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RESEARCH ARTICLE

Species-specific root architecture and its role in soil nutrient dynamics in a multispecies tree stand

Aatish Kumar Sharma[1*], **Meenakshi Gupta**[1], **Kamal Kishor Sood**[1], **Sarabdeep Kour**[2], **Manish Kumar Sharma**[3], **Sushil Sharma**[4], **Lalit Mohan Gupta**[5], **Vishal Mahajan**[6] **& Vikas Gupta**[7]

[1]Division of Silviculture and Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu 180 009, Jammu and Kashmir, India
[2]Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu 180 009, Jammu and Kashmir, India
[3]Division of Statistics and Computer Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu 180 009, Jammu and Kashmir, India
[4]Division of Agricultural Engineering, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu 180 009, Jammu and Kashmir, India
[5]Division of Forest Products and Utilisation, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu 180 009, Jammu and Kashmir, India
[6]Krishi Vigyan Kendra (KVK), Kathua, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu 180 009, Jammu and Kashmir, India
[7]Krishi Vigyan Kendra (KVK), Rajouri, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu 180 009, Jammu and Kashmir, India

*Correspondence email - sabhi7984@gmail.com

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Abstract

Root system architecture (RSA) is important for determining tree stability, nutrient uptake and soil health, as well as for understanding interspecies differences in subtropical agro-ecosystems. Understanding RSA helps clarify species differences in nutrient uptake and soil interactions. The work was conducted to assess root intensity and soil properties of tree species (*Pongamia pinnata*, *Cassia fistula*, *Tectona grandis*, *Aegle marmelos* and *Dalbergia sissoo*) at Sher-e-Kashmir University of Agricultural Sciences and Technology (SKUAST), Jammu, India. Fine roots and coarse roots, as well as total root intensity, were measured using the profile wall method at five depth intervals (0–10, 10–20, 20–30, 30–40 and 40–50 cm). Soil nutrient parameters were measured at four soil depth intervals (0–15, 15–30, 30–45 and 45–60 cm). Root intensity demonstrated significant interspecific variation, with *D. sissoo* showing the highest fine root intensity (FRI) (2523.50 no. m^{-2}), followed by *P. pinnata* and *T. grandis*, with most fine roots concentrated in the upper 30 cm. *Tectona grandis* recorded the highest coarse root intensity (1425.75 no. m^{-2}). Soil analysis showed that *P. pinnata* and *D. sissoo* had higher surface nitrogen, phosphorus, potassium and organic carbon compared to other species. These findings highlight the promising roles of *D. sissoo*, *T. grandis* and *P. pinnata*, which exhibited intensive root spread, in promoting soil stabilisation and nutrient cycling in subtropical agroforestry systems.

Keywords: coarse roots; fine roots; root intensity; soil nutrient dynamics

Introduction

The spatial distribution and geometric arrangement of roots, which differ greatly between species and environmental circumstances, are included in the concept of root system architecture (RSA). For example, tree root systems have been described as creating a stiff structure that binds soil well and increases tree stability, especially in windy regions (1). Plants require fine roots (usually less than 2.5 mm in diameter) to survive, since they are primarily responsible for absorbing nutrients and water from the soil. These roots are highly sensitive to changes in the environment and change rapidly. This property allows plants to adapt efficiently to variations in soil moisture and nutrient levels (2). Beyond supporting plant growth, roots are critical in nutrient cycling and carbon storage, thereby contributing to soil nutrient dynamics and carbon sequestration (3). Fine and coarse roots play different, yet correlated roles in plant physiology and ecology. Their importance makes them a central focus for researchers seeking to understand plant adaptation and resource acquisition. They are involved in carbon exudation and also have symbiotic relationships with mycorrhizal fungi, which play a major role in nutrient cycling and soil health (4). Conversely, coarse roots, which have a diameter of more than 2.5 mm, play a vital role in structural support and the storage of nutrients and water, thus enabling plants to withstand environmental stresses, including drought (5, 6). Studies have revealed that coarse roots are capable of controlling the flow of water and nutrients, thereby improving the health and growth of the entire vegetation (7). Moreover, it has been found that the distribution patterns of both types of roots may have a significant impact on the cycling of carbon and nutrients in ecosystems (8, 9). Understanding the functional differences between fine and coarse roots helps clarify species–specific adaptations to altered environmental conditions, which have important implications for plant resilience under changing climate conditions and for applications in breeding programmes and sustainable agriculture (10–12).

Differences in RSA among species directly influence plant responses to variations in soil nutrients, ultimately impacting their growth and yield (13). Understanding how root systems develop and function is crucial to identifying a tree species' ecological niche and optimising its benefits in a variety of land-use systems (14, 15). The spatial distribution of roots, root density and root biomass are important for measuring root system efficiency. A strong correlation exists between root characteristics and nutrient uptake efficiency, especially under stress conditions, which helps trees survive for long periods of time (16, 17). However, limited information exists on how these five subtropical tree species differ in depth-wise root intensity and how these differences relate to soil nutrient status.

