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The role of coffee agroforestry on available water capacity and root length density in smallholder plantation

AFIFATUL KHOIRUNNISAK[1], SUGENG PRIJONO[2,♥], KURNIAWAN SIGIT WICAKSONO[2]
[1]Graduate Program, Faculty of Agriculture, Universitas Brawijaya. Jl. Veteran No. 1 Malang 65145, East Java, Indonesia
[2]Department of Soil, Faculty of Agriculture, Universitas Brawijaya. Jl. Veteran No. 1, Malang 65145, East Java, Indonesia. Tel./fax.: +62-341-553623, ♥email: spj-fp@brawijaya.ac.id

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Abstract. *Khoirunnisak A, Prijono S, Wicaksono KS. 2023. The role of coffee agroforestry on available water capacity and root length density in smallholder plantation. Biodiversitas 24: 55-61.* The application of coffee agroforestry has several advantages, such as increasing the cycle of nutrients and soil organic matter as well as improving soil physical properties. However, there is still an information gap related to the interaction between coffee plants and shade plant roots. This study aimed to evaluate coffee agroforestry on available water capacity (AWC) and root length density (RLD). The research was carried out at the smallholder coffee plantation in Dampit District in four shade types (coffee-open, shaded with *Leucaena leucocephala* and shaded with *L. leucochepala*). Soil and root samples were taken at three depths (0-20 cm, 20-40 cm, and 40-60 cm) and at two distances (near the coffee stems and between the coffee shade). The variables observed were AWC, RLD, soil organic C, soil aggregate stability, and soil penetration resistance. The result was coffee plants with shade trees increased AWC value and root density compared to coffee-open. The type of shade significantly affected RLD, where shaded with *Gliricidia sepium*, and shaded with *L. leucochepala* were better than coffee-open. This indicates that there was no root competition between coffee plants and shade trees. However, shaded with *Musa* sp. had lower RLD than coffee-open. Soil depth had a significant effect on the AWC value and root length density of coffee plants, where the most AWC values and coffee root distribution were higher at a depth of 0-20 cm.

Keywords: Agroforestry, available water capacity, coffee shade, root length density, soil depth

INTRODUCTION

Coffee is one of the main plantation commodities in Indonesia that has an important role in increasing non-oil export in Indonesia. Indonesia is the fourth largest coffee producer in the world, with a total production of 660,000 tons in 2017 (Sujatmiko and Ihsaniyati 2018). Coffee is cultivated across Indonesia's major islands from the west part to the east, and East Java Province occupies the position of the top five largest coffee fields in Indonesia (BPS 2019). One of the coffee production areas is Dampit Sub-district, Malang District, East Java. Robusta coffee is the most commonly cultivated in Dampit, which is grown at an altitude of 600-700 masl with a coffee area of around 5,467.75 ha (in 2017) and productivity of 400-700 kg ha^{-1} (Fikriani and Slamet 2019). It shows that coffee productivity is still low compared to Brazil and Vietnam, which reached 2000 kg ha^{-1} and 1500 kg ha^{-1} (ICO 2019).

The fluctuation of coffee production is caused by several factors, including changes in coffee land area and climate change. Coffee plants in Dampit Sub-district are generally cultivated by the rainfed system. Water is one of the limiting factors for the success of rainfed agriculture because it only relies on rainwater as the main source of water input. The frequency of precipitation is important in rainfed agriculture because it indicates how often the soil water is filled up by natural precipitation during a certain time (Sohoulande et al. 2019). This makes rainfed crop production much more vulnerable to the effects of environmental stresses, especially climate variability and extremes (Eeswaran et al. 2021).

Most farmers cultivate agroforestry coffee to solve these problems. Agroforestry is an ecologically and economically efficient agricultural practice. Thus the practice supports biodiversity conservation, increases water use efficiency and is economically beneficial (the tree produces fruits, timber, etc.) (Dori et al. 2022). Several studies have shown that the use of shade trees can improve the physical and chemical characteristics of the soil through increasing soil nutrients (tree roots can penetrate deeper and reach nutrients that may not be accessible to the coffee roots), and the addition of organic matter through tree and coffee litter (Moreira et al. 2018; Etafa 2022), also indirectly increase available water capacity (AWC). Available water capacity is the ability of the soil to hold water for a certain period of time (Olorunfemi et al. 2016). Increasing the available water capacity is needed to maintain groundwater conditions in order to remain available in accordance with the coffee phenology phase.

Although many farmers cultivate coffee agroforestry systems, there are still information gaps related to the belowground interactions between coffee roots and shade trees, whether there is competition or complementarity. Root competition can be defined as a phenomenon where the roots of shade plants reduce the access of coffee plant roots in absorbing water and nutrients and significantly affect tree biomass and productivity (Defrenet et al. 2016). Sarmiento-Soler et al. (2019) reported that the use of water in coffee agroforestry systems was higher than in monoculture coffee, potentially reducing water availability for coffee. On the other hand, several studies have shown that there may be water competition between coffee and shade plants under dry conditions (Bayala et al. 2015). The selection of shade plants with different root structures causes plant roots to absorb water in different soil layers, thereby reducing competition and water loss through deep percolation (Sarmiento-Soler et al. 2019). To answer these questions, a study was conducted with the aims of (i) analyzing the effect of coffee shade on available water capacity and coffee root density and (ii) analyzing the effect of soil depth on available water capacity and coffee root density under coffee agroforestry systems in smallholder plantations.

