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Impacts of diverse walnut intercropping models on fine root biomass and nutrient stocks

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Abstract

Intercropping impacts on the plant fine root growth by improving soil fertility and productivity. This study assessed the seasonal dynamics of fine root biomass and nutrient stock of the different intercropping models by planting ginger (WGI), sweet potato (WSP), soybean (WSB), and potato (WPO) in a walnut plantation as compared to pure walnut (CK). Soils in the 0–20 cm and 20–40 cm layers were collected in four seasons, and a membership function was applied to integrate multiple fine-root traits and soil fertility indicators into a comprehensive evaluation value (CEV) for intercropping models. All intercropping models in the same soil layer and season showed increase in biomass and carbon, nitrogen, phosphorus, and potassium stocks of fine root, which clearly showed mean annual fine root nutrients stock in the 0–40 cm layer in autumn and summer and declines in winter; soil organic matter (SOM), alkali-hydrolysable nitrogen (AHN), available phosphorus (AVP), and available potassium (AVK) content in the 0–40 cm layer were highest in winter and spring. All intercropping models significantly ($p< 0.05$) increased fine root biomass and the accumulation of carbon (C), nitrogen (N), phosphorus (P), and potassium (K) in the 0–40 cm layer as compared to the CK; these indices in the 0–20 cm layer were higher than those in the 20–40 cm layer. Fine root biomass and nutrient stocks were maximum in summer and autumn, particularly the WGI system showed the highest nutrient accumulation. CEV ranged from 0.33 to 2.79 and ranked as WGI > WSB > WPO > WSP > CK. Correlation analysis revealed significant ($p< 0.05$ or $p< 0.01$) positive relationships among the CEV, fine root traits, and soil fertility indicators of the 0–40 cm layer. The WGI (walnut + ginger) model was identified as the most effective intercropping of walnut plantation for improving fine root nutrient stock and soil fertility. This highlights the critical role of seasonal fine root dynamics and intercropping in enhancing nutrient retention and cycling in the walnut agroforestry systems.

Keywords: Walnut plantation, intercropping, fine root biomass, nutrient stock

Introduction

Intercropping has been practiced worldwide in both traditional and sustainable agriculture to feed the growing population (Lv *et al*., 2021). Intercropping, a sustainable and environmentally sound practice that enhances yield stability and nutrient use efficiency by optimizing spatiotemporal resource utilization. It also promotes biodiversity and contributes to improved soil health (Qui *et al.,* 2025). Walnut (*Juglans regia* L.) is an edible fruit tree cultivated worldwide for its fruits, wood, and as an urban tree. Globally, there is growing concern for preserving the genetic diversity of trees with high economic and ecological value (Tenche-Constantinescu *et al.,* 2024). However, producing high-quality walnuts is not very profitable due to the extension of cultivation area and management practices. Recently, intercropping in orchards has appeared as an efficient measure and is very simple for enhancing production and profit of the whole orchard (Li *et al.,* 2022). Intercropping not only enhances the productivity (Qin *et al.,* 2013; Li *et al.,* 2020) and improves the utilization efficiency of land (Agegnehu *et al.,* 2008), but also enhances soil fertility (Cong *et al.,* 2015). It increases production and consistency (Raseduzzaman and Jensen, 2017) and reduces the reliance on synthetic fertilizers and risks of leaching as

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compared to monocropping (Hauggaard-Nielsen *et al.,* 2003; Corre-Hellou *et al.,* 2006).

They are responsible for nutrient and water acquisition from soil, and it is widely recognized that fine roots play a significant role in the carbon and biogeochemical cycle in forest ecosystems (Lukac, 2012). It has been estimated that approximately one-third of annual net primary productivity was consumed in fine roots due to the rapid growth and turnover rate (Børja *et al.,* 2008). The activity of fine roots in forests has been regarded to be under strong genetic control, and different species adopt different strategies to meet the nutrient and water demands from soils (Inagaki *et al*., 2009); fine roots also show variations in biomass, spatial distribution, and morphology in response to stand ages and environmental changes (Jia *et al.,* 2015).

The cropping system did not show a consistent effect on the other indicators; however, clear temporal variations were observed, indicating their sensitivity to external changes (Thompson *et al.,* 2024). Fine root biomass and productivity in various species are related to many factors such as soil depths (Raizada *et al.,* 2013), ploughing depth (Newaj *et al.,* 2013), seasons in the year (Kern *et al*., 2004), intercrops (Smith *et al*., 1999), nutrient availability (Nadelhoffer *et al.,* 2002) and soil type (Kochsiek *et al.,* 2013). Therefore, studying intercropping models in walnut orchards and clarifying the knowledge gap related to the rhizosphere of these intercropping models is crucial for the development of the walnut industry.

Fine roots are smaller in size, 2 mm or less than 2 mm in diameter, and are the most active organs in soils. Fine roots are responsible for nutrient and water transportation from soil to different plant parts, and it is also known that fine roots have a significant role in the carbon (C) cycle and other biogeochemical cycles in forest ecosystems (Brunner *et al.,* 2013). Fine root biomass (FRB) is dependent upon a wide range of both biotic and abiotic factors, such as climatic conditions, soil properties, and stand characteristics (Farfał, 2010; Jagodzin´ski and Kałucka, 2011). Distributions of the fine roots within the soil profile are varied because of the competition with crops and trees, and go deeper when growing in forest ecosystems (Rolo and Moreno, 2012; Cardinael *et al.,* 2015). Root biomass C contributes to soil C storage directly and indirectly through the soil profile. The root contribution to soil C stocks occurs through rhizo-deposition, fine root turnover, and mortality of plants after harvest annually (Pausch and Kuzyakov, 2018). Root quality determines root litter decomposition rates, influencing its soil residence time (Bonanomi *et al.,* 2021). Indeed, roots contribute to soil organic matter (SOM) formation 2 to 5 times more than the aerial parts of plants (Lin *et al.,* 2020; Villarino *et al.,* 2021). Intensive agricultural practices have a negative impact on the environment, leading to soil degradation, water pollution, and biodiversity loss. Intercropping offers a sustainable alternative by optimizing the use of natural resources, enhancing biodiversity, and reducing the reliance on agrochemicals (Moreira *et al.,* 2024).

