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Root Plasticity as Influenced by Planting Material and Planting Density in Teak Using Logarithmic Spiral Trenching in Kerala, India

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Abstract: Teak (*Tectona grandis* L.f.), a premier tropical timber species, is widely adopted in agroforestry systems, though its shallow, spreading root system raises concerns over competition with intercrops. Traditionally established through stump planting teak typically develops horizontally oriented, fibrous roots with limited vertical development. Alternatively, root trainer seedlings are hypothesized to promote deeper, more compact root systems, potentially mitigating belowground competition. This study investigates the root distribution of five-year-old teak plantations established through stump and root trainer methods at 3 × 3 m spacing in Karakkad, Kalady Range, Malayattoor Forest Division, Kerala, using the logarithmic spiral trenching method. Additionally, it evaluates the effect of tree spacing (2 × 2 m vs. 3 × 3 m) on the root distribution of root trainer-raised teak. Root intensity (roots m^{-2}) was quantified at various lateral distances from the teak plants and soil depths up to 50 cm. Root trainer-grown trees consistently showed higher root intensities (3205 roots m^{-2}) than stump-grown trees (2750 roots m^{-2}) at 0.35 m lateral distance, while the corresponding root intensities were 1355 and 900 roots m^{-2} at 2.35 m lateral distance from the tree base, for root trainer and stump-grown trees, respectively. Root trainer seedlings also exhibited higher root presence at deeper soil layers. Tree spacing significantly influenced the rooting behavior with the closely spaced (2 x 2 m) stand showing root intensity confining to the proximal distance to the tree while the widely spaced (3 x 3 m) stand showed better root spread with respect to vertical and lateral distribution. The findings demonstrate the superior vertical rooting of root trainer-raised teak, reducing crop competition and improving resource uptake making it well-suited for agroforestry. The spacing-induced root plasticity highlights the importance of tree density in shaping root distribution patterns and optimizing belowground resource utilization in a plantation as well as agroforestry systems.

Keywords: Agroforestry, Root distribution, Root trainer seedlings, Spiral trenching, Stump planting

Teak (*Tectona grandis* L. f.) is one of the highly valued tropical hardwood species globally, known for its superior timber quality, durability, and high market demand. India accounts for approximately 35% of the world's planted teak area, with an estimated 1.7 million hectares under cultivation (IUFRO–TEAKNET 2022). Kerala holds a significant place in teak history, being home to the world's earliest managed teak plantations established in the 1840s at Nilambur (Chandrasekharan 1973). The major portion of teak timber supply originates from homegardens, which contribute nearly 80 per cent of the state's total timber output (Krishnankutty and Chundamannil 2012). However, despite its ecological and economic importance, the root system characteristics of teak particularly its shallow, spreading roots pose challenges in agroforestry contexts. When propagated through conventional root-shoot cuttings (stumps), teak tends to produce numerous fibrous roots concentrated in surface soil, leading to heavy competition for water and nutrients with adjacent crops (Khedkar and Subramanian 1997, Rao et al., 2001). This shallow rooting habit may also restrict anchorage and limit deeper resource uptake. In contrast, container-raised seedlings using root trainers are gaining prominence for producing more compact and deeper root systems that promote better vertical soil exploration and reduce belowground competition. Field studies in humid Kerala have shown that teak raised in root trainers outperforms stump-grown plants in early growth, including height, diameter, and survival rate, likely due to improved root system (George et al., 2019). Rooting depth, lateral spread, and root diameter classes have been recognized as critical determinants of root spread and resource acquisition patterns for optimizing tree–crop interactions, water and nutrient acquisition, and long-term plantation stability (Huang et al., 2024).

Although differences in nursery-level performance between stump-planted and root trainer-raised teak are well documented, limited research has examined their root distribution pattern under field conditions. Understanding how planting material influences root distribution is crucial for enhancing the design of agroforestry systems and improving resource-use efficiency. Similarly, the influence of spacing on root distribution remains poorly understood, particularly in the context of root trainer-grown teak plantations. In this regard, the present study investigates the comparative root distribution patterns of five-year-old teak plantations established using stump and root trainer planting materials under uniform spacing (3 × 3 m), employing the logarithmic spiral trenching method in the Malayattoor Forest Division, Kerala. Additionally, the study evaluates the effect of spacing on the root distribution of root trainer-grown teak. This study aims to assess both lateral and vertical rooting behavior across soil depths and distances from the tree base, providing insights into the suitability of each planting material and spacing regime for effective resource utilization.