MATERIALS AND METHODS

Study area

The research was conducted at a few selected smallholder coffee plantations in Srimulyo Village, Dampit Sub-district, Malang District, East Java, Indonesia (8.25654-8.27093 S, and 112.7747-112.7792 E) (Figure 1). Dampit is one of the largest coffee producers in Malang, with a land area of 3,372.5 ha and a total production of 2,280.3 tons (BPS 2019). The research is located at an altitude of 480-565 m asl. Based on the Schmidt Ferguson climate, the location was classified to D class, which is divided into two periods; the wet month (rainfall >100 mm) and the dry month (rainfall <60 mm) with an average annual rainfall of 2209 mm (climate stations of Karangploso, Malang). The soil type is Inceptisol (Sari and Prijono 2019). The research was carried out between October 2021 - May 2022. The sample analysis process was carried out at the Soil Physics, Chemistry and Biology Laboratory, Faculty of Agriculture, Brawijaya University, Indonesia.

Experimental design

The study used a survey method to determine the research location and soil sampling sites. The research design was a randomized block design with four different systems; coffee-open (KO), coffee with *Musa* sp. shade (KP), coffee with *Gliricidia sepium* shade (KG), and coffee with *Leucaena leucocephala* shade (KL) with 3 replications. The research plot was 20 m x 20 m. The plots were selected based on the following criteria: i) coffee age between 25-30 years, and ii) located on a flat slope. The type of coffee cultivated is Robusta coffee with a spacing between coffee plants of 2.5 m x 2.5 m. Fertilization was carried out twice a year, at the beginning of the rainy season and the end of the rainy season at the rate of 205 kg N ha^{-1}, 76 kg P_2O_5 ha^{-1}, and 167 kg K_2O ha^{-1} per year.

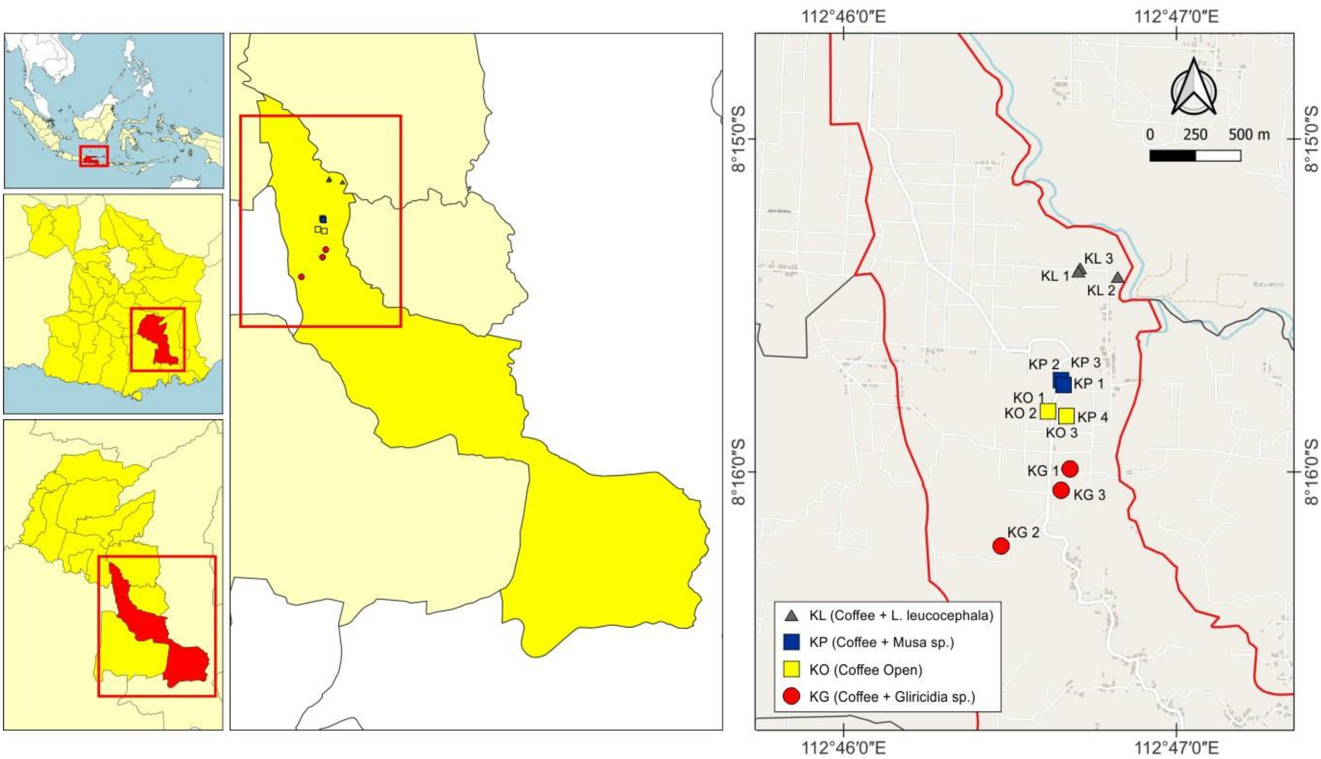

Figure 1. Soil and root sampling site at the coffee smallholder plantation in Srimulyo Village, Dampit Sub-district, Malang District, East Java, Indonesia