Previous studies on walnut-based intercropping systems have highlighted beneficial effects on soil quality, microbial diversity, and fine root dynamics; however, notable limitations that need further investigation. Liu *et al.* (2022) demonstrated that intercropping enhanced fine root length and density in surface soils. It improved nutrient uptake and adaptive root strategies in response to shading and soil competition. Similarly, Duan *et al.* (2019) found that intercropping alters root morphology and promotes plasticity. It also introduced interspecific competition that reduced overall root diameter and surface area. Bai *et al.* (2022) extended this by studying intercropping and showed that it improved soil nutrient availability and microbial structure, yet their study lacked detailed seasonal root biomass data and did not account for root contributions to soil nutrient stock formation. This study aimed to (1) to integrate existing research on fine root systems to assess the nutrient absorption and accumulation of C, nitrogen (N), phosphorus (P), and potassium (K) in fine roots among the different intercropping models of walnut plantation; and (2) to identify the seasonal variations when fine root biomass and nutrient stocks reach at its optimum, thereby creating sustainable management standards for walnut based intercropping and soil quality. The findings provide crucial insights for determining appropriate intercropping models that support sustainable walnut cultivation.

Materials and Methods

Overview of the study area

The experimental site was located in a walnut cultivation demonstration of Zhengzhi Town, Nanjiang County, Bazhong City, Sichuan Province, China (106°06′E, 31°96′N), at an altitude of 682–770 m with slopes ranging from 15° to 21°. The region's average annual precipitation is 1200 mm.

The walnut (*Juglans regia*) trees were planted in the autumn of 2016 at a spacing of 4 m × 5 m; the cultivar was 'Qingxiang'. To improve the ecological and economic benefits of walnut plantation during the young growth stage, intercropping models were initiated in the spring of 2017 to combine long-term and short-term benefits. Crops planted

under the walnut plantation include soybean (*Glycine max*), potato (*Solanum tuberosum*), ginger (*Zingiber officinale*), and sweet potato (*Ipomoea batatas*). Four intercropping models were developed: Walnut + ginger (WGI), walnut + sweet potato (WSP), walnut + soybean (WSB), and walnut + potato (WPO), along with the pure walnut plantation (CK) as a control to investigate the effects of different intercropping models of the walnut plantation on fine root biomass and nutrient return.

Experimental design

The experiment was conducted using a randomized complete block design. Based on an investigation of the experimental site, three 10 m × 10 m standard plots were established in four intercropping models and a pure walnut plantation in October 2022. These plots were selected according to representativeness and similar slope aspect, gradient, position, and elevation. The three standard plots in each model used five random sampling points in each plot to collect the fine root and soil samples (Gong *et al.,* 2012; Lv *et al.,* 2022).

Sampling and determination

The soil and fine root samples were collected from the plots in different intercropping models of walnut plantation in four seasons (including the middle of October 2022, January, April, and July 2023). Soil and fine root samples were collected from 0–20 cm and 20–40 cm depths and transported to the laboratory. Fresh soil samples were first broken into smaller pieces than 1 cm in diameter, with visible plant and animal debris and stones removed. Each soil sample was air-dried indoors, ground, and used for soil chemical properties. For fine root biomass (FRB) analysis, the visible fine roots in samples were picked directly, and the rest fine roots in soil particles were collected by water washed. All collected fine roots were cleaned and combined into one, then oven-dried to a constant weight and then weighed to calculate the FRB (Lv *et al.,* 2022). The oven-dried fine root samples were ground for analysis of carbon and nutrient content. Fine root carbon (FRC) and soil organic matter (SOM) content were measured by the wet oxidation method at a temperature of 170 °C to 180 °C (Nelson and Sommers, 1996). Alkali-hydrolysable nitrogen (AHN), available phosphorus (AVP), and available potassium (AVK) content in soil was determined by alkaline hydrolysis dilution, Bray-P, and flame photometry method, respectively (Wang *et al*., 2015). Nitrogen (LNC), phosphorus (LPC), and potassium (LKC) content in fine root was determined by the micro-Kjeldahl, ascorbic acid-molybdenum blue-colorimetric, and flame photometric method, respectively, after digesting the fine root samples with H_2SO_4-$HClO_4$ (Gong *et al.,* 2012; Wang *et al.,* 2015). Fine root carbon (FRCS), nitrogen (FRNS), phosphorus (FRPS), and potassium (FRKS) stocks were calculated according to FRB multiplied by the related content. Fine root carbon (FRCS), nitrogen (FRNS), phosphorus (FRPS), and potassium (FRKS) stocks were calculated as FRB multiplied by its respective nutrient content (FRC, FRNC, FRPC, or FRKC).

Statistical analysis

Excel 2010 and SPSS Statistics 20 software were used for statistical analysis, and Origin 2021 software was used for drawing. Indices among the different models were analyzed by one-way ANOVA followed by Duncan's test at $p < 0.05$. FRB, FRCS, FRNS, FRPS, FRKS, SOM, AHN, AVP, and AVK were selected to calculate subordinate degrees. Those indices were divided into three groups: the first included FRB and FRCS, the second included FRNS, FRPS, and FRKS, and the third included SOM, AHN, AVP, and AVK. The formula for those indices to calculate subordinate degree is $X(u) = (X - X_{min})/(X_{max} - X_{min})$, as was followed by Saba *et al.* (2022). Comprehensive evaluation value (CEV) is the total value of the average subordinate degree in each group. The higher CEV represents better improvement to FRB, nutrients fixed by fine root, and soil fertility. All data were expressed based on oven-dry weight, and the mean with standard deviation.

