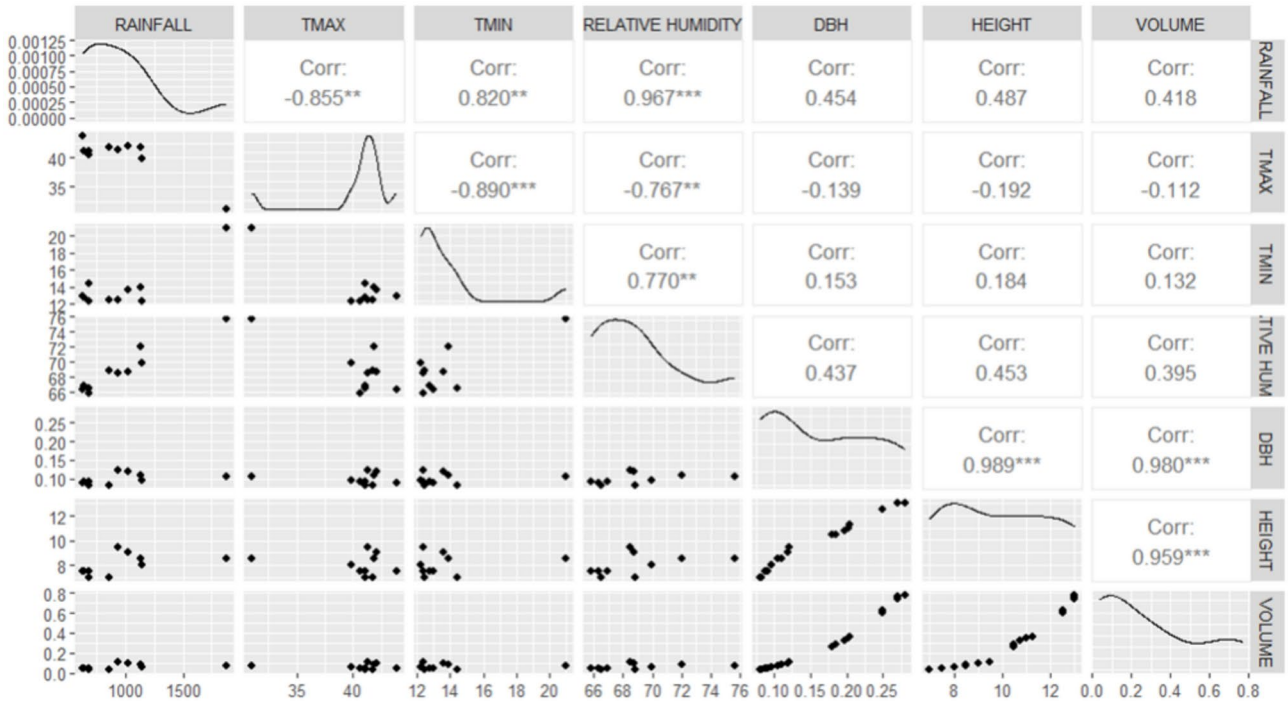

Fig. 7. Correlation for Tree biometrics versus Climatic factors in boundary plantations of High Rainfall Zone.