MATERIAL AND METHODS

The study was carried out in five-year-old teak (*Tectona grandis* L. f.) plantations located at Karakkad Station (10°12′10.88″ N, 76°28′36.31″ E), within the Kalady Range of the Malayattoor Forest Division in Kerala, India. The area is characterized by a tropical monsoon climate, receiving an average annual rainfall of approximately 3000 mm, with mean annual maximum and minimum temperatures of 31.3 and 24.2 °C, respectively. The plantations were established using two types of planting materials: conventional stump plants (root-shoot cuttings) and root trainer-raised container seedlings with a 3 × 3 m spacing. For the experiment, three trees were randomly selected from each treatment combination (planting material × spacing × age class), ensuring uniformity in tree size and microsite conditions to reduce variability caused by site heterogeneity.

Spiral trenching method: To study root distribution, the logarithmic spiral trenching method was employed, with modifications suited to field conditions in tropical humid soils. This technique enables quantitative assessment of both lateral and vertical root spread with minimal disturbance to tree stability. The trench trajectory was laid out using a mathematical model based on the following equations:

$x = 1.5\,(d)$

$y = [\ln (r/d)]/\pi$

$z = x\, e^{y\theta}$

Where:

d = diameter at breast height (in meters)

r = average crown radius measured at four cardinal directions (in meters)

x = initial radial distance from the base of the tree (m)

θ = angle of measurement along the spiral arc (°), taken at 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°, and 180°

z = distance to the spiral point from the tree base at each angle (m)

Plastic ropes were used to mark the spiral layout, and trenching was done to a depth of 60 cm and width of 60 cm. Proper care was taken to prevent soil collapse and maintain trench wall integrity (Fig. 1).

Root sampling and classification: Root sampling was conducted along both the inner and outer walls of the trench using a 50 × 50 cm quadrat placed at four fixed lateral distances from the tree base: 0.35 m, 0.75 m, 1.55 m, and 2.35 m. Each quadrat was vertically divided into five successive soil depth intervals: 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm. Within each depth layer, all severed, live roots intersecting the quadrat surface were recorded. The roots were then classified into four diameter-based categories such as fine roots (<2 mm), small roots (2–5 mm), medium roots (>5 mm), and coarse roots (>1.0 cm). This systematic approach enabled the spatial and vertical distribution of root size classes to be assessed in relation to the tree base. The recorded root counts were converted into rooting intensity, expressed as the number of roots per square meter (roots/m²), following the protocol outlined by (Böhm 1979) . Statistical analysis was performed to evaluate differences in rooting intensity across various factors, including planting material types (stump vs. root trainer), soil depth classes, and lateral distances from the tree base. The independent t-test was employed to determine statistically significant differences between mean values.

RESULTS AND DISCUSSION

Influence of planting material on the root distribution: Root distribution was significantly influenced by the types of planting material used. In five-year-old plantations, root trainer-raised seedlings consistently exhibited higher total root intensity across all lateral distances compared to stump-grown trees (Table 1). At 0.35 m from the tree base, root trainer trees recorded 3205 roots m^{-2}, while stumps showed 2750 roots m^{-2}. This trend continued up to 2.35 m, with root trainer trees maintaining greater root presence

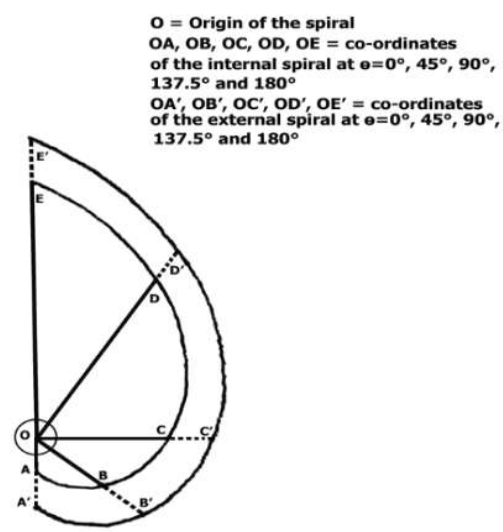

Fig. 1. Schematic diagram showing co-ordinates of logarithmic spiral trench

(1355 roots m⁻²) than stumps (900 roots m⁻²). Although root intensity declined with increasing lateral distance in both planting types, the decline was more gradual and sustained in root trainer trees, indicating a more expansive rooting pattern.