The Jammu subtropical region, particularly the Kandi belt, is characterised by undulating terrain, shallow to moderately deep sandy loam soils, low organic matter content and a predominantly rainfed hydrological regime. The region experiences erratic rainfall, frequent drought episodes and prolonged periods of soil moisture stress, which strongly influence vegetation establishment and soil nutrient cycling (18). Under such environmentally constrained conditions, tree root system architecture plays a critical role in soil stabilisation, nutrient acquisition and the regulation of belowground ecological processes. Although RSA is known to influence soil processes, comparative evidence linking species-specific root distribution to depth-wise soil nutrient availability in subtropical plantations remains limited. This information is important for strengthening the understanding of root–soil interactions and for guiding species selection in agroforestry and land restoration under subtropical conditions.

The present study aims to develop an understanding of the rooting patterns of selected tree species in the rainfed Kandi area of the Jammu subtropics and their implications for soil properties. The study is part of a research work on root architecture, that aims to identify potential tree species for soil conservation and amelioration in the Kandi area. The study hypothesises that the rooting behaviour of selected trees in a mixed plantation would significantly influence depth-wise soil nutrient dynamics.

Materials and Methods

Study site

The experiment was conducted at the experimental farm of Sher-e-Kashmir University of Agricultural Sciences and Technology (SKUAST), Jammu, situated at coordinates 32°39′24″ N and 74°48′36″ E at an elevation of 296 m above mean sea level. The study was conducted during the year 2023–2024. The site receives an average annual rainfall of 1492.02 mm and has a mean annual temperature of 22.5 °C. Prior to plantation establishment, the site remained under routine field conditions with no major interventions that could have influenced soil fertility.

Soil characteristics

For soil analysis, five composite soil samples were collected from the site following a random sampling procedure (19). The collected samples were mixed thoroughly, air-dried, ground, sieved and kept in cloth bags for subsequent analysis. These initial soil samples were collected before the root sampling study began to characterise the baseline soil conditions of the site. The soil was sandy loam in texture with low to medium water-holding capacity. The values of different soil parameters obtained after analysis are presented in Table 1.

Experimental setup

This research was conducted in a plantation established at the SKUAST-Jammu experimental site, comprising five tree species; *P. pinnata, C. fistula, T. grandis*, *D.sissoo* and *A. marmelos*. The plantation consisted of two continuous rows per species, with a spacing of 4 m × 5 m. The study was carried out five years after plantation establishment, assuming that the root systems had matured and fully stabilised. Each tree was considered an experimental unit and four individual trees were selected for each species, serving as replications. A single healthy tree from each plot was sampled.

Root sampling and measurement

Root intensity was determined using the profile wall technique, which provides clear visualisation of belowground root distribution. Trenches measuring 4 m long, 1 m wide and 0.6 m deep were dug at a distance of 1.5 m from the tree trunk on one side of each tree. The vertical trench wall was carefully washed to expose visible roots. A metal grid (50 cm × 60 cm) with 10 cm × 10 cm squares was placed against the profile wall to assist in root counting. The number of roots passing through each square of the grid was recorded at five depth classes: 0–10, 10–20, 20–30, 30–40 and 40–50 cm. Root counts from all grid squares were averaged to obtain the final root intensity value for each depth. Roots were differentiated into fine roots (< 2.5 mm diameter) and coarse roots (> 2.5 mm diameter) to standardise root intensity, expressed as root number per square metre (no. m^{-2}), for comparison across species and soil layers.

Soil sampling and analysis

Soil cores were extracted at four depth ranges (0–15, 15–30, 30–45 and 45–60 cm) from locations in close proximity to the root zone of each sampled tree. Soil sample were taken between trees within the same species row to minimise interspecific interference. Before analysis, the samples were air-dried, ground and sieved through a 2 mm mesh. Organic carbon, available nitrogen (AN), available phosphorus (AP) and available potassium (AK) were estimated

Table 1. Initial nutrient status of the study area

S. No	Nutrient status	Test value	Method
1	pH	7.54	1:2.5 Soil water suspension electrode pH Meter (23)
2	Available nitrogen(kg ha^{-1})	233.35	Alkaline potassium permanganate method (21)
3	Available phosphorus(kg ha^{-1})	16.1	Olsen method (22)
4	Available potassium(kg ha^{-1})	145.3	Ammonium acetate method (23)
5	Organic carbon (%)	0.50	Walkley and Black method (20)

using standard procedures (20–24).

Statistical analysis

Data were statistically analysed using R software and SPSS. The experiment was laid out in a randomised block design (RBD) and the effects of tree species and soil depth on root and soil parameters were evaluated using one-way analysis of variance (ANOVA). Treatment means were compared using Tukey's honest significant difference (HSD) test at a 5 % level of significance. Normality and homogeneity of variances were tested prior to performing ANOVA.

