

Analysis of Soil Penetration Resistance in Coffee Plantation Agroecosystems in Bangelan, Malang, East Java

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ABSTRACT

Agriculture land shows soil compaction problems due to long-term agricultural cultivation activities. Soil compaction indicator can be seen from the value of soil penetration resistance at different soil depths (0 - 60 cm). This research aimed to determine soil penetration resistance at different coffee plantation ages with different soil depths and to analyze the relationship between soil penetration resistance with soil physical characteristics and coffee productivity. The survey activities include observation of minipits, measuring soil penetration resistance at soil depths of 0-20 cm, 20-40 cm, and 40-60 cm using a hand penetrometer, and soil sampling. The results showed that the soil penetration resistance at each LU and soil depth suggested variation were categorized into moderate and high soil penetration resistance classes (1.34 MPa - 3.35 MPa). Soil characteristics, such as soil aggregate stability, water content, bulk density, porosity, silt content, and clay content, significantly correlate with soil penetration resistance. However, soil penetration resistance has a negative correlation with coffee productivity. The value of soil penetration resistance (at a depth of 0-60 cm) has a significant negative correlation with the average productivity of coffee plantations ($r=-0.5936^{**}$). Therefore, increased soil penetration resistance decreased root growth, decreasing plant productivity.

Keywords: Coffee plantation, Penetration resistance, Soil depth

ABSTRAK

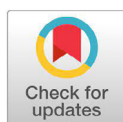
Lahan pertanian menunjukkan masalah pemadatan tanah karena kegiatan budidaya pertanian jangka panjang. Indikator pemadatan tanah dapat dilihat dari nilai ketahanan penetrasi tanah pada kedalaman tanah yang berbeda (0 - 60 cm). Penelitian bertujuan untuk mengetahui ketahanan penetrasi tanah pada berbagai umur tanaman kopi dengan kedalaman tanah yang berbeda dan untuk menganalisis hubungan ketahanan penetrasi tanah dengan karakteristik fisik tanah, serta produktivitas kopi. Kegiatan survey meliputi observasi minipit, pengukuran ketahanan penetrasi tanah pada kedalaman 0-20 cm, 20 - 40 cm, dan 40 - 60 cm dengan menggunakan hand penetrometer; dan pengambilan sampel tanah. Hasil penelitian menunjukkan bahwa ketahanan penetrasi tanah pada setiap LU dan kedalaman tanah menunjukkan adanya variasi, dan dikategorikan ke dalam kelas ketahanan penetrasi tanah sedang dan tinggi (1,34 MPa - 3,35 MPa). Karakteristik tanah seperti kestabilan agregat tanah, kadar air, berat isi tanah, porositas tanah, kadar lanau, dan kadar lempung menunjukkan korelasi yang signifikan dengan ketahanan penetrasi tanah. Namun ketahanan penetrasi tanah menunjukkan korelasi negatif dengan produktivitas kopi. Nilai ketahanan penetrasi tanah (pada kedalaman 0-60 cm) memiliki korelasi negatif yang signifikan dengan rata-rata produktivitas tanaman kopi ($r=-0,5936^{**}$). Oleh karena itu, peningkatan ketahanan penetrasi tanah dapat menyebabkan penurunan pertumbuhan akar, sehingga produktivitas tanaman juga menurun.

Kata kunci: Tanaman Kopi, Ketahanan Penetrasi, Kedalaman tanah

INTRODUCTION

Indonesian coffee production dominates the global coffee market, in addition to Vietnam, Brazil, and Colombia (Atmadji et al., 2019). Coffee plantations are dominated by robusta coffee, which reaches 90% of total coffee plantations (Rahardjo, 2017). National coffee production in 2016-2018 gradually decreased, and the National productivity

in 2018 was 775 kg/ha. Provinces with the highest coffee productivity in Indonesia are North Sumatra (1,081 kg/ha), Riau (949 kg/ha), Jambi and South Sumatra (878 kg/ha), and East Java (809 kg/ha) (BPS, 2020). Although coffee productivity in East Java Province is above the national average, it is still lower than coffee productivity in North Sumatra,



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Riau, Jambi, and South Sumatra. Judging from its geographical conditions, East Java Province has the possibility to increase coffee production. Thus, plantations in East Java Province are expected to meet the increasing demand for coffee, which in 2017 increased by 43% compared to 2010, which was 36.5%.

In order to increase coffee productivity, one of the obstacles faced by coffee farmers is soil quality in the root zone of coffee plants, especially soil penetration ([Nzeyimana et al., 2013](#)), in which a more suitable level of soil penetration is important for the growth and development of coffee plant roots ([Silva et al., 2019](#)). The roots of coffee plants are divided into horizontal and vertical roots, and the growth is influenced by plant factors, growing environment, and soil characteristics. The development of roots that spread into the soil layer vertically and horizontally impacts increasing soil macroporosity. The destruction of soil aggregates that enters the soil layer along with the flow of water causes blockage of soil pores so that soil penetration resistance increases and macroporosity decreases.