The changes in root intensity and distribution pattern for stump and root trainer grown teak stands showed interesting trends. In general, both the stands showed decrease in root intensity with increasing lateral distance from the tree base and increasing soil depth. However, the changing trends

Table 1. Total root intensity as affected by planting techniques and distance from the tree in five-year-old teak plantations

Planting techniques	Total root intensity (number per m^2) at different distance from the base of the tree (m)			
	0.35	0.75	1.55	2.35
Stump	2750	1510	1065	900
Root trainer	3205	1970	1965	1355
P value	0.064^{ns}	0.05*	0.006*	0.088^{ns}

Table 2. Variation in root intensity across the lateral distance and soil depth influenced by stump and root trainer grown at 3x3 m spacing of five-year-old teak plantation

Soil depth (cm)	Stump	Root trainer	Stump	Root trainer	Stump	Root trainer	Stump	Root trainer
	0.35		0.75		1.55		2.35	
Root intensity (number per m^2) at different distance from the base of the tree (m)								
<2 mm								
0-10	855	700	510	455	415	475	390	400
10-20	610	555	435	410	365	380	345	340
20-30	410	485	315	275	185	365	55	280
30-40	380	470	95	360	30	295	-	130
40-50	155	195	-	170	-	160	-	110
Total	2410	2405	1355	1670	995	1675	790	1260
2 mm-5 mm								
0-10	80	110	50	55	30	25	55	5
10-20	75	105	30	30	10	25	10	15
20-30	30	115	15	25	10	35	20	10
30-40	65	130	10	30	5	35	-	10
40-50	5	55	-	35	-	35	-	5
Total	255	515	105	175	55	155	85	45
>5 mm								
0-10	30	50	20	25	5	15	15	15
10-20	15	65	15	30	5	15	-	5
20-30	15	95	10	30	5	35	10	10
30-40	25	50	5	25	-	25	-	10
40-50	0	25	-	15	-	45	-	10
Total	85	285	50	125	15	135	25	30
>1 cm								
0-10	20	-	-	5	-	-	-	
10-20	15	25	-	-	5	-	-	5
20-30	5	35	5	20	-	-	-	
30-40	-	10	-	5	-	5	-	
40-50	-	-	-	-	-	15	-	
Total	40	70	5	30	5	20	-	5

were different. For instance, the stump based teak stand showed better intensity of small roots in the top soil (0-20 cm) which was 61% of the total root intensity (2410 number per m^2) at proximal end (0.35m) at 50 cm soil depth for 5 year old stand (Table 2). The corresponding root intensity for root trainer based stands was only 52% of the total root intensity at the proximal lateral distance and 50 cm soil depth (2405 number per m^2). However, the trends showed gradual reversal at deeper soil depths with an increase in root intensity of root trainer based teak stands. For example the corresponding root intensities for stump and root trainer stands at deeper depth (30-50 cm) were 22 and 28%, respectively of the total root count at the same proximal lateral distance (0.35 m). These trends clearly illustrate the differences in the root growth habit of the two stands. The increase in root intensity at deeper soil for root trainer trees clearly indicates its better vertical spread contributed by multiple taproots. However, stump grown trees lack a well-defined tap root system leading to lower vertical root. It is also noteworthy that in the absence of prominent tap root, the stump grown teak produced larger number of small roots at shallow depth at proximal end. Further, this increase could not be maintained neither with increase in lateral distance nor with increase in soil depth.

Analysis of root size class and soil depth revealed clear differences between the two planting materials (Table 2). In both stump- and root trainer-grown teak, fine roots (<2 mm) dominated the root system, particularly in surface layers. However, root trainer trees consistently exhibited greater root intensity across all diameter classes, especially at deeper soil depths and greater lateral distances from the stem base. At shallow depths (0–10 cm) and close proximity (0.35 m), stump-grown trees recorded slightly more fine roots than root trainer trees (855 vs. 700 roots m^{-2}), indicating a tendency for surface-level concentration. Yet, as depth and lateral distance increased, root counts in stumps declined sharply, whereas root trainer trees maintained substantial root presence even at 40–50 cm depth and 2.35 m lateral distance.

For medium roots (2–5 mm), root trainer trees had significantly higher counts at depth—for instance, at 50 cm and 0.35 m distance, they recorded 515 roots m^{-2} versus 255 roots m^{-2} in stump-planted trees. Large roots (>5 mm and >1 cm) were nearly absent beyond 1.55 m in stumps but remained present in root trainer trees, reflecting superior soil penetration and anchorage capacity. These contrasts in root composition between planting types are further visualized in Fig. 3c, which shows that root trainer seedlings developed a more balanced proportion of fine, medium, and coarse roots compared to the fine root dominance observed in stumps. These differences in root spread are visually illustrated in Fig. 2a and 2b, where root trainer seedlings show significantly higher root counts at each radial interval compared to stump-raised plants, confirming the numerical values observed in Tables 1 and 2.