Results and Discussion

Fine root intensity (FRI) was found to differ significantly among tree species at each depth level ($p < 0.001$ to $p < 0.01$) (Table 2). At 0–10 cm, the maximum FRI was observed in *D. sissoo* (2523.50 no. m^{-2}), followed by *P. pinnata* (2266.00 no. m^{-2}) and *T. grandis* (2011.02 no. m^{-2}), while the lowest values were observed in *C. fistula* (1313.50 no. m^{-2}) and *A. marmelos* (1262.07 no. m^{-2}). A similar pattern was observed throughout the 10–30 cm depth, with *D. sissoo*, *P. pinnata* and *T. grandis* exhibiting higher FRI. At 30–40 cm depth, the maximum value was recorded in *T. grandis* (1305.17 no. m^{-2}), which was statistically at par with *D. sissoo* (1296.25 no. m^{-2}), while *C. fistula* and *A. marmelos* showed the lowest FRI. Fine root intensity decreased with increasing depth, with minimum values observed at 40–50 cm depth. Most of the fine roots were confined to the upper 30 cm of soil across all species.

The highest percentage of FRI was observed in *D. sissoo* and *P. pinnata* within the upper 30 cm depth, with values of 74.17 % and 72.51 % respectively. However, the lowest FRI (68.35 %) was observed *A. marmelos* (Fig. 1). These findings indicate that the rooting capacity of *D. sissoo, T. grandis* and *P. pinnata* was higher compared to *C. fistula* and *A. marmelos* (Fig. 1).

Coarse root intensity (CRI) varied highly among species at all depths except at 0–10 cm, where the variation was not statistically significant (NS). The highest CRI observed was in *T. grandis* (1425.75 no. m^{-2}) at 10–20 cm and was significantly higher than *D. sissoo* (1003.50 no. m^{-2}) and *C. fistula* (997.50 no. m^{-2}). Similar trends were observed at 20–40 cm, with *T. grandis*, *P. pinnata* and *A. marmelos* recording the highest values. At the deepest depth (40–50 cm), all species had the lowest CRI values except *T. grandis* (900.75 no. m^{-2}) and *P. pinnata* (857.15 no. m^{-2}), which recorded the maximum CRI, while the minimum CRI (571.50 no. m^{-2}) was in *C. fistula* (Table 2).

Most of the CRI was concentrated in the top 10–40 cm of soil among all the species considered (Fig. 1). The highest CRI was found in *T. grandis* (70.30 %) and *A. marmelos* (70.50 %), while the lowest was observed in *P. pinnata* (68.60 %). This pattern suggests a general tendency for these species to develop most of their coarse roots in the intermediate soil layer.

The total root intensity (TRI), i.e., the sum of fine and coarse root intensities, differed greatly among the species ($p < 0.001$ to $p < 0.01$) (Table 2). *Dalbergia sissoo* recorded the highest TRI of 3080.75 no. m^{-2} at 0–10 cm, followed by *P. pinnata* with 2958.07 no. m^{-2} and *T. grandis* with 2770.27 no. m^{-2} and these were statistically higher than *C. fistula* (1807.50 no. m^{-2}). At a depth of 20–30 cm, the highest TRI was recorded in *D. sissoo* (1807.50 no. m^{-2}) and the lowest was observed in *C. fistula.* The TRI also decreased with increasing depth. Overall, along the soil profile (up to 50 cm), *T. grandis* tended to have the highest TRI, especially at 20–30 cm (2828.30 no. m^{-2}), whereas *C. fistula* consistently showed the lowest values. The overall trend showed a depth-dependent decrease in TRI in all species.

Soil nutrient availability beneath individual tree species

Regarding soil nutrient availability beneath the trees, a wide range of AN content was observed in the first three soil layers, whereas no significant difference was found at the deeper depth (45–60 cm) (Table 3). The highest nitrogen content was observed under *P. pinnata* (284.44 kg ha^{-1}) at 0–15 cm depth, which was significantly higher than that under *C. fistula*, *T. grandis* and *A. marmelos*. The lowest AN was observed in *T. grandis* (231.01 kg ha^{-1}). At 15–30 cm, *P. pinnata* recorded the maximum AN (268.73 kg ha^{-1}), while *T. grandis* (221.58 kg ha^{-1}) recorded the lowest. At 30–45 cm, the highest AN was observed under *P. pinnata* (237.30 kg ha^{-1}) and the minimum was recorded in *T. grandis* (205.87 kg ha^{-1}). Similar trends were observed at

Table 2. Fine, coarse and total root intensity (no. m^{-2}) of five tree species at different soil depths