Results

Fine root biomass

FRB in the 0–20 cm (0.077–0.327 Mg ha^{-1}), 20–40 cm (0.099–0.385 Mg ha^{-1}), and 0–40 cm (0.175–0.700 Mg ha^{-1}) layers of the different models showed obvious seasonal variation. Mean annual FRB in the 0–40 cm layer significantly ($p < 0.01$) differed among the models, ranking as WGI (0.572 Mg ha^{-1}) > WSB (0.493 Mg ha^{-1}) > WPO (0.363 Mg ha^{-1}) > WSP (0.330 Mg ha^{-1}) > CK (0.206 Mg ha^{-1}). Mean seasonal FRB in the 0–40 cm layer of models ranked as autumn (0.700 Mg ha^{-1}) > summer (0.699 Mg ha^{-1}) > winter (0.492 Mg ha^{-1}) > spring (0.398 Mg ha^{-1}). (Figure 1).

Fine root carbon content and stock

FRCC in the 0–20 cm (423.143–449.875 g kg^{-1}), 20–40 cm (416.550–439.465 g kg^{-1}), and 0–40 cm (419.436–444.064 g kg^{-1}) layers remained relatively stable across the seasons, and there were no significant ($p > 0.05$) differences among the models. In contrast, FRCS in the 0–20 cm (0.034–0.146 Mg ha^{-1}), 20–40 cm (0.042–0.168 Mg ha^{-1}), and 0–40

cm (0.076–0.310 Mg ha^{-1}) layers showed clear seasonal variation and significant (p< 0.05) differences among the models. Mean FRCS in the 0–40 cm layers of models ranked as autumn (0.308 Mg ha^{-1}) > summer (0.310 Mg ha^{-1}) > winter (0.212 Mg ha^{-1}) > spring (0.172 Mg ha^{-1}). (Figure 2).

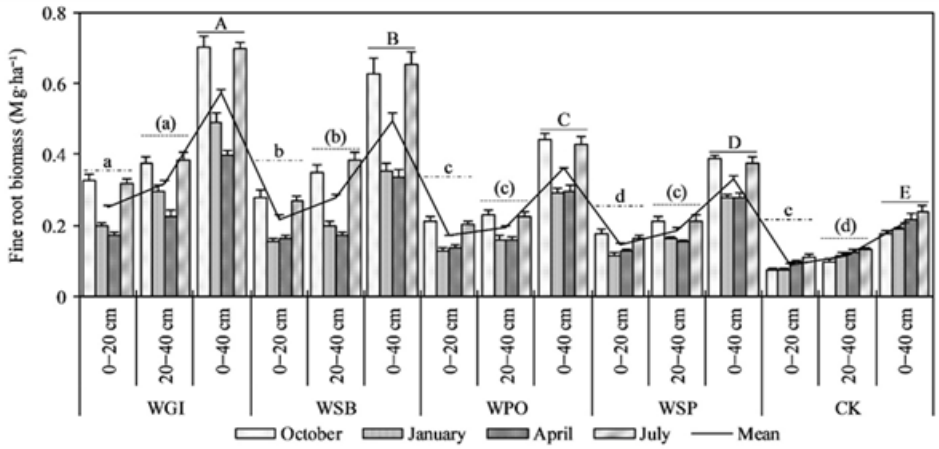

Figure 1: Seasonal variation of fine root biomass among the different intercropping models of walnut plantation. Bars with different letters (lower case, lower case in brackets, and upper case for mean in the 0–20 cm, 20–40 cm, and 0–40 cm layer of four seasons, respectively) show significant differences at p< 0.05.

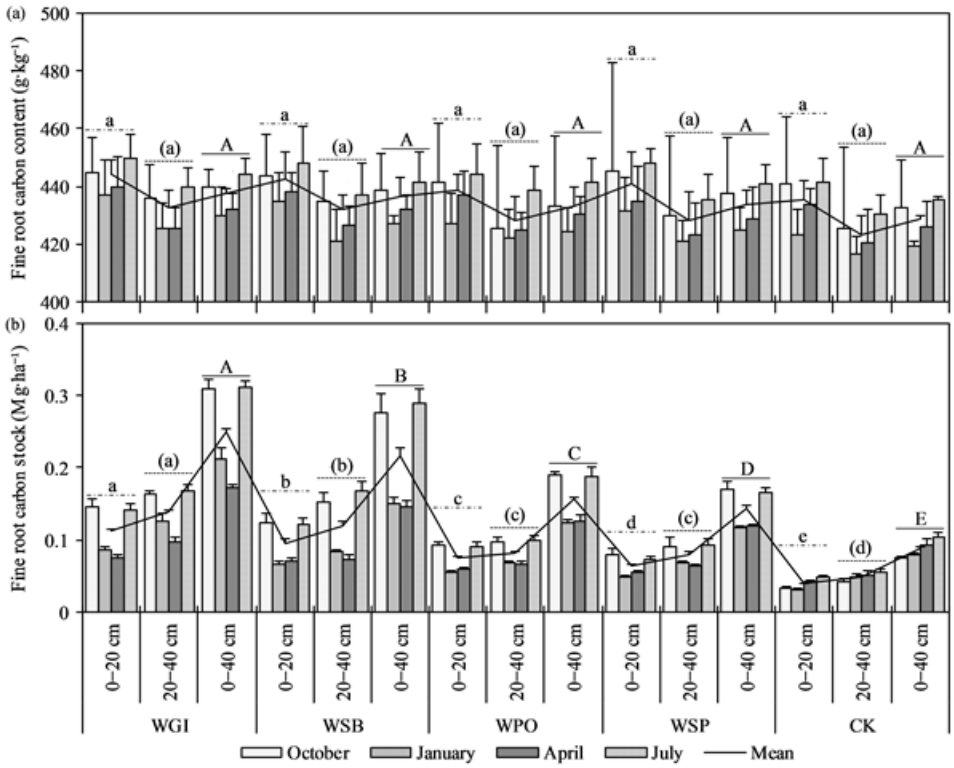

Figure 2: Seasonal variation of fine root carbon content and stock among the different intercropping models of walnut plantation. Bars with different letters (lower case, lower case in brackets, and upper case for mean in the 0–20 cm, 20–40 cm, and 0–40 cm layer of four seasons, respectively) show significant differences at p< 0.05

