Morphological adaptation of cocoa fine roots under shaded of langsat tree in exploring stony soil

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Morphological adaptation of cocoa fine roots under shaded of langsat tree in exploring stony soil

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Abstract. Cocoa fine roots are responsive to changes in the soil environment to maximize nutrient and water absorption for plant growth. The presence of rock increases soil density and decreases available water content, promoting modification of fine root development. The purpose of this study was to clarify the effect of the physical properties of stony soil on the morphological properties of fine roots. In three land-use systems, soil samples were taken from four depths using a sample core measuring 385 cm3 in three land-use systems. Fine roots were extracted by the immersion method, to measure the length of fine roots from five classes of orders based on diameter. We notes, the bulk density of stony soil increases as the rock mass increases, and the depth increases. The available water content decreases with the increase in bulk density, and this decrease is more pronounced in the lower soil layer. Fine root length was found more in the lower order diameter class, decreasing soil moisture against the bulk density gradient. The bulk density in the topsoil layer reaches 1.71 g cm-3, increasing to 1.84 g cm-3 in the lower soil layer. It seems unreasonable, when compared to the general density of soil mass. Still, this result is solely due to the high fraction of rock with a higher density. Fine roots were dominated by orders 1 and 2 with root diameters < 0.25 mm and < 0.50 mm, reaching 70% of the total fine root length. Fine roots in this diameter class act as absorbent roots, acquiring water and nutrients from the soil.

Keywords: ***Cocoa fine roots, density, soil layer, soil mosture***

1. Introduction

Farmers in West Sulawesi, Indonesia, have been cultivating cocoa (Theobroma cocoa L.) on sloping land with fruit trees as shade in an agroforestry system. Langsat (Lansium domesticum) is the dominant tree growing in the cacao tree line, providing suitable environmental services for lower strata crops. Shade functions to filter excess light, reduce air temperature, contribute organic litter, and increase farmers' income sources in the agroforestry system, making the soil dominated by rock fractions more productive.

Stony soil is mixed a fine soil with a size of <2mm with rock particles having a particle size greater than 2mm. High rock composition has an impact on soil properties such as both increase in diameter and, density macropore, other than, it also caused an increase in bulk density [1, 2]. These properties have an impact on reduced of the soil in terms of ability to water holding capasity, and with moderate to rapid rate permeability [3], the amount of water lost from this soil can reach 23% [1], water seeps quickly into deeper soil layers, transporting nutrients through nutrient leaching [3]. In addition, the higher density of stony soils compared to other soil types bulk density, inhibits root development to the subsoil fraction at the bottom [4,5].

Roots play a role in regulating the ability of plants to absorb water and nutrients, as well as parameters for the amount of organic matter transferred by plants into the soil. The rock fraction in rocky soil creates barriers to root growth exploring deeper soil layers [7], The high bulk density of rocky soil is a limiting factor for fine root growth, to reach a depth of 40 cm [1], that condition, Fine roots are limited to soil exploration, which means that less water and nutrients are absorbed from the soil, resulting in decreased plant growth and production [8,7].

Plants respond to unfavorable soil environmental conditions by the modifying root development. Information regarding the impact of the presence of rock fractions and effect of hight bulk density to morphological of fine roots of cocoa is limited. The order of fine roots based on diameter provides information about the ability of plants to respond to changes in the surrounding physical environment in the form of hight soil bulk density, limited water availability, and other elements of the soil environment unprofitable. Variations in the diameter of fine roots have different functions and roles [9], an increase soil bulk density causes a decrease in the diameter of fine roots up to 0.2 mm, where fine roots in this diameter range act as absorbing roots that absorb nutrients and water from the soil. [5]. In this paper, we focused on investigating the morphological response of fine roots of cocoa trees to changes in soil mass density and water availability in rocky soils, including the presence of shade tree roots that absorb water and nutrients in the same soil layer as toot cocoa tree. The results of this study help to understand the specific adaptation of cacao fine roots in harsh soil environments.