Sampling and sample measurement

Soil and root sampling were carried out at three depths (0-20 cm, 20-40 cm, and 40-60 cm), and two distances: near the coffee stem (75 cm from the coffee stem) and between coffee-shade tree (100-150 cm from coffee stems). The distance of 75 cm refers to the limit of coffee fertilization around the stem and the distance of 100-150 cm refers to the middle distance of coffee-shade tree. The middle distance of the coffee-shade tree is different in a different system, where the middle distance of KP and KG is 100 cm, and the middle distance of KO and KL is 150 cm. The variables observed were Available Water Capacity (AWC) and root length density (RLD) as the main variables. AWC is soil characteristics that determine soil water supply, which is defined as the difference between volumetric water content at field capacity and the permanent wilting point of the soil (Kukal et al. 2022). The supporting variables were soil organic carbon, soil aggregate stability and soil penetration resistance. Disturbed soil was used for the analysis of soil organic carbon using the Walkey and Black method. Soil aggregate sampling was used for the analysis of soil aggregate stability (Mean Weight Diameter: MWD) using the wet sieve method. Measurement of soil penetration resistance was carried out directly in the field using a hand penetrometer.

Available water measurement

The undisturbed soil sample was used to analyze available water capacity using a ring sample with a diameter of 5 cm and a length of 6 cm. Available water capacity was measured as the differences between volumetric water content at field capacity (0.03 MPa; pF 2.5) and wilting point (1.5 MPa; pF 4.2) (Ghassemi-Golezani and Farhangi-Abriz 2021). The methods used were the sanbox (pF 2.5) and the pressure plate apparatus method (pF 4.2).

Root length density measurement

Measurement of root length density was carried out on coffee trees with a stem diameter of 5-20 cm. Root samples were taken using an iron block in size 20 cm x 20 cm x 10 cm (modified research of Saleh et al. 2022). Furthermore, coffee roots were separated from the soil using a dry sieve method carried out in the field and a wet sieve carried out in the laboratory. The sieves used were 2 mm and 250 µm in diameter.

Root density analysis was carried out using the Line Intersect method by Tennant (1975). The sub-sample of the coffee root was cut into small pieces of about 2 cm and spread on grid paper (the grid size was 1 cm x 1 cm). Then, the intersection of the roots with horizontal and vertical lines on grid paper was calculated manually. The calculation of RLD is presented in equation 1.

$$\text{RLD} = \frac{\pi\,((H+V)D)}{4} \qquad (1)$$

Where: H: total of roots intersection in horizontal lines; V: total of roots intersection in vertical lines; D: the grid size

Data analysis

The collected data were analyzed by variance analysis and continued with the analysis of Tukey's HSD (honestly significant difference) at a level of 5% to determine the significant difference among treatments. Correlation analysis was performed to measure the relationship between roots and soil parameters (i.e. RLD, AWC, C-organic, soil aggregate stability, and soil penetration resistance). All analyses were performed by using SPSS 25 for windows.

RESULTS AND DISCUSSION

Analysis of the variance of AWC and RLD variables is presented in Table 1. The effect of coffee shade type on AWC and RLD values was presented in Table 2, and the effect of soil depth on AWC and RLD values was presented in Table 3.

Table 1. Analysis of variance of Available Water Capacity (AWC) and Root Length Density (RLD)

Source of variation	AWC	RLD
	p value	
Type of coffee shade (S)	0.281 ns	0.022*
Soil depth (De)	0.002*	<0.0001**
Distance(Di)	0.597 ns	0.002*
S x De	0.061 ns	0.484 ns
S x Di	0.738 ns	0.308 ns
De x Di	0.867 ns	0.262 ns
S x De x Di	0.215 ns	0.619 ns

Note: ns: not significant, *: significant (p value<0,05), **: very significant (p value <0,001)

Table 2. Available Water Capacity (AWC) and Root Length Density (RLD) values at the different coffee shade

Code	Coffee shade	AWC	RLD
		$cm^3\ cm^{-3}$	$cm\ cm^{-3}$
KO	Coffee open	0.08	0.03 ab
KP	Coffee + *Musa* sp.	0.10	0.02 a
KG	Coffee + *G. sepium*	0.07	0.07 b
KL	Coffee + *L. leucocephala*	0.08	0.04 ab

Note: Numbers followed by different letters in the same column are significantly different at the 5% Tukey's test

Table 3. Available Water Capacity (AWC) and Root Length Density (RLD) values at different soil depths

Soil depth (cm)	AWC	RLD
	$cm^3\ cm^{-3}$	$cm\ cm^{-3}$
0-20	0.10 b	0.07 b
20-40	0.06 a	0.02 a
40-60	0.08 ab	0.04 ab

Note: Numbers followed by different letters in the same column are significantly different at the 5% Tukey's test

Available water capacity

Available water capacity was not affected by coffee shade (Table 1). The KP treatment had the highest AWC value, while the KG treatment had the lowest AWC value (Table 2). AWC value was significantly affected by soil depth (Table 1). The highest AWC values were at a depth of 0-20 cm and significantly different at a depth of 20-40 cm (Table 3). AWC is water stored in soil pores where it can be utilized by plant roots. The available water capacity is influenced by several factors, one of which is soil structure. The KP (coffee-*Musa* sp.) treatment had a stable soil structure, so the AWC value was also high. In line with the statement of Basset et al. (2023), soils that have a more stable structure can increase water infiltration and have the ability to absorb and retain water during irrigation or rain. Besides soil structure, the AWC value is also influenced by soil organic matter. The soil surface (0-20 cm depth) had a higher AWC value because the soil organic matter content was greater than at other depths (Table 4). Increasing the percentage of soil organic C may change the soil surface area and balance the proportion of soil pore size distribution. These alternations can result in increased water retention and retain moisture between field capacity and permanent wilting point, or available water content (Safadoust et al. 2014). AWC value was influenced by soil organic carbon and soil aggregate stability (MWD) which were presented in Table 4.