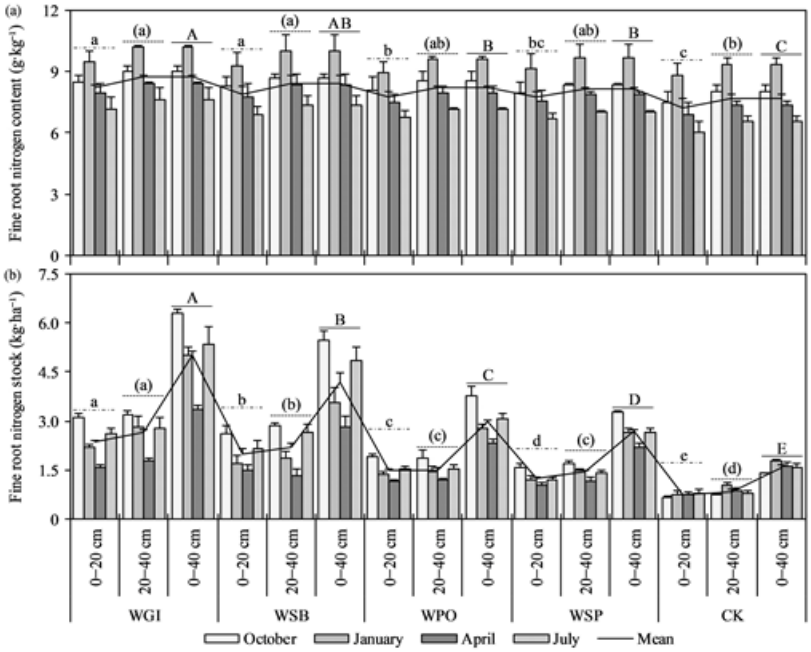

Figure 3: Seasonal variation of fine root nitrogen content and stock among the different intercropping models of walnut plantation. Bars with different letters (lower case, lower case in brackets, and upper case for mean in the 0–20 cm, 20–40 cm, and 0–40 cm layer of four seasons, respectively) show significant differences at *p*< 0.05.

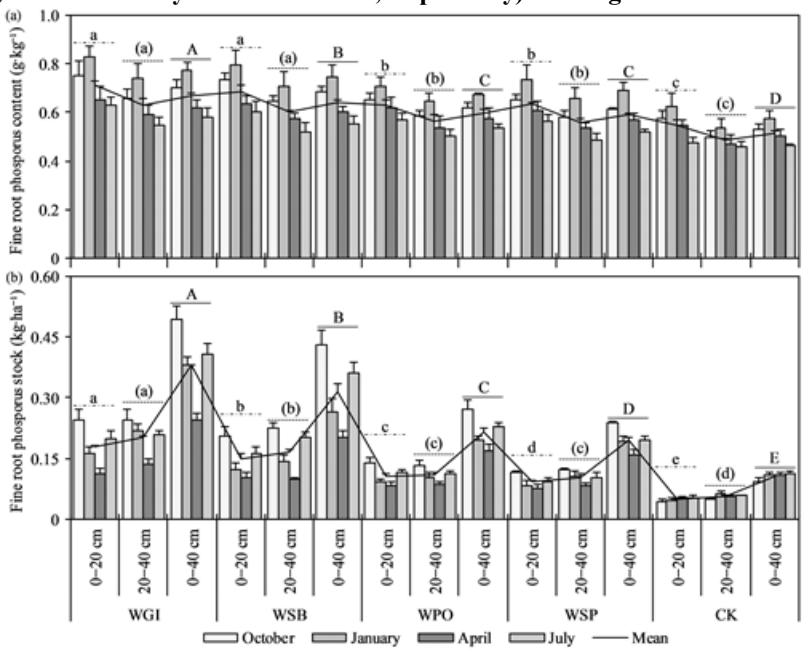

Figure 4: Seasonal variation of fine root phosphorus content and stock among the different intercropping models of walnut plantation. Bars with different letters (lower case, lower case in brackets, and upper case for mean in the 0–20 cm, 20–40 cm, and 0–40 cm layer of four seasons, respectively) show significant differences at *p* < 0.05.

Fine root nitrogen content and stock

FRNC in the 0–20 cm (6.891–9.483 g kg^{-1}), 20–40 cm (6.553–10.173 g kg^{-1}), and 0–40 cm (7.412–9.828 g kg^{-1}) layers showed no significant (p> 0.05) differences among the models. In contrast, FRNS in the 0–20 cm (0.662–3.124 kg ha^{-1}), 20–40 cm (0.739–3.167 kg ha^{-1}), and 0–40 cm (1.401–6.291 kg ha^{-1}) layers showed clear seasonal variation and significant (p< 0.05) differences among the models. Mean FRNS in the 0–40 cm soil layer of models ranked as autumn (6.291 kg ha^{-1}) > summer (5.347 kg ha^{-1}) > winter (5.005 kg ha^{-1}) > spring (3.360 kg ha^{-1}). (Figure 3).

Fine root phosphorus content and stock

FRPC in the 0–20 cm (0.475–0.827 g kg^{-1}), 20–40 cm (0.458–0.738 g kg^{-1}), and 0–40 cm (0.466–0.774 g kg^{-1}) layers differed significantly (p< 0.05) among the models. In contrast, FRPS in the 0–20 cm (0.044–0.246 kg ha^{-1}), 20–40 cm (0.049–0.246 kg ha^{-1}), and 0–40 cm (0.093–0.492 kg ha^{-1}) layers showed clear seasonal variation and significant (p< 0.05) differences among the models. Mean FRPS in the 0–40 cm layer of models ranked as autumn (0.492 kg ha^{-1}) > summer (0.406 kg ha^{-1}) > winter (0.381 kg ha^{-1}) > spring (0.246 kg ha^{-1}). (Figure 4).