Soil penetration is an important indicator in soil management systems ([Girardello et al., 2014](#)) and soil quality in agricultural evaluation that can directly affect root growth and production ([Bengough et al., 2011](#)). Soil penetration is influenced by soil texture, bulk density, and porosity. The negative impact of increased soil penetration is related to decreased aeration, availability of water and nutrients, reduced root growth ([Beutler et al., 2004](#)), soil ability to hold water, and water movement in the soil. In addition, soil depth and soil moisture can also affect the growth of coffee roots ([Kufa & Burkhardt, 2013](#); [Silva et al., 2016](#)).

Coffee plants are suitable for planting in soils that are not compact with loam and clay loam textures ([Yadessa et al., 2008](#); [Tarigan et al., 2015](#); [Nzeyimana et al., 2017](#)). However, the existence

of coffee plantation management activities and the maintenance of coffee plants, especially in the surface layer, has decreased soil quality, such as compaction. The management of coffee plantations and the maintenance of coffee plants include machinery and human foot stamping in the long term ([Alakukku et al., 2003](#); [Miranda, et al., 2003](#); [Araujo-Junior et al., 2008](#); [Tracy et al., 2011](#); [Martins et al., 2012](#); [Hundera et al., 2013](#); [Utomo et al., 2015](#); [Sitania et al., 2018](#)). Soil compaction affects the growth and production of the coffee plant because it is difficult for plant roots to penetrate the soil to meet water and nutrient requirements ([Chancellor, 1971](#); [Allmaras et al., 1988](#)). In addition, plant roots will be stunted because they face a fairly high resistance to soil penetration ([Shierlaw & Alston, 1984](#); [Taylor & Brar, 1991](#); [Unger & Kaspar, 1994](#); [Kirby & Bengough, 2002](#); [Clark et al., 2003](#); [Masaka & Khumbula, 2007](#); [Place et al., 2008](#); [Masulili et al., 2014](#)).

Soil compaction indicators can be seen from its penetration resistance and soil physical characteristics ([Carter, 1990](#); [Assouline et al., 1997](#); [Richard et al., 2001](#)). This soil penetration resistance reflects the ease or difficulty of soil penetration by plant roots. High soil penetration resistance can inhibit root penetration through the soil mass ([Bengough & Mullins, 1990](#); [Chen & Weil, 2010](#); [Andrade et al., 2018](#)). Barriers to root penetration can cause a decrease in plant growth and production ([Ishaq et al., 2001](#); [Lipiec & Hatano, 2003](#); [DaMatta et al., 2007](#); [Siqueira et al., 2013](#)). Soil compaction in coffee cultivation lands inhibits coffee plant growth due to the difficulty of infiltrating water into the soil and hindering the growth of plant roots, and it can reduce coffee productivity ([Fernandes et al., 2012](#)).

The age of the coffee plant is thought to affect the plant roots penetration level. Coffee and tamarind (shade plants) contribute a lot of litter

along with increasing plant age and plant biomass, which increases the activity of soil microorganisms, thereby increasing soil organic carbon content, nutrients, soil moisture, and other physical properties (Araujo et al., 2008; Hansel et al., 2008). Braun et al., (2009) showed that the greater the added organic matter, the greater the infiltration, water retention, aeration, temperature, and soil penetration (Oliveira et al., 2009).

The need for information on the importance of root penetration distribution for better management of coffee plantation agroecosystems requires research on this matter. Therefore, this study was conducted to analyze the soil penetration resistance of the root zone at several ages of coffee plantations and determine the distribution of soil penetration resistance and its relationship with soil physical characteristics and coffee plantation productivity.

MATERIALS AND METHODS

Place and sample selection

This research was carried out from November 2019 to February 2020. Rainfall during the research reached 9215 mm in January 2020. Besides, the soil water content in the five Land Units Map was 21-41%. The research location was in the Robusta coffee plantation owned by PTPN XII, Bangelan, Wonosari, Malang. PTPN XII Bangelan has located at 8°05'38.3" South Latitude and 8°05'38.3" East Longitude. Soil types in Bangelan are classified as Alfisols and Inceptisols, but the soil type in the study area is Inceptisols. The height of the plantation from sea level ranges from 450 - 680 m asl. Topographic points of flat land are classified based on the slope of 0 - 8% covering an area of 707.20 ha (80%), 8 - 15% covering an area of 93.05 ha (11%), and 15 - 40% covering an area of 82.95 ha (9%). The soil's physical characteristics were analyzed at the Soil Physics Laboratory, Faculty of Agriculture, Universitas Brawijaya.