The highest soil organic C content was in the KL treatment and the lowest soil organic C was in the KO treatment (Table 4). It means that coffee agroforestry has a higher organic C value than coffee without shade. Similarly, Tumwebaze and Byakagaba (2016) reported that coffee agroforestry had significantly higher soil organic C compared to coffee monoculture. This may be due to the continuous input of leaves and dead roots of shade and coffee trees. In addition, coffee agroforestry had the potential to store more soil organic C than plots without shade trees. The increase in soil depth was followed by lower soil organic C values (Table 4). According to Thomazini et al. (2015), topsoil (0-30 cm depth) stores almost half of the soil's organic C and three times the carbon stored in plants. Other research shows that about 71 to 76% of the total carbon is stored at 0-30 cm soil depth (Adiyah et al. 2022). The high value of soil organic C in topsoil is the result of the decomposition of organic matter from several sources, such as dead organisms (i.e. animals, insects), plant litter, and root exudates (Kunlanit et al. 2019).

Agroforestry coffee contained a higher soil aggregate stability than coffee-open, and aggregate stability decreased with increasing soil depth (Table 4). Soil aggregate stability was affected by several factors, one of which is soil organic matter. Similarly, Rieke et al. (2022) reported that soil aggregate stability was positively correlated with soil organic C, indicating that increasing soil organic C was followed by increasing soil aggregate stability. The KL treatment had high soil organic matter; therefore, the soil aggregate was more stable. On the other hand, the KO treatment had low organic matter; therefore, the soil aggregate stability was also low. Soil organic matter can increase the activity of soil microorganisms and increase the binding capacity and elasticity between soil particles, thereby increasing the resistance and stability of soil aggregates (Karami et al. 2012). Soil aggregate stability is an important physical property that affects soil stability, and plays a key role in maintaining soil porosity, water holding capacity, permeability, reducing erosion and soil carbon conservation, and can be used as an evaluation of soil quality (Thomaz 2021; Ma et al. 2022).

Correlation between AWC, soil organic C, and soil aggregate stability

Soil organic C was significantly positively correlated with the AWC value (Table 5). Increasing soil organic C could increase the available water capacity. Similar results were shown by Hanuf et al. (2021) that the increase in soil organic C was followed by an increase of available water capacity. Soil organic matter content affects the available water capacity either directly or indirectly. Increasing soil organic C content can increase the number of oxygen-containing functional groups (e.g. carboxylic, phenolic hydroxyl and amino groups) in soil. These groups provide sorption sites for water molecules. However, the decrease or increase of sorption sites with increasing soil organic C depends on soil clay content (Zhou et al. 2020). Indirectly, organic matter increases the available water capacity by improving soil physical properties such as soil aggregation, pore size distribution (increasing the activity of soil organisms which has an impact on the formation of new soil pores, especially around the root zone), bulk density, and porosity (Guhra et al. 2022). On the other side, increasing soil water content can increase soil organic C. Increased soil water content provides food for soil biota by increasing the content of microbial biomass, where microbial activity ideally occurs when the soil moisture content is close to field capacity (Ramesh et al. 2019).

Soil aggregate stability was significantly positively correlated with the AWC value (Table 5). It shows that the increase in soil aggregate stability was followed by an increase in AWC value. The more stable the soil aggregate, the less easily crushed by external pressure (rainwater or soil management) so that the pore space is maintained, which results in an increase in available water capacity.

Root length density

The type of coffee shade significantly affected root length density (RLD) (Table 1). KG had the largest RLD value, while the KP treatment had the lowest RLD value (Table 2). Soil depth significantly affected the RLD value (Table 1). The soil depth of 0-20 cm had the highest RLD value and was significantly different from other soil depths, while the depth of 20-40 cm had the lowest RLD value.

KO and KP treatments had lower RLD values than KG and KL treatments. In the KP treatment, it was suspected that *Musa* sp. root system inhibits the growth of coffee roots. *Musa* sp. roots are adventitious roots with a shallow root system and spread widely on the soil surface (Panigrahi et al. 2021). Thus, it has a low potentiality to uptake water and nutrient from deep soil layers and is vulnerable to water stress. In addition, *Musa* sp. is characterized by a large shoot system i.e. broad leaves, which these usually associated with a high evapotranspiration rate (Ali et al. 2015). This indicated that there was a possibility of water competition on the soil surface between coffee plants and *Musa* sp. plants, especially during the dry season.