The relatively higher count of larger roots (> 1 cm) for root trainer grown trees indicated the prominent nature of multiple tap rooting habit of root trainer grown plants. Kalsi et al. (2025) reported that variation in the container type also showed significant variation in the root shoot ratio reported that tree spacing and thinning significantly affect root distribution, with thinning contributing to increased DBH and enhanced root reinforcement. Root trainer grown plantations showed more lateral root spread along with more DBH reported positive relation of rooting depth and total tree height. The current investigation also showed similar findings, with better rooting depth for root trainer origin trees along with higher height growth. The depth-wise decline in fine root intensity is also evident in Figure 3d, where root trainer trees maintained a relatively consistent number of fine roots across all five soil layers, while stump-grown trees showed a marked reduction beyond the top 20 cm. This supports the conclusion that root trainer planting stock promotes deeper and more functionally diverse root systems in teak.

These patterns are visually reinforced by Figure 2a and 2b, which show heat maps and schematic root profiles of stump- and root trainer-grown teak, respectively, both at 3 × 3 m spacing. While Fig. 2a reveals a sharp drop in root intensity with increasing depth and distance in stump-grown trees, Figure 2b illustrates the more balanced and deeper rooting behaviour of root trainer trees, with relatively uniform root intensity across both soil depth and lateral spread.

Influence of spacing on root intensity on root trainer plantations: Root intensity was also impacted by tree spacing. In five-year-old root trainer plantations (Table 3), closely spaced trees (2×2 m) had higher root density near the base (4010 roots m^{-2} at 0.35 m), while wider spacing (3×3 m) favoured greater lateral root spread, with significantly higher intensity at 2.35 m (1355 vs. 460 roots m^{-2}). This suggests that closer spacing increases belowground competition, concentrating roots near the tree, whereas wider spacing facilitates more balanced and extensive root system development. These spacing-induced patterns in root distribution are depicted in Fig. 3b, where the line graph illustrates the contrasting trajectories of root intensity across distances in 2×2 m and 3×3 m spacing regimes. The graph confirms that while narrow spacing favours early resource uptake near the stem, wider spacing promotes a more efficient root spread into deeper and farther zones.

This trend in the root distribution could be primarily attributed by the competitive nature of trees in the closer spaced stand. The trees concentrate more roots at proximal region to base of tree and reduce spread as compared to wider spaced stand. Similar result was observed in young *Acacia mangium* plantation while analyzing the effect of stand density and pruning on root activity by using ^{32}P soil injection method. The result revealed that high stand density of *Acacia mangium* induces greater root uptake capacity close to the stem and from the subsoil and low-density plantations showed higher root activity at far lateral distance from tree base. Spacing trials demonstrated that narrow spacing (2 × 2 m) resulted in a higher concentration of fine and small roots near the tree base, whereas wider spacing (3 × 3 m) facilitated the extension of roots into deeper and more lateral soil zones (Table 4). At 2.35 m lateral distance,