Fine root potassium content and stock

FRKC in the 0–20 (3.405–4.769 g kg^{-1}), 20–40 cm (2.978–4.305 g kg^{-1}), and 0–40 cm (3.171–4.489 g kg^{-1}) layers differed significantly (p< 0.05) among the models. In contrast, FRKS in the 0–20 cm (0.303–1.562 kg ha^{-1}), 20–40 cm (0.348–1.535 kg ha^{-1}), and 0–40 cm (0.667–3.097 kg ha^{-1}) layers showed clear seasonal variation and significant (p < 0.05) differences among the models. Mean FRKS in the 0–40 cm soil layer of models ranked as autumn (3.097 kg ha^{-1}) > summer (2.524 kg ha^{-1}) > winter (2.200 kg ha^{-1}) > spring (1.787 kg ha^{-1}). (Figure 5).

Soil organic matter and available nutrients content

Soil organic matter (SOM) and available nutrients exhibited seasonal dynamics and were significantly different (p< 0.05) among the models. The mean annual SOM, AHN, AVP, and AVK content in 0–20 cm (26.104–41.385 g kg^{-1} for SOM, 95.798–185.673 mg kg^{-1} for AHN, 14.225–34.382 mg kg^{-1} for AVP, and 207.896–341.652 mg kg^{-1} for AVK), 20–40 cm (18.066–28.649 g kg^{-1} for SOM, 57.648–135.934 mg kg^{-1} for AHN, 8.582–18.361 mg kg^{-1} for AVP, and 106.262–198.427 mg kg^{-1} for AVK), and 0–

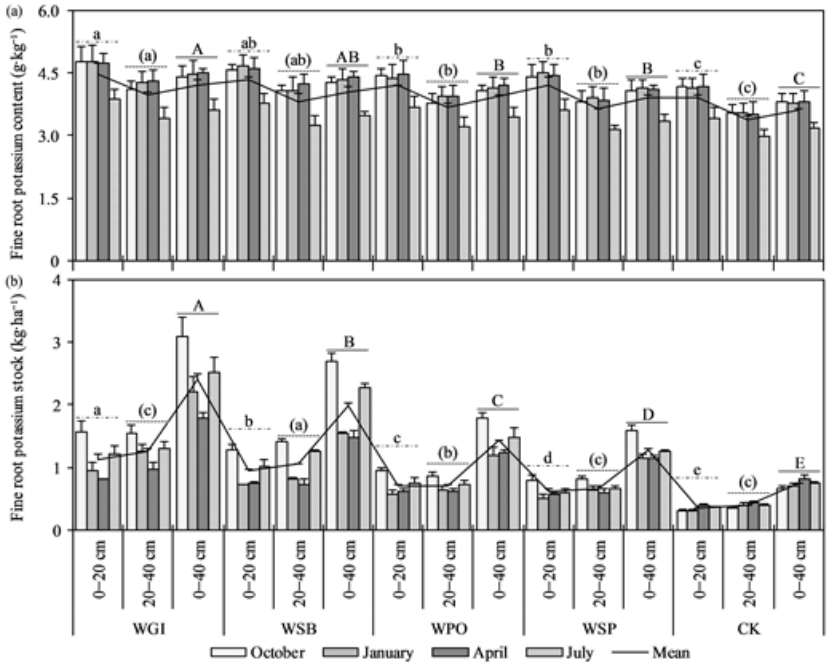

Figure 5: Seasonal variation of fine root potassium content and stock of the different intercropping models of walnut plantation. Bars with different letters (lower case, lower case in brackets, and upper case for mean in the 0–20 cm, 20–40 cm, and 0–40 cm layer of four seasons, respectively) show significant differences at *P* < 0.05.

40 cm (21.909–34.656 g kg^{-1} for SOM, 70.662–159.928 mg kg^{-1} for AHN, 11.289–25.621 mg kg^{-1} for AVP, and 154.763– 260.687 mg kg^{-1} for AVK) soil layers were significant (p< 0.05) differences among the models.

The mean annual SOM, AVP, and AVK content in 0–40 cm ranked as WGI (33.619 g kg^{-1} for SOM, 25.621 mg kg^{-1} for AVP, 260.687 mg kg^{-1} for AVK) > WSB (32.470 g kg^{-1} for SOM, 20.928 mg kg^{-1} for AVP, and 233.526 mg kg^{-1} for