KG and KL treatments had a higher RLD value than coffee open. This indicated that there was no competition between coffee plant roots and *G. sepium* roots or *L. leucocephala* roots on the topsoil. *G. sepium* and *L. leucocephala* plants are legume plants, where the roots of legume plants are in symbiosis with N-fixing bacteria, thereby increasing soil fertility. The roots of *G. sepium* and *L. leucocephala* are able to penetrate deep into the soil and resist drought (Okoye et al. 2022), so they do not interfere with coffee roots.

The roots of coffee plants are most widely distributed at a depth of 0-20 cm. Several other studies have shown similar results that about 50-70% of fine roots of coffee plants are distributed on the soil surface (Carducci et al. 2015; Padovan et al. 2015). This is due to the contribution of organic matter through plant litter and the application of fertilizers, which are mostly concentrated on the soil surface. The distribution and growth of coffee roots are strongly influenced by environmental and soil conditions (Padovan et al. 2015). In dry conditions, the distribution of coffee roots tends to the deeper parts of the soil. Meanwhile, in wet conditions, the coffee roots on the topsoil (up to 40 cm soil depth) play a more important role in absorbing water and nutrients (Silva et al. 2020).

The distance from the coffee plant significantly affected the RLD value. RLD at the coffee stem was greater than between the coffee plants-shade tree (inter-row) (Figure 2). According to Schmidt et al. (2022), coffee roots have greater root lengths near the coffee stem (up to 60 cm away from the coffee stem). This is probably because these plants are fertilized at that distance. Root growth depends on other processes, such as nutrient cycling, which near the coffee stem (row) from the coffee plant is the fertilization area. Otherwise, soil mineral deficiency may limit coffee root development (Nunes et al. 2020). Factor affecting root length density

Penetration resistance is one of the factors that affect root growth. Soil penetration resistance is an important soil physical property to water access which also affects root elongation. Soil penetration resistance is influenced by soil characteristics (such as bulk density, soil aggregates stability, soil texture, organic matter, and soil moisture content) and tillage (Souza et al. 2021). Coffee combined with shade plants had better penetration resistance than coffee without shade. This is presumably because the combination of coffee with shade trees can increase soil organic matter through plant litter and increase the stability of soil aggregates, which can improve soil penetration resistance. In accordance with the opinion of Gabriel et al. (2021) that the presence of cover crops can reduce soil compaction because the plant canopy can protect against the destruction of soil surface aggregates by rainwater, and the organic matter can improve soil aggregation. Penetration resistance >2.5 MPa usually inhibits root elongation and adversely affects plant growth (Souza et al. 2021). The overall treatment had a penetration resistance value of < 2.5 Mpa, so soil compaction was not the main factor inhibiting root elongation.

The value of soil penetration resistance increased with increasing soil depth (Table 5). Otherwise, the value of RLD decreased with increasing soil depth (Table 3 and Figure 2). Increasing penetration resistance in the deep layer indicated that soil compaction occurred in the deep layer. Penetration resistance at 0-40 cm soil depth was <1 Mpa. It indicated that there was no soil compaction and did not inhibit root growth. Meanwhile, at a depth of 40-60 cm, the penetration resistance value is >1.1 MPa, which indicates that soil compaction occurs and there is little inhibition for root growth. It can be seen in Figure 2 that root growth decreased with increasing soil depth, which indicates that root growth restriction occurred in the deep layers.

Soil penetration resistance had a negative correlation with RLD values (r = -0.036, p>0.05). In line with previous research which showed that root growth rate was significantly negative correlated with soil penetration resistance (Lipiec et al. 2012; Valentine et al. 2012). With increasing soil penetration resistance, roots need to exert higher mechanical forces and stresses to penetrate the soil, leading to an increase in the metabolic costs of soil exploration. A further impact on the root phenotype, namely resistance to soil penetration, can lead to shallower root growth, root thickening, and a reduction in the number of lateral and axial roots. A decrease in the rate of root elongation, shallower root growth, root thickening and a decrease in the number of roots reduces the volume of soil that can be explored by plants in absorbing water and nutrients (Colombi et al. 2018), thus affecting plant growth. This mechanism shows that soil compaction can inhibit root growth.

Table 4. Soil organic carbon and Mean Weight Diameter (MWD) at the different coffee shades and soil depth

Code	Soil organic carbon	MWD	Soil depth (cm)	Soil organic carbon	MWD
	%	mm		%	mm
KO	0.41 a	1.59 a	0-20	0.72 c	3.12 c
KP	0.42 a	2.08 a	20-40	0.46 b	1.83 b
KG	0.46 a	1.69 a	40-60	0.28 a	1.26 a
KL	0.66 b	2.93 b			

Note: Numbers followed by different letters in the same column are significantly different at the 5% Tukey's test

Table 5. Pearson correlation of AWC (Available Water Capacity), soil organic carbon, and MWD (Mean Weight Diameter)

	AWC	Soil organic carbon	MWD
Soil organic carbon	0.248*	1	0.722**
MWD	0.346**	0.722**	1
AWC	1	0.248*	0.346**

Note: *correlation is significant at 0.05 level, **correlation is significant at 0.01 level