2. Materials and Method

2.1. Study site

The sampling location was a cocoa plantation in Binuang District, Polewali Mandar Regency, West Sulawesi. These locations are at the coordinates of 03° 25' 28.9" South Latitude and 119° 23' 10.7" East Longitude to 03° 2 0 15' 52.1" South Latitude and 119° 23' 13.3" East Longitude, it those are spread at an altitude of between 100 - 400 m asl (meters above sea level).

2.2. Prosedure

The bulk density of stony soil can be expressed as the sum of the bulk density of fine earth, and rock fragments [10]. The bulk density of stony soil is measured using a soil sample undisturbed by volume 20 x 20 x 20 cm (or Vb = 8000 cm^3). The calculation method begins by first separating the soil constituent materials, rock volume; fine earth fragments volume (Vf in cm^3) using equation #1, rock volumetric ratio (Rv) using equation #2, Rock mass ratio (Rm) using equation #3), rock bulk density (ρ_b^{rf} in g cm^{-3}) using equation #4); fine earth bulk density (ρ_b^f in g cm^{-3}) uses equation #5; Stony soil bulk density(ρ_b^b in g cm^{-3}) uses equation #6.

$$V^f = V^b - V^{rf} \quad (1)$$

$$Rm = \frac{m_d^{rf}}{m_d^b} \quad (2)$$

$$\rho_b^{rf} = \frac{m_d^{rf}}{V^{rf}} \quad (3)$$

$$\rho_b^f = \frac{\mathrm{m}_\mathrm{d}^\mathrm{f}}{\mathrm{V}^\mathrm{f}} \tag{4}$$

$$\rho_b^b = (1 - R_v)\rho_b^f + R_v \rho_b^{rf} \tag{5}$$

$$Rv = R_m \frac{\rho_b^b}{\rho_b^{rf}} \tag{6}$$

Vrf is the volume of rock fragments (in cm^3) calculated directly in the field for mineral fragments larger than 5 mm, while mineral materials 2-5 mm were measured in the laboratory using a sub-sample soil that passed a 5 mm sieve, m_d^{rf} is a dry weight of rock fragments, and m_d^f is a dry weight of fine soil fragments, m_d^b is a dry weight of rock fragments + dry weight of fine soil fragments.

2.3. *Measurement of root length and diameter*

Soil samples to extract fine roots were extracted from three land-use systems; the system is replicated four times each, so we have a total of 12 main unit plots. In each field, sampling points were under two cocoa trees, at three different distances from the base of the cocoa tree trunk, at a distance of 0.4 m, 1.2 m, and 1.7 m from the base of the cocoa tree, using core samples were 7 cm in diameter, soil samples were taken at a depth of 0-10, 10-20 cm, 20-30 cm, and 30-40 cm. The roots were extracted using the soaking method, and the base was cleaned. Only cacao and langsat fine roots are counted. Both cacao and langsat fine roots were smeared on millimeter paper for scanning using a Canon EOS M_3 type camera. Next, the fine root length was divided into five diameter classes with a slight modification of the method [12]. Fine roots of order 5 (2-5 mm diameter), order 4 (diameter 1-2 mm), order 3 (diameter 0.5-1 mm, order 2 (0.25-0.5 mm diameter) and order 1 (diameter < 0.25 mm).

2.4. *Statistic analysis*

All delicate root length data was transformed into a square root transformation (SQRT +0.5)0.5, while the soil data was adapted from the Box-Cox family [13] to meet normally distributed. Applied analysis of variance from the factorial randomized block design formula was root analysis. Compared the mean with Tukey's test with a confidence level of $P < 0.05$. Person correlation test for analysis of the relationship between observed variables.

3. Result

3.1. *Stony soil bulk density*

The results of the analysis of soil density at a depth of 0-20 were significantly lower than those at a depth of 20-40 cm. The increase in BD with increasing depth is accompanied by an increase in a rock mass (Table 1).