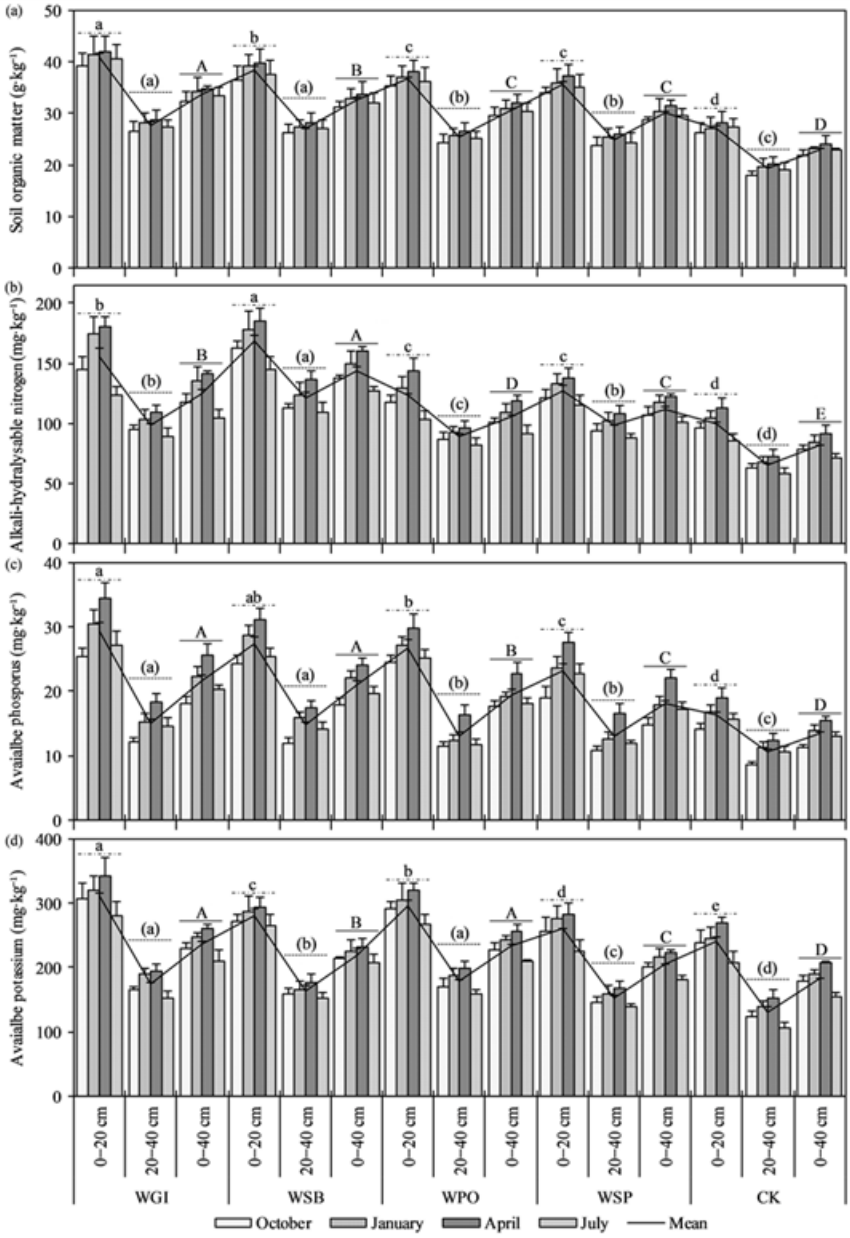

Figure 6: Seasonal variation of soil organic matter and available nutrients content among the different intercropping models of walnut plantation. Bars with different letters (lower case, lower case in brackets, and upper case for mean in the 0–20 cm, 20–40 cm, and 0–40 cm layer of four seasons, respectively) show significant differences at p< 0.05.

AVK) > WPO (30.626 g kg^{-1} for SOM, 19.399 mg kg^{-1} for AVP, and 219.506 mg kg^{-1} for AVK) > WSP (30.034 g kg^{-1} for SOM, 18.020 mg kg^{-1} for AVP, and 205.285 mg kg^{-1} for AVK) > CK (23.043 g kg^{-1} for SOM, 13.444 mg kg^{-1} for AVP, and 183.077 mg kg^{-1} for AVK). The mean annual AHN is ranked as WSB (143.421 mg kg^{-1}) > WGI (124.421 mg kg^{-1}) > WSP (111.850 mg kg^{-1}) > WPO (105.335 mg kg^{-1}) > CK (81.410 mg kg^{-1}). The mean SOM, AHN, AVP, and AVK content among the models ranked as winter > spring > autumn> summer. Those indices were higher in the 0–20 cm than in the 20–40 cm. (Figure 6).

Comprehensive evaluation value

The comprehensive evaluation value (CEV) calculated from fine root traits and soil fertility indicators revealed significant (p< 0.05) improvements under the intercropping models as compared to the CK. The WGI model has significantly (p< 0.05) the best performance among all intercropping models and ranked as WGI (2.79) > WSB (2.28) > WSP (1.34) > WPO (0.94) > CK (0.33). This ranking reflects that the WGI model significantly (p< 0.05) improves fine root development and soil fertility. (Figure 7).

Correlation analysis

Correlation analysis was conducted to examine the relationships between fine root traits and soil properties. The results revealed strong and statistically significant (p< 0.05 or p< 0.01) correlations across most variables (Table 1). FRB exhibited highly significant (p< 0.05 or p< 0.01) positive correlations with all measured parameters, including FRCS, FRNC, FRNS, FRPC, and FRPS. Strong (p< 0.01) correlations were also found with FRKC, FRKS,

Table 1: Correlation coefficients of fine root and nutrients with soil organic and available nutrients

	FRB	FRCS	FRNC	FRNS	FRPC	FRPS	FRKC	FRKS	SOM	AHN	AVP	AVK
FRB	1	1.00**	0.91**	1.00**	0.96**	1.00**	0.90**	1.00**	0.92**	0.85**	0.93**	0.81**
FRCS	1.00**	1	0.90**	1.00**	0.96**	1.00**	0.89**	1.00**	0.91**	0.85**	0.92**	0.81**
FRNC	0.91**	0.90**	1	0.93**	0.91**	0.91**	0.85**	0.91**	0.85**	0.74**	0.88**	0.84**
FRNS	1.00**	1.00**	0.93**	1	0.96**	1.00**	0.90**	1.00**	0.90**	0.83**	0.92**	0.82**
FRPC	0.96**	0.96**	0.91**	0.96**	1	0.97**	0.88**	0.95**	0.96**	0.85**	0.93**	0.830**
FRPS	1.00**	1.00**	0.91**	1.00**	0.97**	1	0.89**	1.00**	0.91**	0.84**	0.91**	0.801**
FRKC	0.90**	0.89**	0.85**	0.90**	0.88**	0.89**	1	0.92**	0.90**	0.81**	0.90**	0.80**
FRKS	1.00**	1.00**	0.91**	1.00**	0.95**	1.00**	0.92**	1	0.91**	0.84**	0.92**	0.81**
SOM	0.92**	0.91**	0.85**	0.90**	0.96**	0.91**	0.90**	0.91**	1	0.86**	0.96**	0.86**
AHN	0.85**	0.85**	0.74**	0.83**	0.85**	0.84**	0.81**	0.84**	0.86**	1	0.86**	0.60*
AVP	0.93**	0.92**	0.88**	0.92**	0.93**	0.91**	0.90**	0.92**	0.96**	0.86**	1	0.89**
AVK	0.81**	0.81**	0.84**	0.82**	0.83**	0.80**	0.80**	0.81**	0.86**	0.60*	0.89**	1
CEV	0.99**	0.99**	0.91**	0.99**	0.93**	0.99**	0.91**	0.99**	0.94**	0.77**	0.96**	0.94**

FRB: Fine root biomass, FRCS: Fine root C stock, FRNC: Fine root N content, FRNS: Fine root N stock, FRPC: Fine root P content, FRPS: Fine root P stock, FRKC: Fine root K content, FRKS: Fine root K stock, SOM: Soil organic matter, AHN: Alkali-hydrolysable N, AVP: Available P, AVK: Available K.