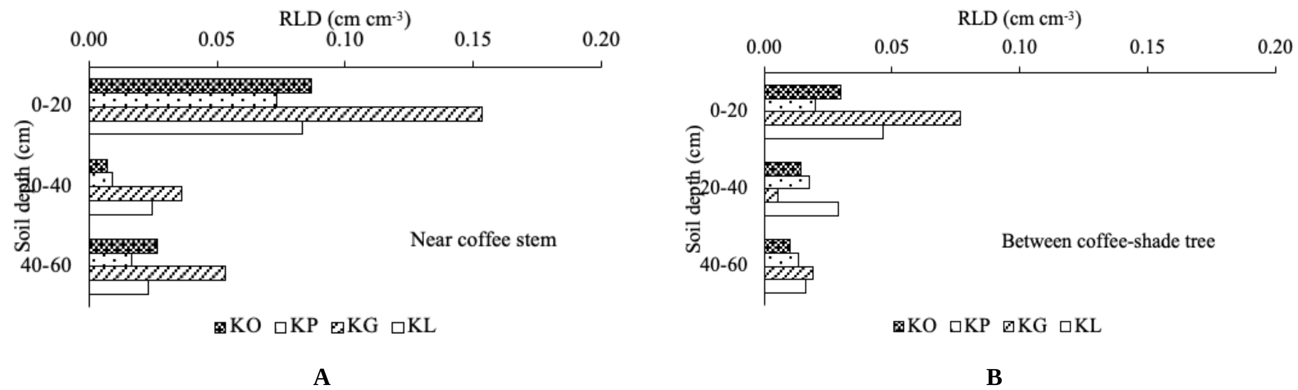

Figure 1. Root length density (cm cm-3). A. Near the coffee stem (row); B. Between coffee plants-shade tree

Table 5. Soil penetration resistance at the different coffee shades and soil depth

Code	Coffee shade	Penetration resistance MPa	Soil depth (cm)	Penetration resistance Mpa
KO	Kopi tanpa naungan	1.01	0-20	0,88 a
KP	Kopi + Musa sp.	1.10	20-40	0,97 b
KG	Kopi + *G. sepium*	0.93	40-60	1,26 c
KL	Kopi + *L. leucocephala*	1.10		

Note: Numbers followed by different letters in the same column are significantly different at the 5% Tukey's test

In conclusion, shade plants in coffee plantations could increase AWC and RLD values. The KP treatment had the highest AWC value, although it was not significantly different from the other treatments. Coffee shade significantly affected RLD value. KG and KL treatments had higher RLD values than unshaded coffee. These results indicated that the application of coffee agroforestry with *G. sepium* or *L. leucocephala* had a positive impact on root growth, where there was no competition between coffee plants and shade tree roots. KP treatment had a lower RLD value than coffee open, which indicated that there was a possibility of root competition between coffee plants and *Musa* sp. The overall treatment had a penetration resistance value of <2.5 MPa, which indicated that soil compaction was not a factor inhibiting root growth. Soil depth significantly affected AWC and RLD values. The highest AWC value occurred at topsoil (0-20 cm). Likewise, the highest RLD value also occurred at topsoil (0-20 cm), which indicated that the roots of coffee plants were widely distributed on the soil surface. This happened because the soil surface had high soil organic C, more stable soil aggregates, and low soil penetration resistance compared to other depths.

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REFERENCES

Adiyah F, Micheli E, Csorba A, Gebremeskel T, Gyuricza C, Melenya C, Dawoe E, Owusu S, Fuchs M. 2022. Effects of landuse change and topography on the quantity and distribution of soil organic carbon stocks on *Acrisol catenas* in tropical small-scale shade cocoa systems of the Ashanti region of Ghana. Catena 216: 106366. DOI: 10.1016/j.catena.2022.106366.

Ali ABM, Elshaikh NA, Shuang-En Y, Basheer AK, Alnail M, Alhadi M, Altayeb OA. 2015. Correlation between water deficiency, yield components and crop productivity of banana. J Environ Agric Sci 4: 11-20.

Basset C, Najm MA, Ghezzehei T, Hao X, Daccache A. 2023. How does soil structure affect water infiltration? A meta-data systematic review. Soil Tillage Res 226. DOI: 10.1016/j.still.2022.105577.

Bayala J, Sanou J, Teklehaimanot Z, Ouedraogo SJ, Kalinganire A, Coe R, van Noordwijk M. 2015. Advances in knowledge of processes in soil-tree-crop interactions in parkland systems in the West African Sahel: A review. Agric Ecosyst Environ 205: 25-35. DOI: 10.1016/j.agee.2015.02.018.

BPS. 2019. Indonesian coffee statistics. Sub Direktorat Statistik Tanaman Perkebunan. Central Bureau of Statistics, Indonesia. [Indonesian]

Carducci CE, Oliveira GC, Curi N, Heck RJ, Rossoni DF, de Carvalho TS, Costa AL. 2015. Gypsum effects on the spatial distribution of coffee roots and the pores system in oxidic Brazilian Latosol. Soil Tillage Res 145: 171-180. DOI: 10.1016/j.still.2014.09.015.

Colombi T, Torres LC, Walter A, Keller T. 2018. Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth - A vicious circle. Sci Tot Environ 626: 1026-1035. DOI: 10.1016/j.scitotenv.2018.01.129.

Defrenet E, Roupsard O, Van Den Meersche K, Charbonnier F, Pérez-Molina JP, Khac E, Prieto I, Stokes A, Roumet C, Rapidel B, De Melo Virginio Filho E, Vargas VJ, Robelo D, Barquero A, Jourdan C. 2016. Part of a special issue on root biology: Root biomass, turnover and net primary productivity of a coffee agroforestry system in Costa Rica: Effects of soil depth, shade trees, distance to row and coffee age. Ann Bot 118 (4): 833-851. DOI: 10.1093/aob/mcw153.