Trees	**0–10**	**10–20**	**20–30**	**30–40**	**40–50**
			Fine root intensity		
Pongammia pinnata	2266.00^{a}	1792.50^{a}	1504.30^{a}	1120.03^{ab}	988.95^{a}
Cassia fistula	1313.50^{b}	1133.00^{b}	976.60^{b}	820.67^{b}	525.75^{b}
Tectona grandis	2011.02^{a}	1746.20^{ab}	1524.80^{a}	1305.17^{a}	966.17^{a}
Aegle marmelos	1262.07^{b}	1121.25^{b}	925.20^{b}	855.52^{b}	676.65^{ab}
Dalbergia sissoo	2523.50^{a}	2248.25^{a}	1590.15^{a}	1296.25^{a}	919.37^{a}
***p* - value**	**< 0.001*****	**< 0.001*****	**< 0.001*****	**< 0.01****	**< 0.01****
			Coarse root intensity		
Pongammia pinnata	692.07	1220.75^{ab}	1181.02^{ab}	975.75^{ab}	857.15^{a}
Cassia fistula	494.00	997.50^{b}	924.75^{b}	787.50^{b}	571.50^{b}
Tectona grandis	759.25	1425.75^{a}	1303.50^{a}	1204.25^{a}	900.75^{a}
Aegle marmelos	656.25	1306.50^{a}	1175.25^{ab}	979.00^{ab}	796.75^{a}
Dalbergia sissoo	557.25	1003.50^{b}	971.25^{ab}	927.00^{ab}	591.75^{b}
***p* - value**	**NS**	**< 0.001*****	**< 0.05***	**< 0.05***	**< 0.05***
			Total root intensity		
Pongammia pinnata	2958.07^{a}	3013.25^{ab}	2685.37^{ab}	2095.77^{ab}	1846.10^{a}
Cassia fistula	1807.50^{b}	2130.50^{c}	1901.35^{c}	1608.17^{b}	1097.25^{b}
Tectona grandis	2770.27^{a}	3171.95^{ab}	2828.30^{a}	2509.42^{a}	1866.92^{a}
Aegle marmelos	1918.32^{b}	2427.75^{bc}	2100.45^{bc}	1834.52^{b}	1473.40^{ab}
Dalbergia sissoo	3080.75^{a}	3251.75^{a}	2561.40^{ab}	2223.25^{ab}	1511.12^{ab}
***p* - value**	**< 0.001*****	**< 0.01****	**< 0.001*****	**< 0.01****	**< 0.01****

Within soil depth, different letters indicate significant differences; NS, not statistically significant.