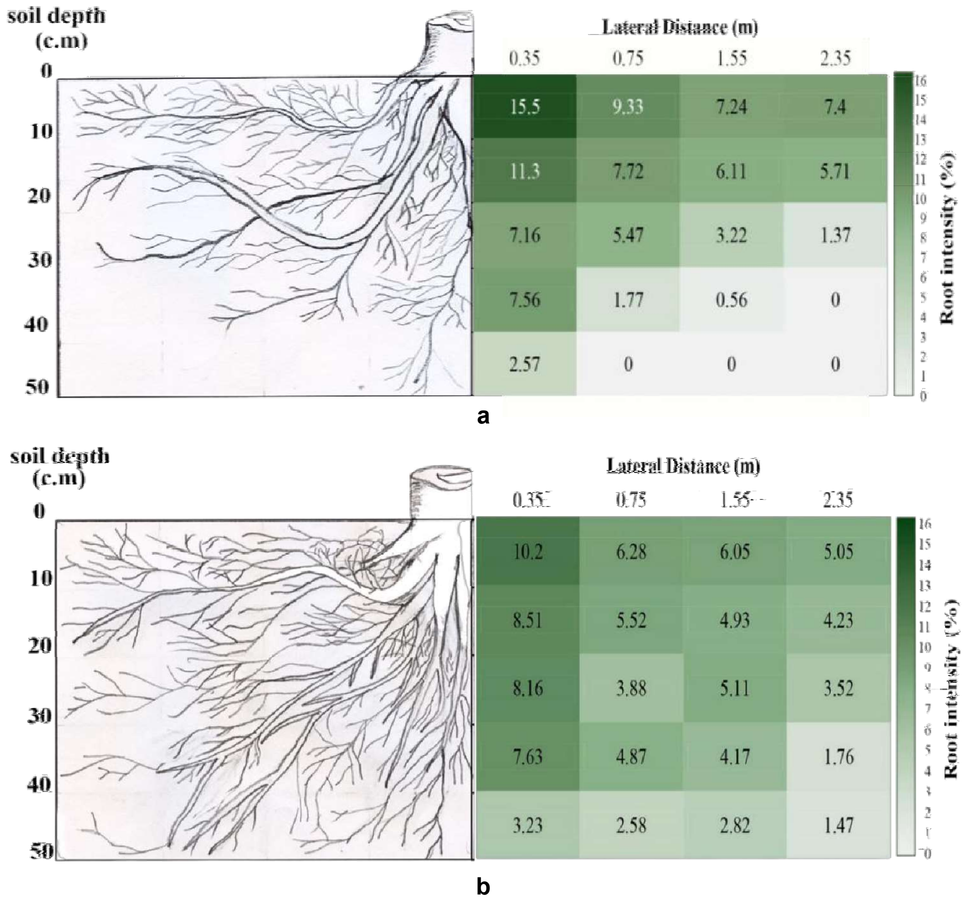

Fig. 2. a) Schematic representation and heat map showing root intensity (%) of stump-grown teak at 3×3 m spacing as influenced by soil depth and lateral distance from the tree base in a five-year-old plantation at Karakkad, Kalady Range, Malayattoor Forest Division, Kerala, and b) Schematic representation and heat map showing root intensity (%) of root trainer-grown teak at 3×3 m spacing in a five-year-old plantation at Karakkad, Kalady Range, Malayattoor Forest Division, Kerala

Table 3. Total root intensity as influenced by planting spacing and distance from the tree base in five-year-old teak plantations (up to 50 cm soil depth)

Planting techniques	Total root intensity (number per m^2) at different distance from the base of the tree (m)			
	0.35	0.75	1.55	2.35
3x3 m	3205	1970	1965	1355
2x2 m	4010	2155	1065	460
P value	0.001*	0.260^{ns}	0.026*	0.004*