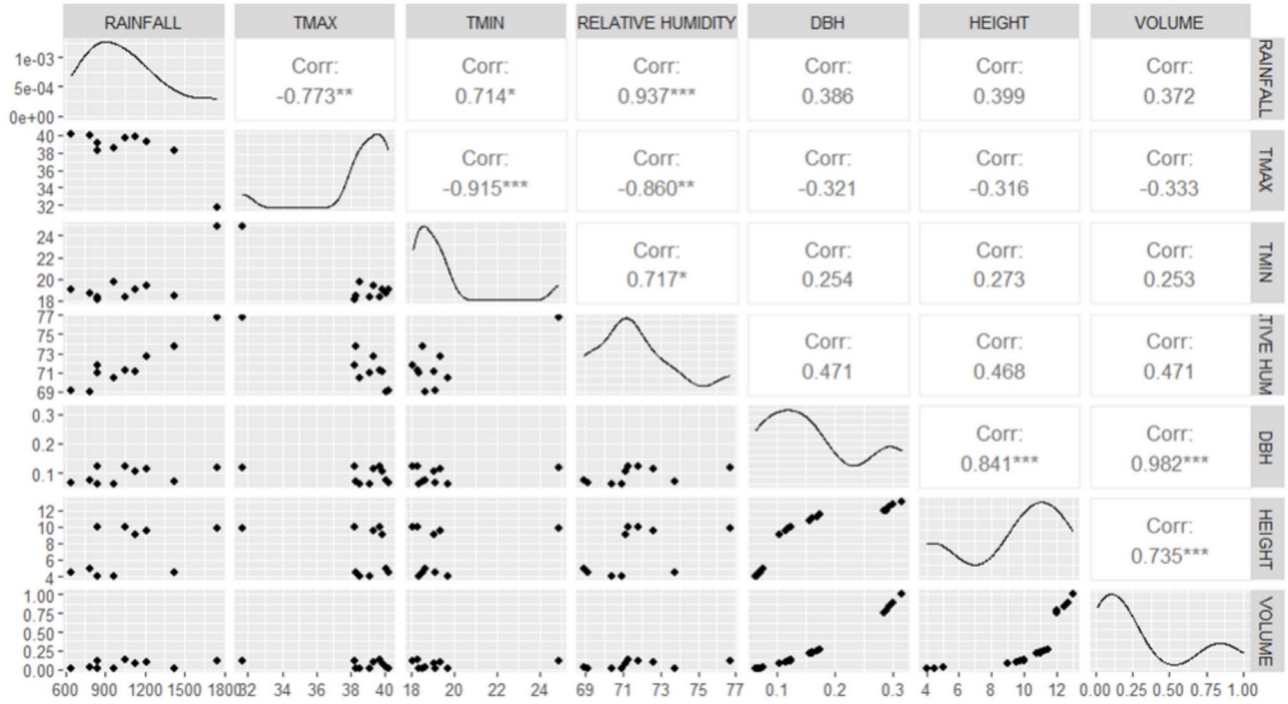

Fig. 8. Correlation for Tree biometrics versus Climatic factors in boundary plantations of Southern Zone.