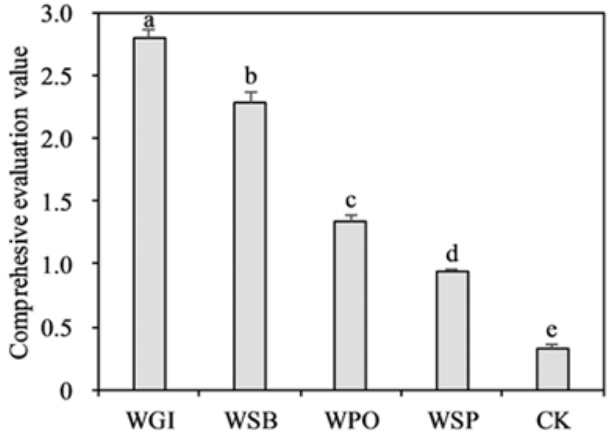

Figure 7: Comprehensive evaluation value under the different intercropping models of walnut plantation. Bars with different letters are significantly differences at p< 0.05.

and SOM. Among soil variables, SOM showed strong (p< 0.01) positive correlations with FRPC, AVP, FRB, and FRKS. AHN was strongly (p< 0.01) positively correlated with FRB, FRNS, and AVP, but showed a comparatively weaker (p< 0.05) correlation with AVK. AVP had strong (p< 0.01) correlations with FRNC, FRPC, and FRKS. Similarly, AVK was strongly (p< 0.01) correlated with fine root variables such as FRNC and FRKS. CEV strongly significantly (p< 0.01) correlated with FRB, FRCS, FRNC, FRNS, FRPC, FRPS, FRKC, FRKS, SOM, AHN, AVP, and AVK. These findings indicate a tight correlation between root nutrient traits and soil nutrient availability. (Table 1).

Discussion

Fine root dynamics are crucial for terrestrial ecosystem productivity and nutrient cycling (Tao *et al.,* 2025). Sustainable forest ecology management requires a comprehensive understanding of the intricate relationships between belowground and aboveground factors in the forest ecosystem. Equally important is identifying the factors that directly affect the growth and development of fine roots below ground (Feng *et al.,* 2024). The concentration of different nutrients in fine roots is higher than that of the tree parts (Gordon and Jackson, 2000). This study demonstrated that fine root biomass was significantly (p< 0.05) affected among the models in different seasons. The WGI model was significantly (p< 0.05) higher, followed by WSB, while the control (CK) remained significantly (p< 0.05) lower across all seasons. Similar patterns were reported by Liu *et al.* (2022), who demonstrated that intercropped soybean under walnut trees significantly (p< 0.05) increased fine root density and diameter in the upper soil layer, enhancing soil resource acquisition. Similarly, Cardinael *et al.* (2015) found that trees in alley-cropping systems grow deeper roots when paired with shallow-rooted crops, improving soil resource use. There were significant positive (p< 0.01) correlations observed between FRB and soil nutrient variables. Overall, our results affirm that intercropping with ginger and soybean boosts fine root growth and soil exploitation, enhancing agroforestry efficiency.

FRB dynamics play a key role in the allocation of C and storage in the forest ecosystem (Wang *et al.,* 2017). In forest ecosystems, soil fertility depends on the production of biomass and C sequestration (Huang *et al.,* 2018). Soil C cycling in agroecosystems is significantly (p< 0.05) affected by the management practices (Hu *et al.,* 2024). Soil organic C has significant (p< 0.05) impacts on agroecosystem stability, including soil quality and crop production (Jia *et al.,* 2025). In our study, both FRCC and FRCS exhibited distinct seasonal trends and were significantly different (p< 0.05) among the intercropping models. FRCS was significantly (p< 0.05) higher in WGI as compared to the control and exhibited distinct seasonal trends, being highest in autumn and lowest in spring. A similar pattern was observed in C stock, indicating that intercropping significantly (p< 0.05) enhances root C accumulation and contributes to strengthening soil C pools. Supporting this by Cardinael *et al.* (2018), who demonstrated that high organic inputs in long-term agroforestry systems significantly (p< 0.05) boost both shallow and deep C storage, correlating with stable root C concentrations. Similarly, Cardinael *et al.* (2025) established guidelines emphasizing the critical role of fine root C and architecture in accurate agroforestry C stock estimation. Monroe *et al*. (2021) also support this, who documented FRCS nearing 0.60 Mg C ha^{-1} (0–10 cm) in a long-established agroforestry system. Significant positive correlations (p< 0.01) were found between FRCS and key soil parameters, confirming their strong relationship. Overall results affirm that intercropping systems can enhance fine root C pools and promote sustainable C sequestration.

Intercropping with walnut trees effectively increases the soil N content and plant biomass (Al-zamanan *et al.,* 2016; Mahmud *et al.,* 2020). Barnard *et al.* (2006) demonstrated that the nitrogenous compounds were significantly (p< 0.05) affected by seasonal variations. FRNC and FRNS changed with the seasons and were significantly (p< 0.05) higher in the different intercropping models as compared to the control. FRNC was the highest in winter and lowest in summer. FRNS was the highest in autumn and lowest in spring. These findings are consistent with Singh *et al.* (2016) who reported strong seasonal patterns in fine root N in agroforestry. Shen *et al.* (2023) also observed elevated fine root N in apple–soybean systems during cooler periods, likely driven by legume N-fixation. Kim and Isaac (2022) demonstrated that agroforestry enhances N cycling and retention as compared to monocultures. Significant positive correlations (p< 0.01) were observed between FRNS and soil available N content across all models. Our results suggest that intercropping ginger and soybeans in tree-based systems can effectively enhance fine root N pools.