Dori T, Asefaw Z, Kippie T. 2022. Soil characteristics under dominant agroforestry systems along toposequence of Gedeo, Southeastern Ethiopia. Environ Sustain Indic 15: 100191. DOI: 10.1016/j.indic.2022.100191.

Eeswaran R, Nejadhashemi AP, Alves FC, Saravi B. 2021. Evaluating the applicability of soil moisture-based metrics for gauging the resiliency of rainfed agricultural systems in the midwestern United States. Soil Tillage Res 205: 104818. DOI: 10.1016/j.still.2020.104818.

Etafa AT. 2022. Effect of dominant shade tree species on selected soil physicochemical properties and coffee production in Sayyo district, western Ethiopia. Trees For People 8: 100245. DOI: 10.1016/j.tfp.2022.100245.

Fikriani C, Slamet J. S. 2019. Peluang dan tantangan pengembangan Kopi Amstirdam. Warta: Pusat Penelitian Kopi dan Kakao Indonesia 31 (3). [Indonesian]

Gabriel JL, García-González I, Quemada M, Martin-Lammerding D, Alonso-Ayuso M, Hontoria C. 2021. Cover crops reduce soil resistance to penetration by preserving soil surface water content. Geoderma 386. DOI: 10.1016/j.geoderma.2020.114911.

Ghassemi-Golezani K, Farhangi-Abriz S. 2021. Plant available water holding capacity of soil under chemically modified biochars. Rhizosphere 21: 100469. DOI: 10.1016/j.rhisph.2021.100469.

Guhra T, Stolze K, Totsche KU. 2022. Pathways of biogenically excreted organic matter into soil aggregates. Soil Biol Biochem 164: 108483. DOI: 10.1016/j.soilbio.2021.108483.

Hanuf AA, Prijono S, Soemarno. 2021. Improvement of soil available water capacity using biopore infiltration hole with compost in a coffee plantation. J Degrad Mining Lands Manag 8 (3): 2791-2799. DOI: 10.15243/jdmlm.

International Coffee Organization (ICO). 2019. World Coffee consumption for 2019/2020. http://www.ico.org/prices/new-consumption-table.pdf.

Karami A, Homaee M, Afzalinia S, Ruhipour H, Basirat S. 2012. Organic resource management: Impacts on soil aggregate stability and other soil physico-chemical properties. Agric Ecosyst Environ 148: 22-28. DOI: 10.1016/j.agee.2011.10.021.

Kukal MS, Irmak S, Dobos R, Gupta S. 2022. Atmospheric dryness impacts on crop yields are buffered in soils with higher available water capacity. Geoderma 429: 116270. DOI: 10.1016/j.geoderma.2022.116270.

Kunlanit B, Butnan S, Vityakon P. 2019. Land-use changes influencing C sequestration and quality in topsoil and subsoil. Agronomy 9 (9): 1-16. DOI: 10.3390/agronomy9090520.

Lipiec J, Horn R, Pietrusiewicz J, Siczek A. 2012. Effects of soil compaction on root elongation and anatomy of different cereal plant species. Soil Tillage Res 121: 74-81. DOI: 10.1016/j.still.2012.01.013.

Ma Y, Cheng X, Kang F, Han H. 2022. Dynamic characteristics of soil aggregate stability and related carbon and nitrogen pools at different developmental stages of plantations in northern China. J Environ Manag 316: 115283. DOI: 10.1016/j.jenvman.2022.115283.

Moreira SLS, Pires CV, Marcatti GE, Santos RHS, Imbuzeiro HMA, Fernandes RBA. 2018. Intercropping of coffee with the palm tree, macauba, can mitigate climate change effects. Agric For Meteorol 256: 379-390. DOI: 10.1016/j.agrformet.2018.03.026.

Nunes ALP, Cortez GL. de S, Zaro GC, Zorzenoni TO, de Melo TR, Figueiredo A, de Aquino GS, Medina C. de C, Ralisch R, Caramori P. H, Guimarães M. de F. 2020. Soil morphostructural characterization and coffee root distribution under agroforestry system with *Hevea brasiliensis*. Scientia Agricola 78 (6): 1-10. DOI: 10.1590/1678-992x-2019-0150.

Okoye PU, Torres-Arellano S, Mejía-Lopez M, Alem JL, Sebastian PJ. 2022. A review on bioenergetic applications of *Leucaena leucocephala*. Ind Crops Prod 182, 114847. DOI: 10.1016/j.indcrop.2022.114847.

Olorunfemi I, Fasinmirin J, Ojo A. 2016. Modeling cation exchange capacity and soil water holding capacity from basic soil properties. Eur J Soil Sci (4): 266-274. DOI: 10.18393/ejss.2016.4.266-274.

Padovan MP, Cortez VJ, Navarrete LF, Navarrete ED, Deffner AC, Centeno LG, Munguía R, Barrios M, Vílchez-Mendoza JS, Vega-Jarquín C, Costa AN, Brook RM, Rapidel B. 2015. Root distribution and water use in coffee shaded with *Tabebuia rosea* Bertol. and *Simarouba glauca* DC. compared to full sun coffee in sub-optimal environmental conditions. Agrofor Syst 89 (5): 857-868. DOI: 10.1007/s10457-015-9820-z.