Table 1. Soil physical properties in the three cocoa production systems: cocoa monoculture (Mono), young cocoa agroforestry (YCAF), and old cocoa agroforestry (OCAF) systems.

Systems	Depth	Rock volume	Rock mass	Bulk density
Mono	0-20	0.34	0.50	1.73
	20-40	0.54	0.68	1.85
YCAF	0-20	0.30	0.41	1.72
	20-40	0.54	0.67	1.89
OCAF	0-20	0.26	0.39	1.68
	20-40	0.48	0.69	1.78
Average	0-20	0.30 b	0.43 b	1.71 b
	20-40	0.52 a	0.68 a	1.84 a
Analysis of variance				
Systems	0-20	0.54ns	0.780ns	0.52ns
Depth	20-40	0.001*	0.002*	0.03*

a,b: Different letters along rows indicate significant differences ($p < 0.05$ according to Tukey's test)

The highest ratio of fine root cacao was found in the diameter class of order 1 with a percentage of 42-52%, while the lowest balance was found in the diameter class of orders 5 and 4 (Fig. 1-a, 1-b, and 1). The highest root ratio acceptable for order 3 langsat trees was 39% in the YCAF system, and the diameter class order 2 was 46% in the OCAF system. The lowest diameter class ratios were recorded in order of 1 of the agroforestry systems (Fig. 1-d and 1-e).

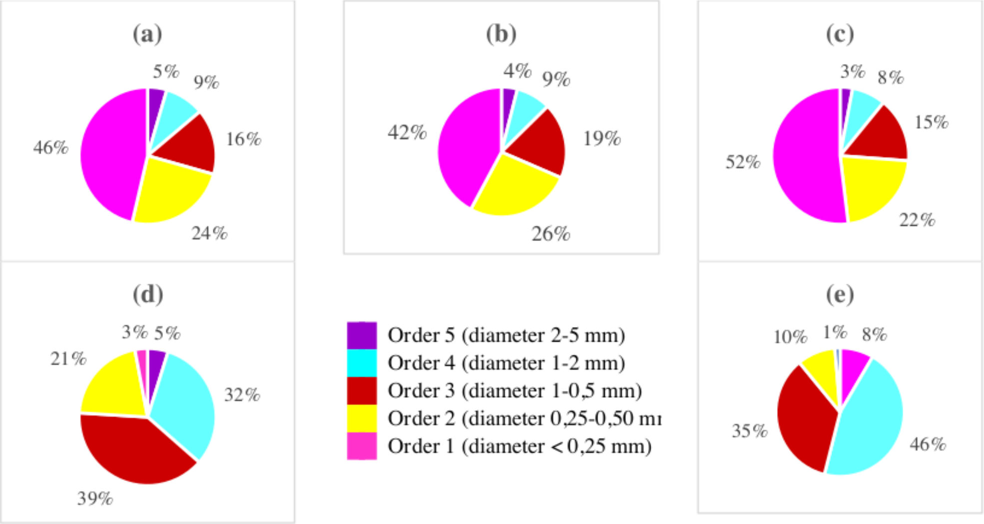

Figure 1. The ratio of diameter class fine root in cocoa and langsat tree; (a) fine root cocoa from a Mono system; (b) YCAF system; (c) OCAF system; (d) fine root langsat tree from the YCAF system; (e) OCAF system.

Land-use systems have different impacts on variations in fine roots based on diameter. The monoculture system gave the highest fine root length in five classes of fine root orders, significantly different from the fine root length recorded in the two cocoa agroforestry systems. Differences in the age of cocoa trees in agroforestry systems did not cause differences in the length of the fine roots of cocoa in all classes of orders (Figure 2-a). Noted no significant differences in the fine root length of langsat trees recorded from below the cacao canopy across all diameter classes (Figure 2-b).