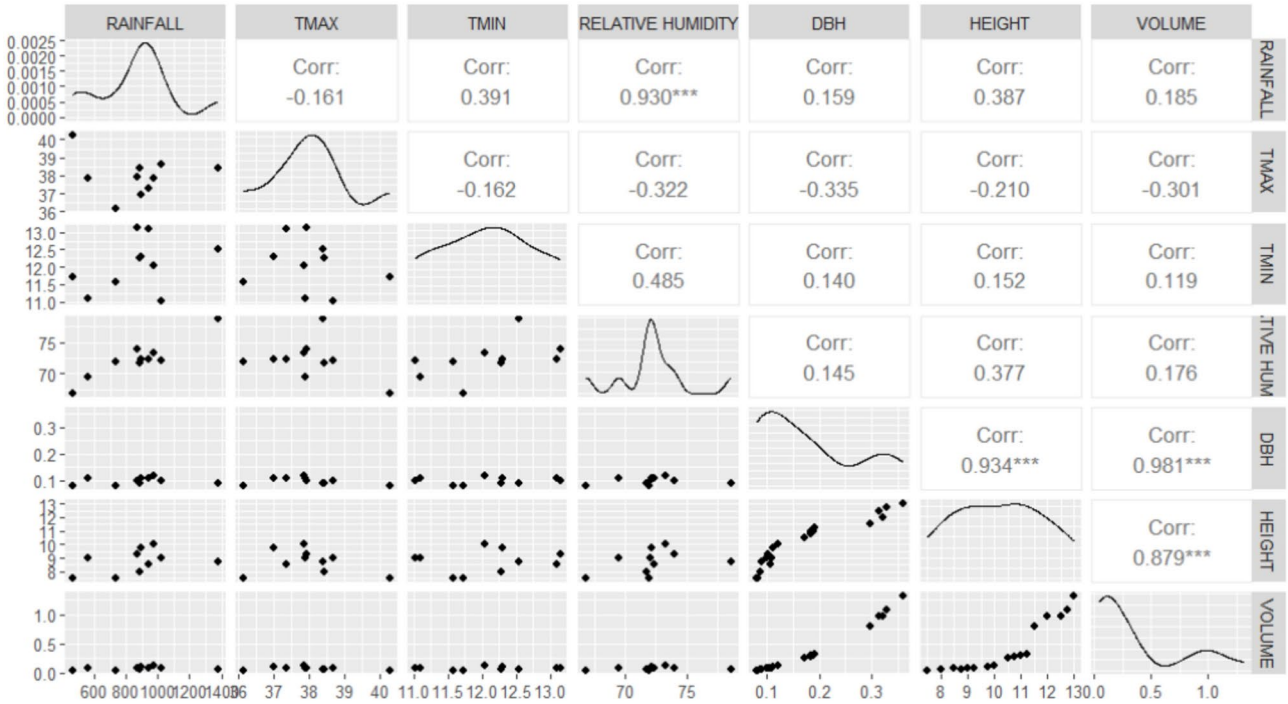

Fig. 9. Correlation for Tree biometrics versus Climatic factors in boundary plantations of Cauvery Delta Zone.

Sl. No	Location	Age class (Years)	Soil pH	EC (dS/m)	Organic Carbon (%)	Available Nitrogen (Kg/ha)	Available Phosphorous (Kg/ha)	Available Pottasium (Kg/ha)	Bulk Density (g/cm^3)	Total Porosity (%)	Soil Texture
Surface Soil (0–15 cm)											
1	Kadayal (HRZ)	0–5	7.20	0.14	0.54	197	22.00	340	1.34	51.10	SL
2	Mankuzhy (HRZ)	6–10	7.74	0.17	0.46	186	19.50	285	1.39	47.60	SL
3	Udayarpallam (HRZ)	11–15	7.45	0.12	0.58	181	17.00	265	1.47	44.86	SL
4	Kilathoor (HRZ)	16–20	7.58	0.16	0.62	184	20.00	320	1.42	45.53	SL
5	Puliyangudi (SZ)	0–5	8.23	0.22	0.44	192	21.50	295	1.38	48.24	SL
6	Asthikulam (SZ)	6–10	8.01	0.19	0.53	188	20.00	270	1.38	47.80	SL
7	Vijayamangalam (SZ)	11–15	8.20	0.23	0.47	171	15.50	255	1.51	43.65	SL
8	Dindigul (SZ)	16–20	7.43	0.16	0.54	182	17.00	268	1.44	45.60	SL
9	Kurumbur (CDZ)	0–5	8.03	0.21	0.45	189	19.00	290	1.39	48.21	SL
10	Karunthirankottai(CDZ)	6–10	7.72	0.18	0.57	183	17.50	277	1.48	43.45	SL
11	Poovatrukudi (CDZ)	11–15	7.56	0.14	0.60	176	15.00	269	1.52	43.10	SL
12	Pudhukottai (CDZ)	16–20	7.89	0.19	0.49	174	15.00	260	1.53	42.78	SL