Panigrahi N, Thompson AJ, Zubelzu S, Knox JW. 2021. Identifying opportunities to improve management of water stress in banana production. Sci Hort 276: 109735. DOI: 10.1016/j.scienta.2020.109735.

Ramesh T, Bolan NS, Beth M, Ok YS, Choudhury BU, Wang H, Tang C, Wang X, Song Z, Freeman OW. 2019. Soil organic carbon dynamics : Impact of land use changes and management practices: A review. Adv Agron 156. DOI: 10.1016/bs.agron.2019.02.001.

Rieke EL, Bagnall DK, Morgan CLS, Flynn KD, Howe JA, Greub KLH, Mac Bean G, Cappellazzi SB, Cope M, Liptzin D, Norris CE, Tracy PW, Aberl E, Ashworth A, Bañuelos TO, Bary AI, Baumhardt RL, Borbón GA, Brainard DC, Honeycutt CW. 2022. Evaluation of aggregate stability methods for soil health. Geoderma 428. DOI: 10.1016/j.geoderma.2022.116156.

Safadoust A, Feizee P, Mahboubi AA, Gharabaghi B, Mosaddeghi MR, Ahrens B. 2014. Least limiting water range as affected by soil texture and cropping system. Agric Water Manag 136: 34-41. DOI: 10.1016/j.agwat.2014.01.007.

Saleh AR, Gusli S, Ala A, Neswati R, Sudewi SRI. 2022. Tree density impact on growth, roots length density, and yield in agroforestry based cocoa. Biodiversitas 23 (1): 496-506. DOI: 10.13057/biodiv/d230153.

Sari IL, Prijono S. 2019. Infiltration and water storage on different shade types in coffee land at Amadanom Village, Dampit Distric, Malang Regency. Jurnal Tanah dan Sumberdaya Lahan 6 (1): 1183-1192. DOI: 10.21776/ub.jtsl.2019.006.1.17. [Indonesian]

Sarmiento-Soler A, Vaast P, Hoffmann MP, Rötter RP, Jassogne L, van Asten PJA, Graefe S. 2019. Water use of *Coffea arabica* in open versus shaded systems under smallholder's farm conditions in Eastern Uganda. Agric For Meteorol 266: 231-242. DOI: 10.1016/j.agrformet.2018.12.006.

Schmidt R, Silva LOE, Ferreira A, Gontijo I, Guimaraes RJ, Ramalho JC, Partelli FL. 2022. Variability of root system size and distribution among *Coffea canephora* genotypes. Agronomy 12: 1-12. DOI: 10.3390/agronomy12030647.

Silva BM, de Oliveira GC, Serafim ME, Carducci CE, da Silva ÉA, Barbosa SM, de Melo LBB, dos Santos WJR, Reis THP, de Oliveira CHC, Guimarães PTG. 2020. Soil management and water-use efficiency in Brazilian coffee crops. Coffee - Prod Res 6: 25. DOI: 10.5772/intechopen.89558.

Sohoulande CDD, Stone K, Szogi A, Bauer P. 2019. An investigation of seasonal precipitation patterns for rainfed agriculture in the Southeastern region of the United States. Agric Water Manag 223: 105728. DOI: 10.1016/j.agwat.2019.105728.

Souza R, Hartzell S, Freire Ferraz AP, de Almeida AQ, de Sousa LJR, Dantas AAC, de Souza ES. 2021. Dynamics of soil penetration resistance in water-controlled environments. Soil Tillage Res 205: 104768. DOI: 10.1016/j.still.2020.104768.

Sujatmiko T, Ihsaniyati H. 2018. Implication of climate change on coffee farmers' welfare in Indonesia. IOP Conf Ser: Earth Environ Sci 200 (1). DOI: 10.1088/1755-1315/200/1/012054.

Tennant D. 1975. A Test of a modified line intersect method of estimating root length. J Ecol 63 (3): 995. DOI: 10.2307/2258617.

Thomaz EL. 2021. Effects of fire on the aggregate stability of clayey soils: A meta-analysis. Earth-Sci Rev 221: 103802. DOI: 10.1016/j.earscirev.2021.103802.

Thomazini A, Mendonça ES, Cardoso IM, Garbin ML. 2015. SOC dynamics and soil quality index of agroforestry systems in the Atlantic rainforest of Brazil. Geoderma Reg 5: 15-24. DOI: 10.1016/j.geodrs.2015.02.003.

Tumwebaze SB, Byakagaba P. 2016. Soil organic carbon stocks under coffee agroforestry systems and coffee monoculture in Uganda. Agric Ecosyst Environ 216: 188-193. DOI: 10.1016/j.agee.2015.09.037.

Valentine TA, Hallett PD, Binnie K, Young MW, Squire GR, Hawes C, Bengough AG. 2012. Soil strength and macropore volume limit root elongation rates in many UK agricultural soils. Ann Bot 110 (2): 259-270. DOI: 10.1093/aob/mcs118.

Zhou H, Chen C, Wang D, Arthur E, Zhang Z, Guo Z, Peng X, Mooney S. J. 2020. Effect of long-term organic amendments on the full-range soil water retention characteristics of a vertisol. Soil Tillage Res 202: 104663. DOI: 10.1016/j.still.2020.104663.