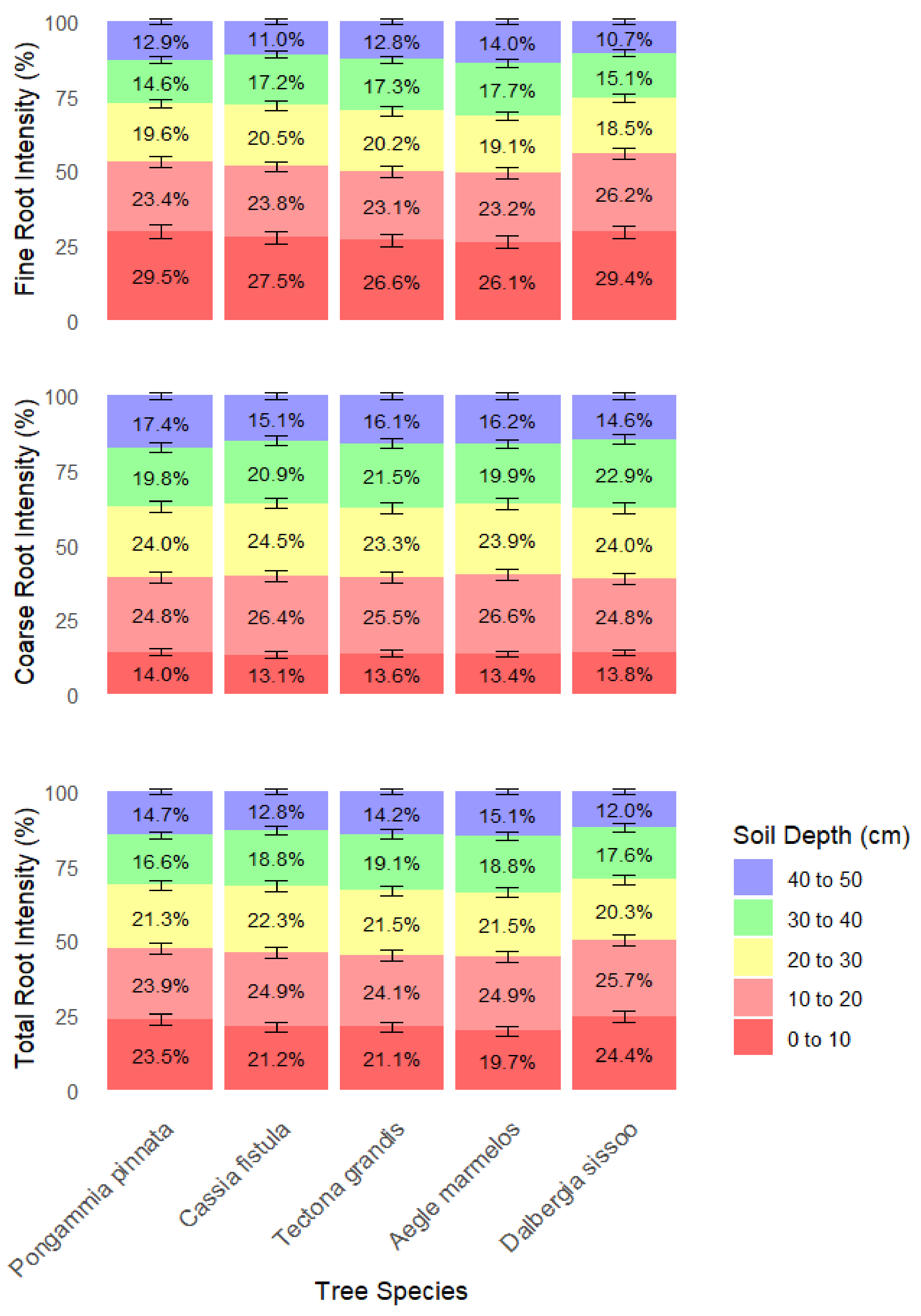

Fig. 1. Depth-wise distribution of root intensity in different tree species. Error bars represent ± SE.

Table 3. Available nitrogen, phosphorus and potassium (kg ha^{-1}) at different soil depths under five tree species

Trees	**0–15**	**15–30**	**30–45**	**45–60**
		Available nitrogen		
Pongammia pinnata	284.44^{a}	268.73^{a}	237.30^{a}	198.00
Cassia fistula	240.44^{b}	238.87^{ab}	226.87^{ab}	187.00
Tectona grandis	231.01^{b}	221.58^{b}	205.87^{b}	169.72
Aegle marmelos	237.30^{b}	232.58^{ab}	229.44^{ab}	176.00
Dalbergia sissoo	267.16^{ab}	251.44^{ab}	231.01^{ab}	191.72
***p* - value**	**< 0.01****	**< 0.05***	**< 0.05***	**NS**
		Available potassium		
Pongammia pinnata	161.95^{a}	143.46^{a}	129.39	102.49^{a}
Cassia fistula	141.58^{bc}	126.23^{ab}	120.95	87.49^{b}
Tectona grandis	129.87^{c}	116.35^{b}	106.61	82.98^{b}
Aegle marmelos	134.42^{c}	119.77^{ab}	111.77	94.51^{ab}
Dalbergia sissoo	151.34^{ab}	129.23^{ab}	121.12	101.87^{a}
***p* - value**	**< 0.01****	**< 0.05***	**NS**	**< 0.05***
		Available phosphorus		
Pongammia pinnata	18.65^{a}	17.10^{a}	13.75^{a}	10.25^{a}
Cassia fistula	17.95^{a}	15.90^{a}	13.08^{ab}	9.23^{bc}
Tectona grandis	14.15^{d}	12.25^{d}	11.40^{b}	7.63^{d}
Aegle marmelos	15.35^{c}	13.38^{c}	12.38^{ab}	9.05^{bc}
Dalbergia sissoo	16.85^{b}	14.23^{c}	12.83^{ab}	9.36^{b}
***p* - value**	**< 0.001*****	**< 0.001*****	**< 0.001*****	**< 0.05***

Within soil depth, different letters indicate significant differences; NS, not statistically significant.

30–45 cm depth, with nitrogen content varying from 205.87 kg ha^{-1} (*T. grandis*) to 237.30 kg ha^{-1} (*P. pinnata*).

Substantial species-wise differences in soil potassium availability were observed across the 0–15, 15–30 and 45–60 cm soil depths beneath the selected tree species (Table 3). In the surface layer (0–15 cm), the soil under *P. pinnata* recorded the highest potassium (161.95 kg ha^{-1}) and the lowest was recorded under *T. grandis* (129.87 kg ha^{-1}), which was statistically at par with *A. marmelos* (134.42 kg ha^{-1}). Within the 15–30 cm layer, *P. pinnata* had the highest potassium content (143.46 kg ha^{-1}), while the lowest AK was recorded in *T. grandis* (116.35 kg ha^{-1}). At 45–60 cm, *P. pinnata* (102.49 kg ha^{-1}) and *D. sissoo* (101.87 kg ha^{-1}) exhibited the highest AK and were statistically at par, while the minimum AK was found in *T. grandis* (82.98 kg ha^{-1}).

Tree species differed significantly in AP content across all soil depths beneath the trees (Table 3). In the surface layer (0–15 cm), *P. pinnata* recorded the highest AP (18.65 kg ha^{-1}), which was statistically at par with *C. fistula* (17.95 kg ha^{-1}), while *T. grandis* (14.15 kg ha^{-1}) recorded the lowest phosphorus content. At 15–30 cm, the maximum phosphorus content was found in *P. pinnata* (17.10 kg ha^{-1}), followed by *C. fistula* (15.90 kg ha^{-1}), *D. sissoo* (4.23 kg ha^{-1}) and *A. marmelos* (13.38 kg ha^{-1}), whereas *T. grandis* (12.25 kg ha^{-1}) had the lowest AP content. Within the 30–45 cm layer, *P. pinnata* recorded the highest phosphorus (13.75 kg ha^{-1}), whereas *T. grandis* (11.40 kg ha^{-1}) recorded the lowest phosphorus content. At 45–60 cm, phosphorus content decreased across all species. *Pongamia pinnata* had the highest value (10.25 kg ha^{-1}) and *T. grandis* recorded the minimum phosphorus content (7.63 kg ha^{-1}).