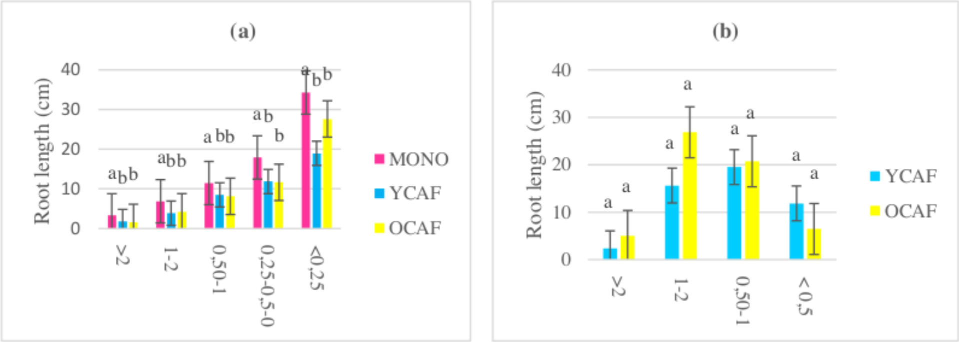

Figure 2. Average fine root length on diameter based, (a) five class fine root orders of cocoa trees based on diameter, (b) Four class of fine root orders langsat tree based on diameter in two agroforestry systems. Including: diameter >2 mm, 1-2 mm, 0.5 - 1 mm, 0.25 - 0.50 mm and < 0.25 mm.

An increase in depth accompanied by increased soil mass density led to a significant decrease in fine root length in all classes based on diameter (Fig. 3). The highest average fine root length recorded at a 0-10 cm depth differed significantly from that recorded below. Root length shortened with increasing depth (Fig. 3-a). The same thing happened to the smooth roots of the langsat tree. The highest root length was found in the topsoil, and decreased significantly with increasing soil depth (Fig. 3-b).

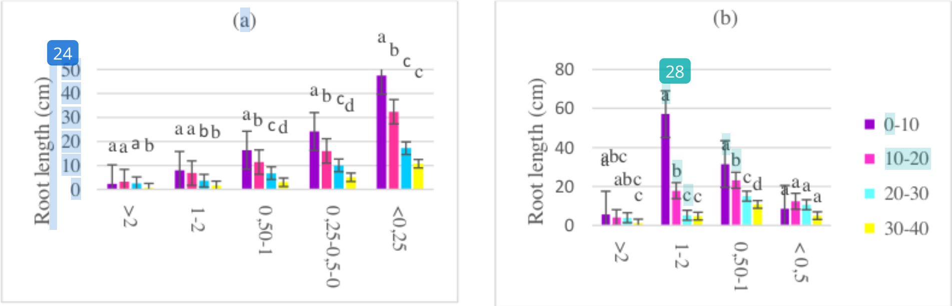

Figure 3. Average fine root length (a) five orders of fine root cacao trees based on diameter; (b) four fine root orders of langsat trees based on diameter, including diameters >2 mm, 1-2 mm, 0.50-1 mm, 0.25-0.50 mm and <0.25 mm, at four depths. different, among others: 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm.

The presence of rock mass causes an increase in soil bulk density, where both are negatively correlated with soil moisture (Table 2). Furthermore, an increase in the rock mass, soil density, and decrease in water content caused a reduction in root length in various classes of fine root diameter in cocoa trees which was indicated by a negative correlation (Table 2). In contrast to langsat fine root, the result showed bulk density and soil moisture did not significantly correlate with the all fine root class order langsat tree (Table 2).