Mean			7.75	0.18	0.52	183.58	18.25	282.83	1.44	45.99	
Sed			0.09	0.01	0.02	2.17	0.70	7.32	0.02	0.75	
CD (0.05)			0.68	0.07	0.13	15.80	5.11	53.27	0.13	5.45	
Subsurface Soil (15–30 cm)											
1	Kadayal (HRZ)	0–5	7.34	0.16	0.49	193	20.5	328	1.36	48.85	SCL
2	Mankuzhy(HRZ)	6–10	7.89	0.14	0.43	184	18	279	1.41	45.78	SCL
3	Udayarpallam(HRZ)	11–15	7.62	0.15	0.55	178	15	258	1.52	43.41	SCL
4	Kilathoor (HRZ)	16–20	7.76	0.24	0.56	177	19	301	1.48	43.52	SCL
5	Puliyangudi (SZ)	0–5	8.12	0.20	0.41	189	18.5	289	1.43	44.67	SCL
6	Asthikulam (SZ)	6–10	7.91	0.21	0.47	184	18	265	1.49	44.90	SCL
7	Vijayamangalam(SZ)	11–15	8.3	0.18	0.40	165	16	240	1.57	40.61	SCL
8	Dindigul (SZ)	16–20	7.54	0.19	0.48	176	15.5	260	1.51	43.30	SCL
9	Kurumbur (CDZ)	0–5	8.19	0.17	0.46	185	17	281	1.44	45.90	SCL
10	Karunthirankottai(CDZ)	6–10	7.85	0.14	0.51	180	16	270	1.56	41.56	SCL
11	Poovatrukudi (CDZ)	11–15	7.67	0.18	0.50	173	14.5	266	1.59	40.53	SCL
12	Pudhukottai (CDZ)	16–20	8.05	179.67	0.47	172	15	245	1.59	40.02	SCL
Mean			7.85	0.17	0.48	2.26	16.92	273.50	1.50	43.59	
Sed			0.08	0.01	0.01	16.42	0.54	7.04	0.02	0.76	
CD(0.05)			0.60	0.07	0.10	16.42	3.95	51.25	0.16	5.52	