Organic carbon content varied significantly across species, with statistically significant differences observed in the soil under different tree species at the upper depths (0–15 cm and 15–30 cm; $p < 0.05$ and $p < 0.01$) (Table 4). In the surface soil (0–15 cm), *P. pinnata* recorded the highest organic carbon content (0.644 %), followed by *D. sissoo* (0.545 %), whereas *T. grandis* recorded the lowest organic carbon content (0.398 %). At the 15–30 cm layer, organic carbon content was highest under *P. pinnata* (0.584 %), while the minimum organic carbon content was recorded in *T. grandis* (0.362 %).

Table 4. Effect of tree species on organic carbon (%) at different soil depths under five tree species

Treatment	**0–15**	**15–30**	**30–45**	**45–60**
Pongammia pinnata	0.644^{a}	0.584^{a}	0.479	0.396
Cassia fistula	0.470^{bc}	0.459^{ab}	0.437	0.345
Tectona grandis	0.398^{c}	0.362^{b}	0.329	0.242
Aegle marmelos	0.467^{bc}	0.426^{b}	0.403	0.321
Dalbergia sissoo	0.546^{ab}	0.501^{ab}	0.460	0.356
p - value	< 0.05*	< 0.01**	NS	NS

NS, not statistically significant.

Regression analysis between FRI and the soil nutrients AN, AK and AP, showed that the relationships were weak among the five tree species studied. The linear models showed low coefficients of determination (R^2 = 0.299 for AN, 0.244 for AK and 0.118 for AP) (Fig. 2), indicating that FRI explains only a minor portion of the variability in soil nutrient concentrations. This pattern was observed across all species (*P. pinnata*, *C. fistula*, *T. grandis*, *A. marmelos* and *D. sissoo*), confirming the generally weak relationship between fine root abundance and soil properties.

Discussion

Root distribution and biomass

The analysis of FRI, CRI and TRI reveals clear differences among *D. sissoo*, *P. pinnata* and *T. grandis* when compared with *C. fistula* and *A. marmelos*. These distinctions underscore the varied adaptive strategies the tree species employ for ecological competition, resource acquisition and their broader roles in shaping soil nutrient dynamics.

Fine root intensity (FRI)

The fine root intensity of the studied tree species varied significantly. *Dalbergia sissoo* demonstrated high FRI in the surface soil layer, suggesting a greater potential for fine root proliferation and efficient uptake of nutrients and moisture from the topsoil. This observation is consistent with research demonstrating similar adaptations in Indian agroforestry systems, where *D. sissoo* plays an essential role