Table 2. Pearson's correlation between physical soil properties (rock volume, rock mass, Bulk density, soil moisturized with all fine root order

Root length order	Rock Mass	BD_t	Moisture
Cocoa root order 5 D 2-5 mm	ns	ns	(+)
Cocoa root order 4 D 1-2 mm	ns	ns	(+)
Cocoa root order 3 D 05-1 mm	(-)	(-)	(+)
Cocoa root order 2 D 0,25-0,50 mm	(-)	(-)	(+)
Cocoa root order 1 D < 0,25_mm	(-)	(-)	(+)
Langsat root order 5 D 2-5 mm	(-)	ns	ns
Langsat root order 4 D 1-2 mm	(-)	ns	ns
Langsat root order 3 D 05-1 mm	(-)	ns	ns
Langsat root order 2 D 0,25-0,50 mm	ns	ns	ns
Langsat root order 1 D < 0,25_mm	(-)	ns	ns
Rm		(+)	(-)
BD_t	(+)		(-)
Kelembaban tanah	(-)	(-)	

ns: non significant (-). Negatively correlation
(+) Positively correlation

Correlation analysis showed that fine root length from high to low order responded significantly to physical soil conditions (Fig. 4). A positive and significant correlation between root length and soil moisture occurred in all classes of fine root diameter of cocoa (Fig. 4-a, 4-b, 4-c, 4-d), indicating that root elongation was highly dependent on moisture or soil water supply. Meanwhile, soil mass density was negatively correlated with fine roots in the 1st and 2nd order fine root diameter classes (Fig. 4-g, 4-h)