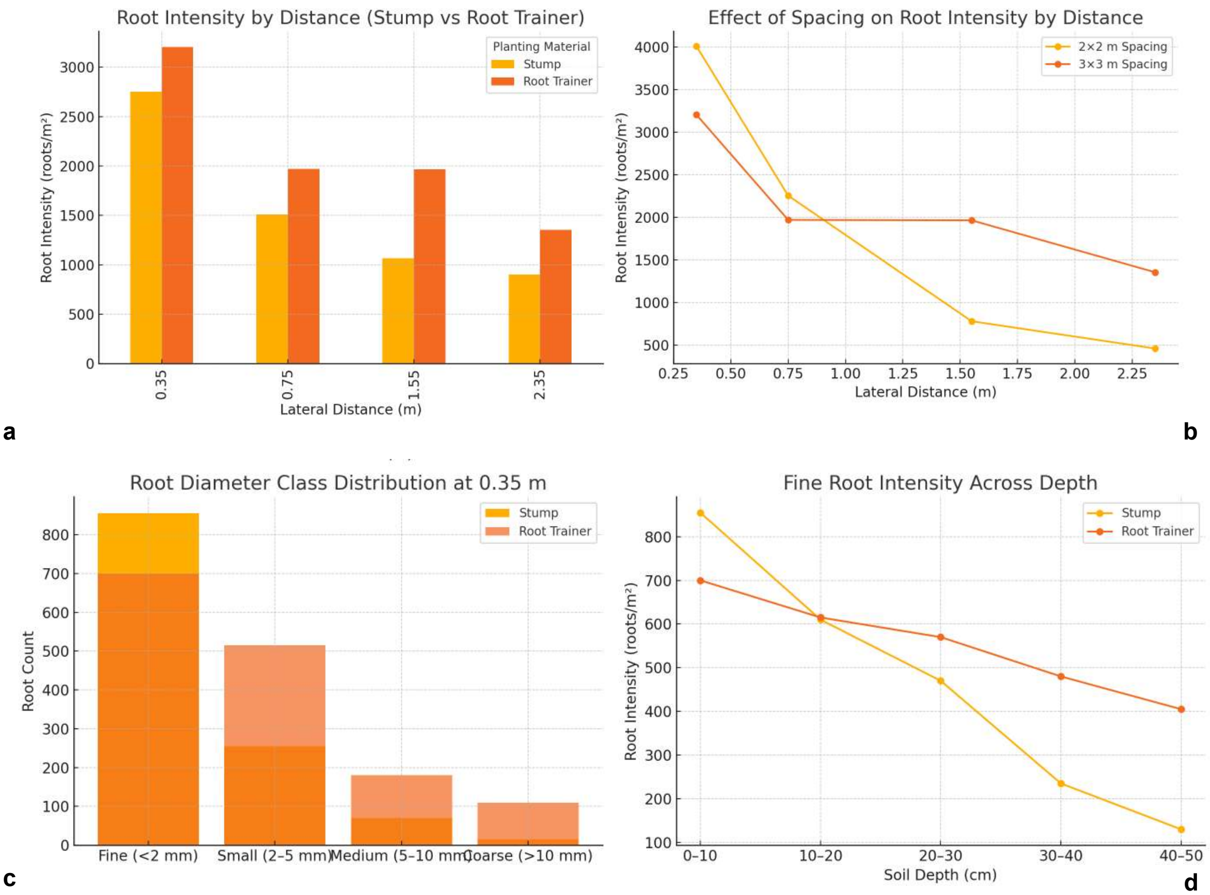

Fig. 3. Visual comparison of root intensity and distribution in five-year-old teak plantations under different planting materials and spacings- (a) Clustered bar chart comparing root intensity at increasing lateral distances for stump- and root trainer-raised trees, (b) Line graph showing the effect of spacing (2×2 m vs 3×3 m) on root intensity at various distances from the tree base, (c) Stacked bar chart of root diameter class distribution at 0.35 m distance for stump and root trainer stock, (d) Line graph of fine root intensity across soil depth layers (0–50 cm) between planting types

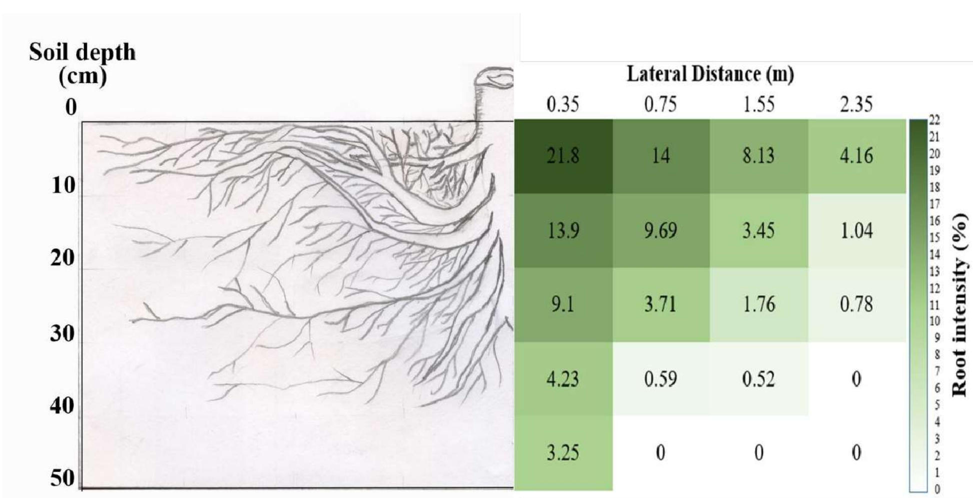

Fig. 4. Schematic representation and heat map showing root intensity (%) of root trainer grown teak tree at 2x2 m spacing at five-years of age plantation

root trainer-grown trees under 3 × 3 m spacing recorded higher root counts across all root diameter classes compared to those under 2 × 2 m spacing, indicating better soil resource exploration.

The 2 × 2 m spacing showed a greater number of fine roots at shallow depths and closer proximity to the stem (e.g., 1180 roots m^{-2} at 0.35 m), this trend reversed at deeper layers. At depths of 30–50 cm and distances beyond 1.55 m, root counts and the presence of medium and large diameter roots were significantly greater under wider spacing. This shift supports the advantage of wider spacing in promoting both vertical penetration and lateral spread of the root system. These trends are clearly illustrated in Figure 2b and Figure 4, which shows that while root trainer-raised trees at 2 × 2 m spacing developed dense rooting near the base compared to the 3 × 3 m spacing, their root expansion was comparatively limited beyond 1.55 m lateral distance—highlighting the spatial constraint imposed by close spacing (Figure 4).

Comparative reduction of root intensity for higher root size class also reported for spacing trial. The distribution of higher sized roots also followed the trend of smaller roots. The distribution of higher sized roots also restricted to the proximal lateral distance and shallow depths for closer spaced trees. This reduction in numbers of roots at deeper soil depths and farthest distance for narrow spaced trees again reiterates the differences in belowground competition on account of the spatial limitations.