Table 10. Soil physico-chemical properties of three agroclimatic zones of Tamil Nadu. SL, Sandy Loam; SCL, Sandy Clay Loam.

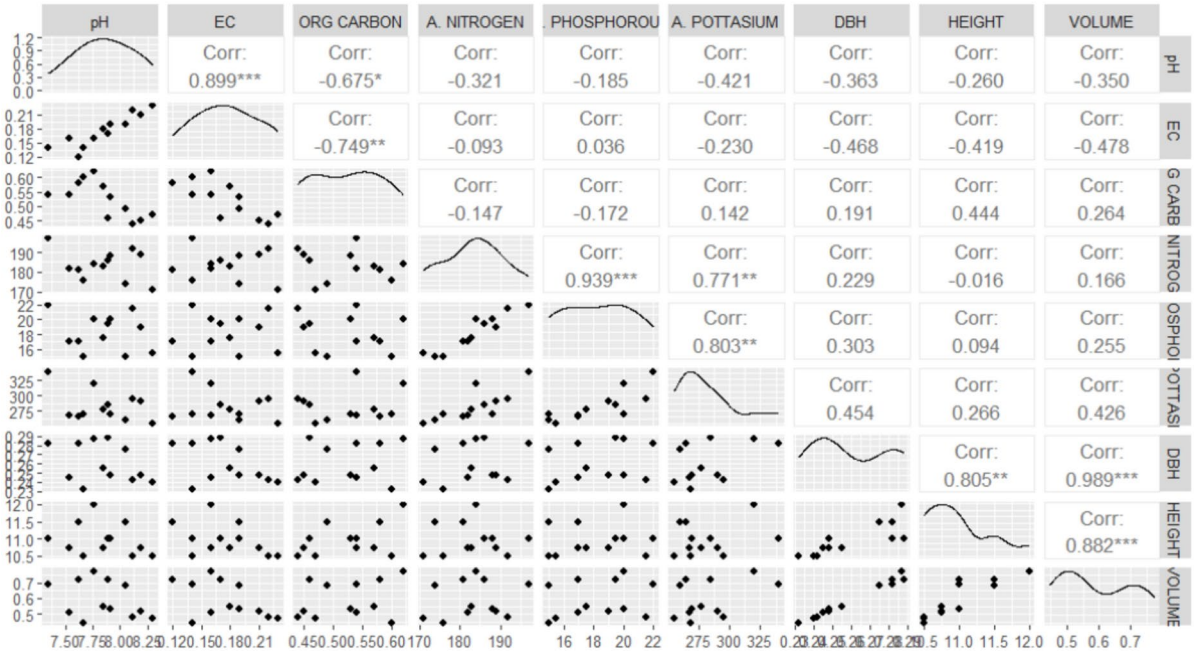

Fig. 10. Correlation for Tree biometrics versus Edaphic factors in block plantations.

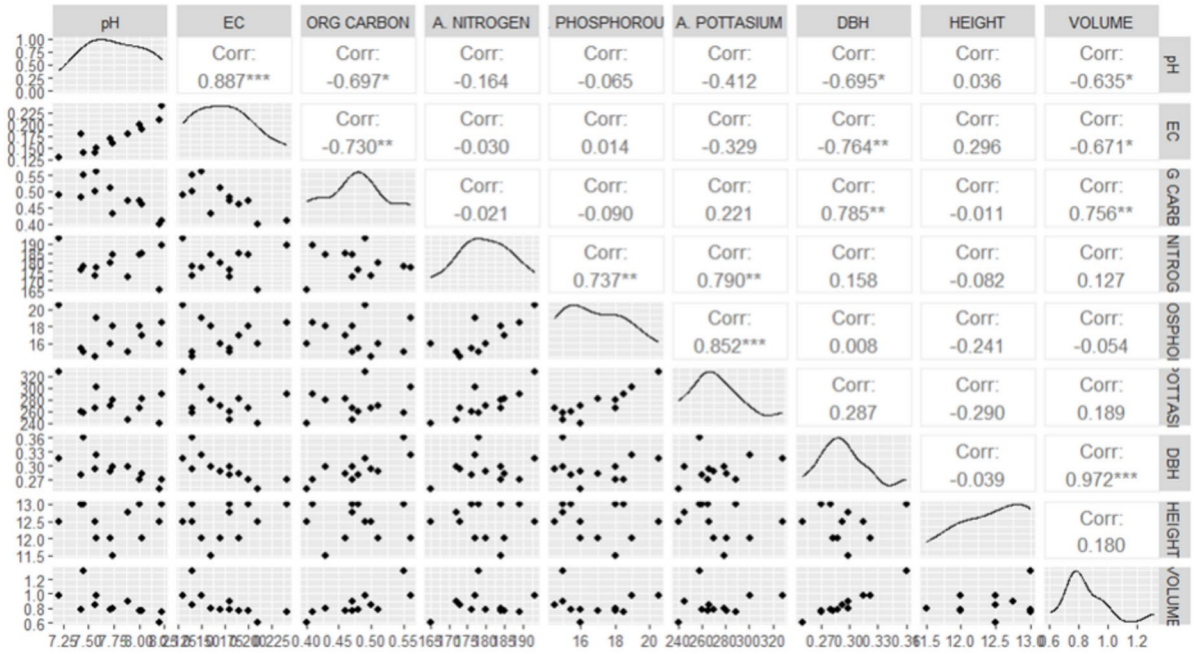

Fig. 11. Correlation for Tree biometrics versus Edaphic factors in boundary plantations.