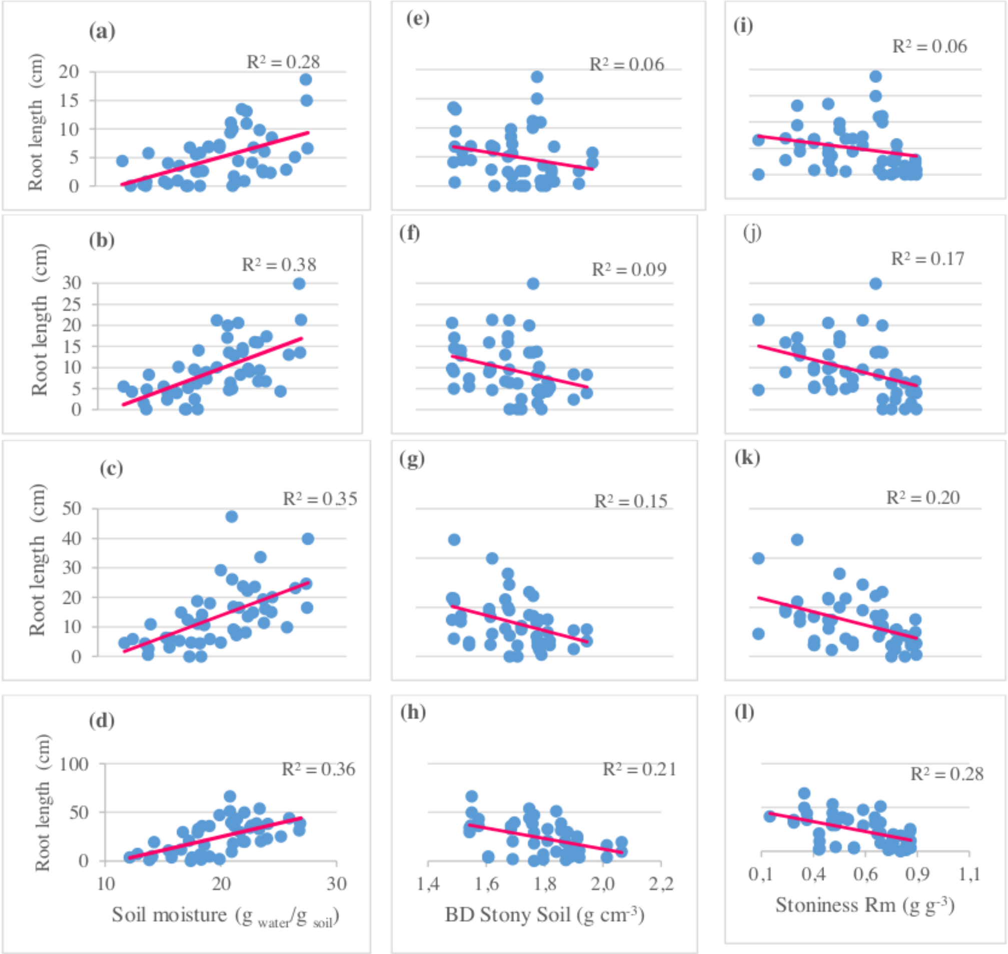

Figure 4. The mean of six cores (n = 6) taken from 4 different plots and three land use systems. Fine root lengths that have been separated based on diameter were collected at a depth of 0–10 cm, 10–20 cm, 20-30 cm, and 30–40 cm; (a), (b), (c) dan (d) are correlation soil moisture with fine root length order 4, order 3, order 2 dan order 1 for root diameter 1-2 mm, 0,5-1 mm, 0,25-0,50 mm and <0,25 mm, respectively ; (e), (f), (g), and (h) are correlation bulk density with fine root length order 4, order 3, order 2 dan order 1 for root diameter 1-2 mm, 0,5-1 mm, 0,25-0,50 mm and <0,25 mm, respectively ; (i), (j), (k), and (l) are correlation rock mass with fine root length order 4, order 3, order 2 dan orde r1 for root diameter 1-2 mm, 0,5-1 mm, 0,25-0,50 mm and <0,25 mm, respectively. Solid lines represent linear correlations with 95% confidence intervals (red lines).

Fine root lengths of order 1, 2, and 3 diameter classes were negatively correlated with rock mass (Fig. 4i, 4j, 4k, 4l. Fine root growth was higher at low specific gravity and less rock content. This occurred presumably because the fine roots are not strong enough to penetrate the high soil density in the subsoil between a depth of 20-40 cm, so that the density of the soil becomes a barrier to root development and limits the access of cocoa roots to mine resources in the lower soil layers.

4. Discussions

Rock mass increased soil mass density and decreased soil moisture level, which negatively affected the development of fine root length from the lowest diameter class to the high diameter class. At our study site, the soil mass density was in the range of 1.5 to 2.3 g cm-3 as measured in the upper layer to a depth of 40 cm, the mass density increased in parallel with increasing depth. Conditions like this are very unfavorable for the development of cocoa roots, fine roots only thrive in the topsoil layer. Significantly few fine roots can propagate to the lower layers of the soil, and develop more in the upper layers. Roots probably avoid high soil mass densities, avoiding obstacles by curving when encountering a hard surface [14].

Several researchers reported that the decrease in root density in the deeper layers resulted from increased soil bulk density [4]. The same thing was noted by Kormanek et al., [5], who studied the effect of soil density on the growth of oak (Quercus petraea Liebl) seedlings. The fact that fine roots cannot mechanically penetrate the hard soil surface limits the volume of soil explored. We also noted that soil moisture was negatively correlated with bulk density, while fine root elongation positively correlated with increased soil moisture. Increased root development caused by soil moisture has been reported by other researchers [4].

A higher ratio of fine roots in the lower order diameter classes (orders 1 and 2) on cacao trees indicated that cocoa plants maximized water and nutrient absorption, [15] indicating that root activity changed with changes in fine root diameter. Roots with a diameter of 0.5 mm are the root that functions as an absorbent role to absorb water and nutrients from the soil. Low-order fine roots are formed due to the branching of higher-order roots, which may be triggered by stiff soil resistance and little water.

5. Conclusion

Our results show that soil density increases with increasing depth correlated with rock mass. The increase in rock mass in rocky soil impacts increasing bulk density and decreasing soil moisture. The interaction of these three factors inhibits root penetration into the lower soil layers. The root morphology that develops is more than the low diameter fine roots that grow in the soil layer near the surface. Due to the limited volume of accessible soil, it encourages the plant to allocate more energy to develop fine roots smaller than 0.5 mm in diameter, which serve as absorbent roots.

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