Soil P availability plays a significant (p< 0.05) role in the efficiency of agroforestry systems (Cherubin *et al.,* 2016; Wang *et al.,* 2017). P content in soil and fine roots was significantly (p< 0.05) affected in different seasons. It was higher in spring and lower in fall (Kavka and Polle, 2016; Kavka *et al.,* 2021). This study evaluated that FRPC

and FRPS changed with the seasons and were significantly (p< 0.05) higher in the different intercropping models. FRPC was the highest in winter and lowest in summer. FRPS was the highest in autumn and lowest in spring. These trends align with Liu *et al.* (2018), who reported that legume-based rubber agroforestry systems maintained elevated P fractions and root nutrient reserves due to symbiotic nutrient cycling and organic matter turnover. Similarly, Singh *et al.* (2016) observed seasonal peaks in fine root nutrient stock in bead tree systems, reflecting dynamic biomass allocation and enhanced P uptake under fertilized conditions. Significant (p<0.01) positive correlation was found between FRPS and AVP across all seasons. Overall, our results demonstrate that ginger in walnut-based systems significantly (p< 0.05) enhances fine root P pools, supporting improved nutrient cycling and agroecosystem resilience.

K is a major plant nutrient that can affect most of the physiological and biochemical processes (Wang *et al.,* 2013). K is necessary for ensuring the high quality and boosting the fruit production (Zeng *et al.,* 2001; Alva *et al.,* 2006; Muhammad *et al.,* 2018). FRKC and FRKS changed with the seasons and were significantly (p< 0.01) higher in the different intercropping models. FRKC peaked in winter, remained relatively high during autumn and spring, and experienced a decline in summer. FRKS exhibited the highest accumulation in autumn and a decline through winter and spring, and again started increasing during summer. These dynamics are supported by Bibi *et al.* (2022), who observed seasonal K variation in the intercropping systems driven by root biomass and interspecific nutrient dynamics. Singh *et al.* (2016) similarly reported peak fine root K accumulation during growth surges in tree-based agroforestry. Significant (p< 0.01) positive correlation was observed between FRKS and AVK content across all treatments and seasons. Overall, our results confirm that integrating ginger into walnut-based intercropping significantly enhances fine root K pools, promoting greater nutrient capture and agroecosystem resilience across seasons.

Agroforestry has positive effects on SOM and available nutrient contents (Rahangdale *et al.,* 2014; Xu *et al.,* 2021). Different intercropping patterns had significant (p< 0.05) effects on improving the total soil nutrients and available soil nutrients (Wan *et al.,* 2024). Intercropping models and retaining grass can significantly (p< 0.01) lower soil pH and increase the content of SOM, total N, total P, available P, and available K (Ma *et al.,* 2017). Similarly, Bisht and Bangarwa (2015) indicated that higher organic matter and nutrients (NPK) were found under canopy cover than in the open. This study demonstrated that SOM and available nutrient contents varied seasonally and with soil depth, showing the highest levels in the upper layers and in the different intercropping models. SOM peaked in spring and showed moderate increases in autumn and winter, and it started declining in summer. These dynamics are consistent with Guo *et al.* (2018), who reported spring SOM peaks and summer declines in ginkgo-based systems due to shifts in microbial respiration. Similarly, Pandher *et al.* (2019) observed elevated C fractions in winter, attributed to reduced decomposition and higher litter accumulation in tree-based systems. Alongside SOM, AHN content exhibited clear seasonal trends. FRNC was significantly (p<0.05) higher in winter, followed by a sharp decline in summer. These patterns are supported by Ji *et al.* (2025), who observed enhanced N metabolism and retention in rapeseed–vetch intercropping, and Wang *et al.* (2025), who reported sustained N availability in walnut–alfalfa systems through regulated cutting cycles. AVP also followed a seasonal change and was significantly (p< 0.05) higher in spring and declined in summer and partially recovered in autumn. These findings align with Ma *et al.* (2025) who reported elevated P levels and phosphatase activity in maize–peanut intercropping, and Tang *et al.* (2021) found a 24% increase in P use efficiency in cereal–legume systems. Similarly, AVK was the highest in spring and then dropped in summer and again started increasing in autumn. Roeva *et al.* (2023) and Islam *et al.* (2023) both reported similar K fluctuations tied to organic matter mineralization and conservation practices. Strong (p<0.01) positive correlations were observed among SOM, AHN, AVP, and AVK content across all models and seasons. Overall, SOM and available nutrients showed clear seasonal fluctuations under different intercropping models.

Conclusion

All walnut intercropping models (including WGI, WSB, WSP, and WPO) significantly (p<0.05) influenced seasonal variations in FRB, C, N, P, and K content and stock, as well as SOM, AHN, AVP, and AVK content. CEV ranked as WGI > WSB > WSP > WPO > CK. Fine root traits and SOM, AHN, AVP, and AVK showed strong (p<0.01) positive correlations. CEV significantly (P < 0.05 or P < 0.01) correlated with all related indices. These intercropping models promoted belowground biomass accumulation and improved soil nutrient cycling and fertility throughout the year. These findings highlight the critical role of seasonal root activity and organic inputs in enhancing soil nutrient status and agroecosystem function. The WGI model was the most effective intercropping of

walnut plantation for increasing root nutrient storage and sustaining higher soil fertility levels across seasons.

Abbreviations

Not applicable.

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors consent to publish the article.

Availability of data and materials

All datasets generated for this study are included in the article.

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Authors' contributions

Wei Gong and Jingyan Wang have supervised related experiments and revised the manuscript. Muhammad Asghar Ali, Xiulin Zhu, Jinri Xue, Weiyi Yang, Fozia Dost Muhammad, and Qi Lu performed the experiments. Muhammad Asghar Ali compiled the data and wrote the manuscript. Fozia Dost Muhammad and Shuaijie Lu revised the manuscript. All authors have read and approved the manuscript.

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