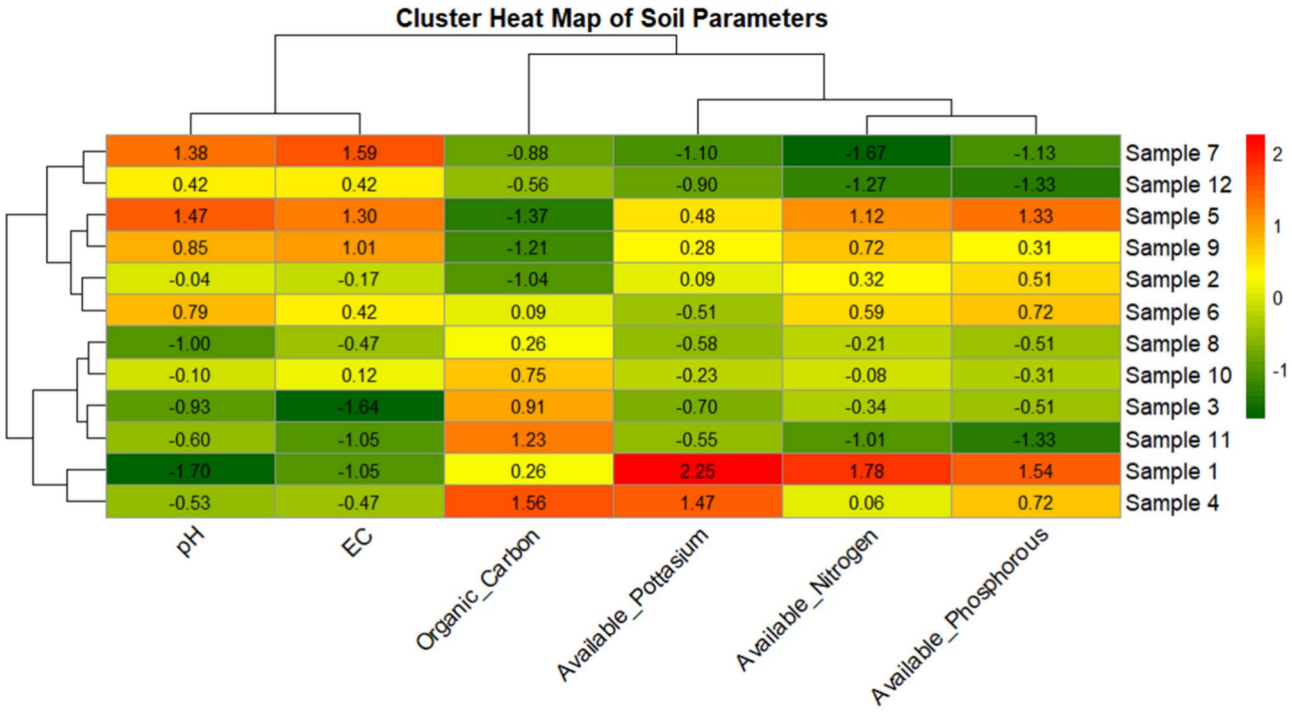

Fig. 12. Cluster heat map of edaphic parameters for three agroclimatic zones (Sample 1-Kadayal (HRZ), Sample 2-Mankuzhy (HRZ), Sample 3-Udayarpallam (HRZ), Sample 4-Kilathoor (HRZ), Sample 5-Puliyangudi (SZ), Sample 6-Asthikulam (SZ), Sample 7-Vijayamangalam (SZ), Sample 8-Dindigul (SZ), Sample 9-Kurumbur (CDZ), Sample 10-Karunthirankottai (CDZ), Sample 11-Poovatrukudi (CDZ), Sample 12-Pudhukottai (CDZ)).

significant negative correlation was observed between available phosphorous and tree volume of *Melia dubia* plantations[73]. Paradoxical to the current study, the studies on growth of teak in drought conditions by Santosa et al.[74], revealed that available phosphorous had a major role in improving the growth attributes of teak in comparison to available nitrogen and available potassium. This may hold true in draught conditions because, available nitrogen and available potassium are generally less mobile whereas in contrast, phosphorus has a different mode of uptake, and under drought conditions, its relative availability and importance might increase because of its role in maintaining growth despite limited water[75].