Table 4. Root density of five-year-old teak plantations established by root trainer grown teak in variable spacing

Soil depth (cm)	3x3 m	2x2 m	3x3 m	2x2 m	3x3 m	2x2 m	3x3 m	2x2 m
	0.35		0.75		1.55		2.35	
Root intensity (number per m^2) at different distance from the base of the tree (m)								
<2 mm								
0-10	700	1180	455	840	475	540	400	245
10-20	555	820	410	655	380	230	340	70
20-30	485	560	275	235	365	135	280	55
30-40	470	260	360	40	295	40	130	-
40-50	195	205	170	-	160	-	110	-
Total	2405	3025	1670	1770	1675	945	1260	370
2 mm-5 mm								
0-10	110	315	55	155	25	65	5	45
10-20	105	155	30	55	25	25	15	10
20-30	115	95	25	40	35	-	10	5
30-40	130	35	30	5	35	-	10	-
40-50	55	35	35	-	35	-	5	-
Total	515	635	175	255	155	90	45	60
>5 mm								
0-10	50	135	25	85	15	20	15	30
10-20	65	85	30	35	15	10	5	-
20-30	95	45	30	10	35	-	10	-
30-40	50	25	25	-	25	-	10	-
40-50	25	10	15	-	45	-	10	-
Total	285	300	125	130	135	30	50	30
>1 cm								
0-10	-	-	5	20	-	-	-	-
10-20	25	30	-	5	-	-	5	-
20-30	35	10	20	-	-	-	-	-
30-40	10	10	5	-	5	-	-	-
40-50	-	-	-	-	15	-	-	-
Total	70	50	30	25	20	-	5	-

Interpretation and ecological relevance: The study clearly shows that root trainer-raised teak develops a deeper, more distributed root system, while stump-planted teak tends to form dense, shallow roots near the base. This has important implications for agroforestry, where reduced belowground competition with crops is essential. Greater rooting depth in root trainer trees suggests better anchorage, improved nutrient and water uptake, and higher system resilience, also emphasized the significance of root distribution for productivity and interspecies competition.

CONCLUSION

The present study demonstrated that the type of planting material significantly influences the root distribution pattern in teak. Root trainer-raised seedlings exhibited higher total root intensity compared to stump-planted trees, particularly at greater soil depths and farther lateral distances from the tree base. The logarithmic spiral trenching method effectively captured both lateral and vertical root spread, revealing that root trainer plants developed a more balanced and deeper rooting, while stump-raised plants showed a predominantly superficial and peripheral root distribution. Spacing also played a crucial role in shaping belowground development. Trees established at wider spacing (3 × 3 m) had more extensive lateral and vertical root systems than those planted at closer spacing (2 × 2 m), suggesting reduced intra-specific competition and greater soil exploration potential. Root intensity decreased with increasing soil depth in all cases, but the decline was more pronounced in stump-grown trees. These findings underline the advantages of using root trainer-raised planting stock for teak establishment, especially in agroforestry systems where belowground competition with crops must be minimized. Adoption of improved planting material and optimized spacing can contribute to better resource-use efficiency, improved tree stability, and enhanced long-term productivity. The study also highlights the need for further research on long-term root dynamics and their functional implications in diverse agroecological settings.

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AUTHOR'S CONTRIBUTION

George conceptualized the study, conducted the fieldwork, collected primary data, Kunhamu formulated the research objectives, and supervised the overall work, and also provided all scientific guidance for the work as major advisor, Bharath associated in fieldwork and prepared the scientific illustrations for the manuscript and contributed to writing the results and discussion sections, Ravuther performed data analysis and interpretation. Prepared tables, figures, and statistical outputs. Contributed to writing the results and discussion sections, Sarath supported literature review, contributed to methodology refinement, and assisted in manuscript drafting and editing, Niyas provided technical guidance, validated analytical results, and reviewed the manuscript for intellectual content, and Sooraj Kumar assisted in drafting the initial sections of the manuscript, managed references and formatting, and contributed to proofreading the final manuscript.

REFERENCES

Al Afas N, Marron N, Zavalloni C and Ceulemans R 2008. Growth and production of a short-rotation coppice culture of poplar-IV: Fine root characteristics of five poplar clones. *Biomass and Bioenergy* **32**(6): 494-502.

Atkinson D 1976. The use of soil resources in high density planting systems. Symposium on High Density Planting **65**: 79-90.