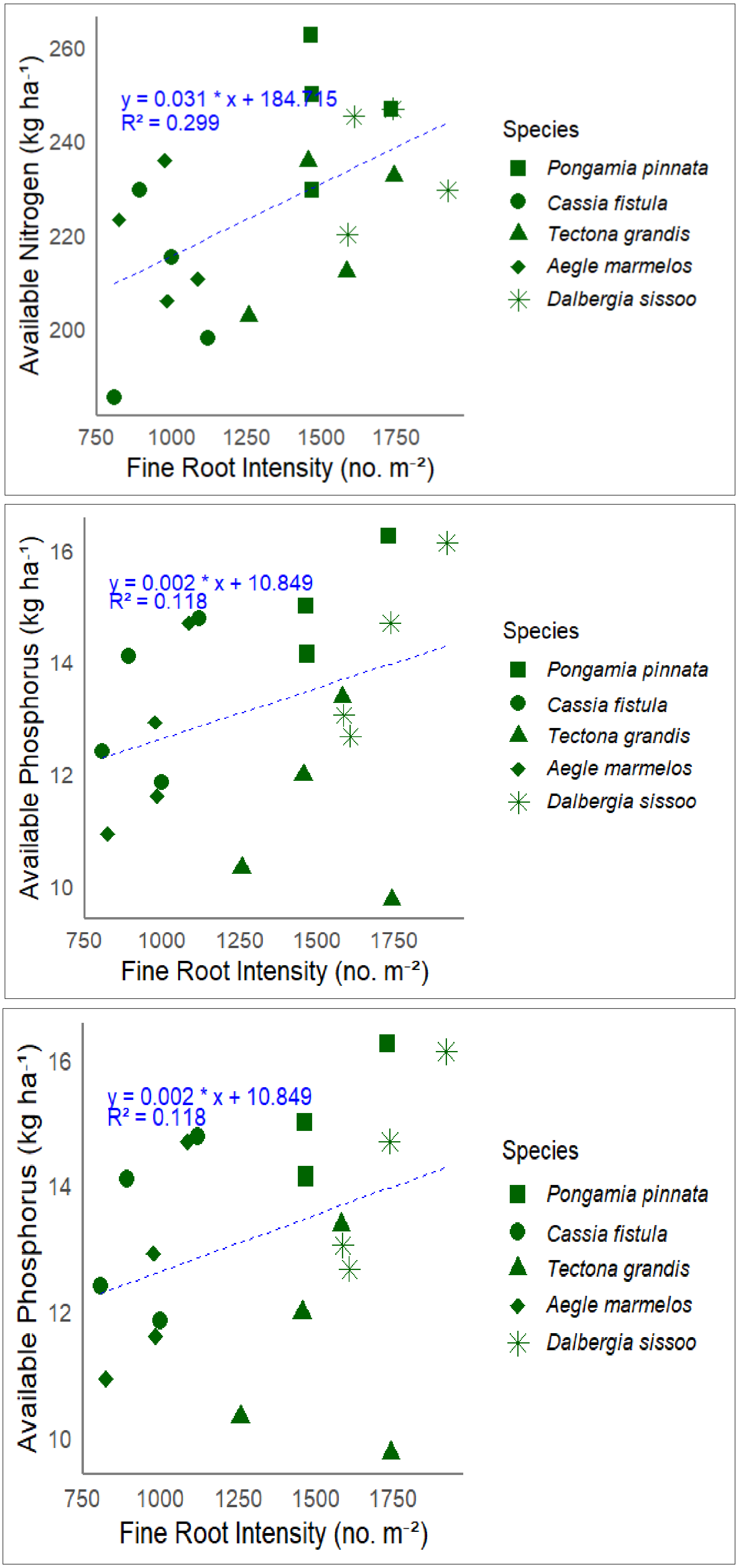

Fig. 2. Relationship between fine root intensity and soil nutrients.

in soil erosion control and biodiversity enhancement (25). Both *D. sissoo* and *P. pinnata* exhibited high FRI, suggesting their adaptability and suitability for land reclamation, afforestation and the restoration of degraded ecosystems (26). In comparison, *T. grandis* also showed substantial FRI, whereas *C. fistula* and *A. marmelos* displayed notably lower FRI. These reduced values may indicate comparatively lower nutrient and moisture uptake capacity (27). Collectively, the pronounced fine root development in *D. sissoo* and *P. pinnata* may reflect their effectiveness in agroforestry, reforestation of Kandi areas and ecosystem restoration strategies.

Coarse root intensity (CRI)

Coarse root intensity in tree species consistently exhibits a vertical distribution pattern, with notably lower values in the surface soil horizon and significantly higher CRI in the subsurface soil layers. This pattern reflects an ecological adaptation, as subsurface soil layers provide more stable moisture and nutrient availability, favouring enhanced root growth and function (28–30).

The analysis of CRI reveals that *T. grandis* exhibits higher values in the subsurface soil depth range, indicating a comparatively greater contribution to maintaining mechanical stability and absorbing nutrients from deeper soil strata (28). Meanwhile, *P. pinnata* demonstrates a convergent root strategy characterised by a deep taproot and lateral spread, supporting efficient anchorage and exploitation of sub-surface moisture (31). In contrast, *C. fistula* and *A. marmelos* exhibit comparatively lower CRI values, reflecting constraints in establishing dense and stable root systems crucial for drought resilience. Notably, *A. marmelos and D. sissoo* possess deep taproots but show reduced root intensity in the upper soil layers, suggesting potential competitive disadvantages in forestry management relative to species such as teak (28).

Total root intensity (TRI)

The assessment of TRI confirms that higher TRI at subsurface soil depths was recorded in *D. sissoo*, *T. grandis* and *P. pinnata*. This equitable resource allocation strategy between fine and coarse roots may contribute to ecosystem productivity, which is essential in plantation management (30). The markedly reduced TRI in *C. fistula* and *A. marmelos* indicates lower competitive ability for belowground resources, corroborating the necessity for integrated nutrient management of *A. marmelos* in agroforestry systems (32).

The root development properties of *D. sissoo*, *T. grandis* and *P. pinnata* indicate that they may be suitable candidates for inclusion in agroforestry and land restoration models. Their well-developed surface and subsurface roots contribute to anchorage, water uptake and soil fertility, suggesting their potential suitability for sustainable land-use practices in tropical and subtropical areas.

Soil properties

Soil nitrogen content differed markedly among species in the upper soil layers, with *P. pinnata* recording the highest nitrogen levels in both surface and subsurface layers. This finding supports previous research indicating that certain tree species can enhance nitrogen levels through symbiotic relationships with nitrogen-fixing bacteria and mycorrhizae, which are essential for nutrient cycling in forest ecosystems (33). The significantly higher nitrogen values observed in *P. pinnata* and *D. sissoo* may reflect their effective nutrient accumulation strategies, which may improve soil fertility and promote plant growth (34, 35).

However, *T. grandis* and *C. fistula* displayed comparatively lower nitrogen levels at subsurface depths compared to *P. pinnata*. The convergence of nitrogen content at deeper layers reflects the tendency of nitrogen availability to diminish with depth, which has been documented in similar ecological studies examining nutrient stratification in forest soils (36). The comparatively lower nitrogen availability associated with deeper-rooting species such as *T. grandis* may partly influence their productivity under nutrient-poor conditions (37).