Thus, overall conclusion can be drawn from the correlation studies between soil parameters and tree growth that, soil organic carbon is the most positively contributing factor among all other edaphic parameters, whereas soil pH and soil electrical conductivity are the factors that have adverse effects on determining the growth of teak raised in farmlands.

Cluster heat map for Edaphic parameters

In the present investigation, a cluster heatmap was developed to reveal key relationships between soil parameters collected from different agroclimatic zones and also to graphically visualize them (Fig. 12). From figure, it could be visualized that parameters like Available Potassium and Available Nitrogen cluster together, suggesting they vary similarly, whereas pH and Electrical conductivity exhibit a similar trend. The colour gradient highlights significant variations, with Sample 1 (HRZ) displaying high nutrient values and indicates a nutrient-rich profile, whereas Sample 11 (CDZ) shows lower values, suggesting poorer soil quality. These cluster heat maps can guide soil management practices, optimizing fertilizer use and improving crop selection and agricultural efficiency[76]. Similarly, the work carried out by Abdel et al.[77], Withers et al.[78] and Keshavarzhi & Kumar[79] also used cluster heat map for visualization of soil parameters.

Principal component analysis

Principal component analysis (PCA) was carried out to illustrate the variation in tree growth in relation to climatic and edaphic parameters. PCA biplot (Fig. 13), across three distinct zones, i.e. HRZ (red), SZ (blue) and CDZ (green) consists of axes, Dim1 and Dim2 that represent the first two principal components, which together explain 100% of the variance in the data, with Dim1 accounting for 84.4% and Dim2 for 15.6%. The analysis results reveal that, among the three zones taken into consideration, high rainfall zone exhibit higher growth performance along with closer positive association with parameters like soil organic carbon, annual rainfall, minimum temperature etc. This strongly suggest that high rainfall zone is the most suitable zone for teak cultivation. Meanwhile, Cauvery delta zone shows strong association with maximum temperature, soil pH and electrical conductivity, hence they display poor growth performance among the three zones taken into consideration. The research work of Joswig et al.[80] on determination of soil and climatic influence on plant trait

(Sample 1- Kadayal (HRZ), **Sample 2-**Mankuzhy (HRZ), **Sample 3-**Udayarpallam (HRZ), **Sample 4-**Kilathoor (HRZ), **Sample 5-**Puliyangudi (SZ), **Sample 6-**Asthikulam (SZ), **Sample 7-**Vijayamangalam (SZ), **Sample 8-**Dindigul (SZ), **Sample 9-**Kurumbur (CDZ), **Sample 10-**Karunthirankottai(CDZ), **Sample 11-**Poovatrukudi (CDZ), **Sample 12-**Pudhukottai (CDZ) **)**