Böhm W 1979. Methods of studying root systems. Springer Science and Business Media.

Boswell SB, McCarty CD and Lewis LN 1975. Tree density affects large-root distribution of 'Washington'Navel Orange Trees1. *HortScience* **10**(6): 593-595.

Chandrasekharan C 1973. *Forest Resources of Kerala-A Quantitative Assessment Kerala Forest Department*. Thivandrum, Pp Xiv+ 2S4.

Cislaghi A, Alterio E, Fogliata P, Rizzi A, Lingua E, Vacchiano G, Bischetti GB and Sitzia T 2021. Effects of tree spacing and thinning on root reinforcement in mountain forests of the European Southern Alps. *Forest Ecology and Management* **482:** 118873.

Douglas GB, McIvor IR, Potter JF and Foote LG 2010. Root distribution of poplar at varying densities on pastoral hill country. *Plant and Soil* **333**(1-2): 147-161.

George E, Kunhamu TK, Jamaludheen V, Santhoshkumar AV and Gopakumar S 2019. Comparative performance of stump and root trainer raised teak plantations in humid Kerala. *Indian Journal of Agroforestry* **21**(2): 18-21.

Gopikumar K and Mahato KC 1993. Germination and growth behaviour of selected tree species in the nursery. *Indian F*orester **119**(2): 154-156.

Huang Y, Hong Y and Liang K 2024. Impact of tree root structure on soil water dynamics: drought adaptation mechanisms and ecological significance. *Molecular Soil Biology* **15**(4): 172-182

IUFRO–TEAKNET 2022. IUFRO - World Series Vol. 44 – *Global Teak Resources and Market Assessment 2022*. https://www.iufro.org/publications/world-series-vol-44-global-teak-resources-and-market-assessment-2022

Kalsi S, Dhakad AK and Singh S 2025. Assessment of root-shoot growth of tree seedlings raised in conventional container type and air-prune pots. *Indian Journal of Ecology* **52**(3): 493-500.

Khedkar MH 1999. Advantages of raising teak (*Tectona grandis*) plantations by using root trainer plants. *Indian Forester* **125**(2): 133-136.

Khedkar MH and Subramanian K 1997. Trials on raising teak (*Tectona grandis*) planting stock in root trainers. *Indian Forester* **123**(2): 95-99

Krishnankutty CN and Chundamannil M 2012. *Timber Supply Situation in Kerala: Projection for the Year 2010-11*. KFRI Research Report. https://docs.kfri.res.in/xxxxKFRI-RR/KFRI-RR426.pdf

Kunhamu TK, Kumar BM, Viswanath S and Sureshkumar P 2010. Root activity of young *Acacia mangium* Willd trees: Influence of stand density and pruning as studied by 32P soil injection technique. *Agroforestry Systems* **78**(1): 27-38.

Lihui M, Xiaoli L, Jie C, Youke W and Jingui Y 2021. Effects of slope aspect and rainfall on belowground deep fine root traits and aboveground tree height. *Frontiers in Plant Science* **12**: 684468.

Mohanan C and Sharma JK 2005. Improvement of seedling production system in forestry sector and its impact on seedling health. Diseases and Insects in Forest Nurseries-proceedings of the *5th Meeting of IUFRO Working Party S7.03.04* At: Kerala Forest Research Institute, Peechi, Kerala, India.

Niiyama K, Kajimoto T, Matsuura Y, Yamashita T, Matsuo N, Yashiro Y, Ripin A, Kassim AR and Noor NS 2010. Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh Forest Reserve, Peninsular Malaysia. *Journal of Tropical Ecology* **26**(3): 271-284.

Noordwijk MV, Lawson G, Hairiah K and Wilson J 2015. Root distribution of trees and crops: Competition and/or complementarity, pp. 221-257. In C.K. Ong, C.R. Black and J. Wilson (eds.), *Tree-crop interactions: Agroforestry in a Changing Climate.* CABI book publisher.

Rao PS, Venkaiah K, Murti SSN and Sattar SA 2001. Root trainer vs. Stump planting of Teak-a comparative study. *Indian Forester* **127**(11): 1289-1293.

Samritika 2013. Belowground architecture and carbon stocks of silver oak (*Grevillea robusta* A. Cunn.) trees. M.Sc. (For) Thesis, Kerala Agricultural University, Thrissur, 150p.

Tomlinson H, Traore A and Teklehaimanot Z 1998. An investigation of the root distribution of Parkia biglobosa in Burkina Faso, West Africa, using a logarithmic spiral trench. *Forest Ecology and Management* **107**(1-3): 173-182.

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