Soil phosphorus content also varied significantly among species, particularly in the upper layers. *Pongamia pinnata* exhibited higher phosphorus content in the surface soil layers compared to *T.grandis*. The pattern of phosphorus availability remaining relatively high at shallow depths and diminishing with depth is common in forest ecosystems and is largely influenced by root biomass and litter quality (38). In India, the contribution of high-quality, decomposable litter, notably from *P. pinnata* and *D. sissoo*, has been demonstrated to accelerate phosphorus cycling, consistent with the broader scientific literature (39).

Similarly, potassium content displayed significant species-specific variations at the surface and subsurface soil depths, with *P. pinnata* showing higher values than *T. grandis* and *A. marmelos*. The concentration of potassium in surface layers is vital for supporting physiological processes and its decreasing trend with depth reiterates the ecological importance of surface root systems for nutrient uptake (40). A previous study confirms that *P. pinnata* and *D. sissoo* show pronounced enrichment of soil potassium, reinforcing their suitability for restoration initiatives (41).

The consistent ability of *P. pinnata* to maintain higher nutrient contents across various soil depths indicates its potential role in forest restoration efforts, reinforcing previous findings that highlight its efficiency in nutrient cycling and soil enrichment (41). *Dalbergia sissoo*, *Acacia nilotica* and *Albizia lebbeck* have shown similar, though slightly less pronounced, positive effects on soil nutrients and structure, including nitrogen and organic carbon accumulation (39).

Organic carbon content demonstrated significant variations among species across different soil depths, with *P. pinnata* exhibiting the highest levels in surface soils. This finding aligns with studies emphasising the importance of organic carbon in enhancing soil structure and fertility. The continuous decrease in organic carbon content with increasing depths reflects the vital role of surface litter and root biomass in contributing to soil organic matter dynamics. Various studies have consistently ranked *P. pinnata* and *D. sissoo* as superior contributors to soil organic carbon among tested native and naturalised species (35, 39).

The observed trends in nutrient availability across species and soil depths reveal fundamental insights into tree species interactions with soil properties. The relatively higher nutrient levels observed in *P. pinnata* and *D. sissoo* across multiple nutrient metrics further indicate their ecological significance, particularly in nutrient-poor environments.

Although FRI varied among species, its relationship with soil nutrient availability was weak, as indicated by low coefficients of determination. This suggests that fine root abundance accounts for only a limited proportion of the variability in soil nutrients, consistent with earlier studies (42, 43). Soil nutrient dynamics are therefore governed by multiple interacting factors, including species identity, litter inputs, microbial activity, soil moisture and microclimatic conditions. Fine root intensity should thus be considered one component of a complex soil-plant system rather than a primary determinant of nutrient availability in mixed plantation systems.

Conclusion

This study highlights the important role of tree roots in influencing soil health. Among the species examined, *D. sissoo*, *T. grandis* and *P. pinnata* exhibited strong root structures, with a greater concentration of fine and coarse roots in the upper 30 cm of soil. Such well-developed root systems are valuable for erosion control, nutrient retention and soil aggregation. In contrast, *C. fistula* and *A. marmelos* displayed comparatively lower root intensities, which may limit their contribution to soil improvement. Soil analyses further showed that *P. pinnata* and *D. sissoo* were associated with higher surface-layer nitrogen, phosphorus, potassium and organic carbon, likely due to their nitrogen-fixing ability and the decomposition of their leaf litter. Nutrient and organic carbon concentrations declined with depth, signifying the importance of maintaining a healthy topsoil layer. Overall, these findings support the use of *D. sissoo*, *T. grandis* and *P. pinnata* for strengthening soil fertility and advancing land restoration efforts in Kandi areas. Expanding these observations through multi-site and longer-term studies would enhance understanding of these species and support the formulation of resilient agroforestry practices and ecological restoration programmes under rainfed conditions.

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Authors' contributions

AKS contributed to the conceptualisation, methodology development, investigation, formal analysis, data curation and preparation of the original draft, as well as review and editing of the manuscript. MG was involved in methodology design, supervision, project administration and manuscript review and editing. KKS contributed to methodology, supervision, provision of resources and review and editing of the manuscript. SK carried out the laboratory analysis, data curation and validation of results. MKS was responsible for the software application, validation and data visualisation. SS contributed to field investigation and data support. LMG provided the necessary resources and review support. VM contributed to validation and manuscript review and editing. VG supported the study by providing resources and technical assistance. All authors read and approved the final manuscript.

Compliance with ethical standards

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

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Declaration on the Use of AI-Assisted Technologies

The authors acknowledge the use of generative AI tools (such as ChatGPT by OpenAI) to assist in language refinement, grammar correction and paraphrasing during the preparation of this manuscript. No generative AI tools were used for content generation, data analysis, or intellectual contribution to the core ideas or findings. All content has been critically reviewed and approved by the authors to ensure accuracy, originality and integrity.

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