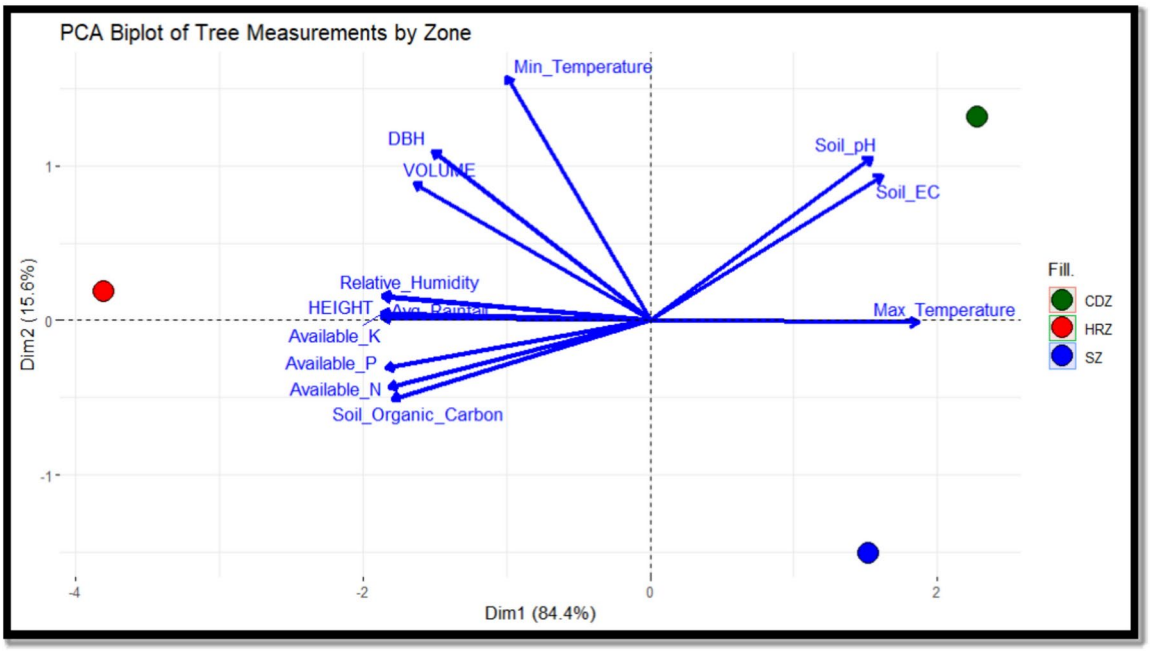

Fig. 13. Principal Component Analysis Biplot for growth and edapho-climatic parameters.

also employed principal component analysis. The studies of Zhou et al.[81] also employed principal component analysis for accurate determination of environmental influence on improving environmental quality.

Conclusion

Cultivating teak on farms has gained prominence as an environmentally conscious approach to meet both economic and ecological objectives. This current investigation, conducted under different age classes and zones has demonstrated that growth patterns of farm-grown teak in Tamil Nadu are significantly influenced by a combination of climate and soil parameters, which also vary significantly across the three agroclimatic zones taken into consideration. The study result with respect to growth biometry suggest that plantations of age class of 15–20 years show higher growth performance and hence can be formulated as suitable age class for harvesting. The correlation analysis and principal component analysis has strongly suggested that edaphic factors and climatic variables play a very crucial role in the growth and development of teak raised in farmlands. Among all climatic variables, annual rainfall and humidity play a positive role in determining the growth rate, whereas maximum temperature fluctuations have negative impacts on growth of farm grown teak. Similarly, with respect to edaphic factors, soil organic carbon has influences beneficial for tree growth and conversely, soil pH and electrical conductivity have detrimental effects on tree growth. The results also strongly portray that High Rainfall Zone exhibiting high annual rainfall, favourable minimum temperature, low bulk density, high porosity, high soil organic carbon along with optimal pH and electrical conductivity display much better growth performance when compared to other zones. Thus, overall conclusions can be drawn that High Rainfall Zone with optimal edapho climatic conditions is the most suitable zone for cultivation of teak to obtain favourable outcome.

Data availability

The datasets used during the current study will be available from the corresponding author on reasonable request, because the datasets were collected from nearly 200 different plantations and is highly voluminous to be listed in this publication. Further based on the need of the requesters the datasets may be provided personally to them by the corresponding author if necessary.

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Author contributions

This manuscript is a complete outcome of review carried out by all the authors. The authors 1, 2 and 3 were the main manuscript writers whereas other inputs like tables, figures etc. were compiled by other authors. The 6th author helped in performing statistical analysis using R-software.

Declarations

Competing interests

The authors declare no competing interests.

The collection of plant material

The collection of plant material was carried out in private plantations with prior and proper permission from respective plantation owners. The study was hence done in accordance with institutional, national and international guidelines and legislation.

Permission was obtained from the respective plantation owners

Permission was obtained from the respective plantation owners for the collection of Teak (*Tectona grandis* Linn. f) grown under farm conditions.

Additional information

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