Data collection

This research applied a survey method, which was divided into three stages: pre-survey, survey, and post-survey. The pre-survey activity is in the form of determining observation points using a purposive sampling method with criteria of land being planted by robusta coffee plants and based on LU maps (Land Units Map), which were made using ArcGIS 10.2.2 software. In this study, there were 5 LU with three replications based on the age of the plant. There are 15 points of soil sampling and measurement of soil penetration resistance. Survey activities include making minipits and measuring soil penetration resistance in coffee plantations aged 7 to 78 years at a depth of 0-20 cm, 20-40 cm, and 40-60 cm (from the soil surface to the optimal limit of coffee root growth). The plant age class interval was divided into five classes with an interval of 16 years. At LU 1, LU 2, LU 3, LU 4, and LU 5, the ages of the coffee plant were 78 years, 56 years, 45 years, 30 years, and 7 years. The measurement of soil penetration resistance using a hand penetrometer.

As supporting data, sampling of whole/ring or composite soil samples is required. The soil physical characteristics observed include soil structure (aggregate stability), bulk density, particle density, actual water content, total soil pores, particle density, and soil texture, which were analyzed using the wet sieve method, cylinder method, pycnometer method, gravimetric method, the calculation of density, and pipette method, respectively. The average productivity of coffee plants was obtained from secondary data from PTPN XII Bangelan.

Post-survey activities include processing data from soil sample analysis in the laboratory, including statistical and spatial data analysis. Classification of soil penetration resistance is presented in Table 1.

Table 1. Soil Penetration Resistance Classes

Class	Penetration Resistance (MPa)
Extremely low	< 0.01
Very low	0.01 – 0.1
Low	0.1 – 1.0
Moderate	1.0 – 2.0
High	2.0 – 4.0
Very high	4.0 – 8.0
Extremely low	> 8.0

Source: [USDA \(1993\)](#)

Data Analysis

The data was analyzed using Microsoft Excel and Genstat Twelfth Edition software. Statistical data analysis performed includes t-test, correlation test, and regression test. The t-test of two unpaired samples was used to analyze the difference in soil penetration resistance between LU at each depth.

RESULTS AND DISCUSSION

Soil Penetration Resistance

Soil penetration resistance in the field was measured at 0-20 cm, 20-40 cm, and 40-60 cm at each LU (Land Unit: coffee plant age). This measurement produced different soil penetration resistance values. LU 1, with an average plant age of 78 years, had the highest penetration resistance

value of 2.71 MPa and the lowest value of 2.24 MPa. Overall, the value of soil penetration resistance in LU1 is classified in the high class, which decreases with soil depth. Table 2 showed several physical characteristics of the soil, such as decreasing soil density, soil porosity, and increasing clay fraction content at each LU 1. According to [Silalahi & Nelvia \(2017\)](#), the factors that affect soil penetration resistance are soil density and total pore space (soil porosity). In addition, soil texture (sand, silt, clay fraction content) also affects soil penetration resistance ([Landsberg et al., 2003](#)).

The high value of soil penetration resistance (>2.0 MPa) indicates inhibition of plant root growth, especially in the top layer of soil (0-20 cm). The results are in accordance with [Silva et al., \(2000\)](#); [Bergamin et al., \(2010\)](#); [Martins et al., \(2012\)](#); [Palma et al., \(2013\)](#); and [Andrade et al., \(2018\)](#), reporting that the critical range of soil penetration resistance for plant root growth is 2-3 MPa, soil penetration resistance that does not inhibit plant root growth is <2 MPa, and soil penetration resistance that cannot be penetrated by roots of annual plants and roots of annual plants is >3 MPa.

Table 2. Soil physical properties at each LU

LU	Coffee plant age	Soil Depth (cm)	AS (mm)	BD (g.cm ⁻³)	PD (g.cm ⁻³)	Por. (%)	WC (g.g ⁻¹)	Sand (%)	Silt (%)	Clay (%)	Texture
1	78 years	0-20	5.02	1.32	2.16	38.83	0.32	13.52	43.93	42.55	SC
		20-40	4.62	1.21	2.21	45.32	0.38	12.55	47.68	39.76	SCL
		40-60	4.76	1.11	2.07	46.30	0.35	16.13	44.49	39.38	SCL
2	56 years	0-20	5.14	1.26	2.07	39.14	0.30	17.47	43.59	38.93	SCL
		20-40	4.78	1.23	2.20	44.24	0.33	16.49	45.73	37.77	SCL
		40-60	4.25	1.25	2.17	42.14	0.27	15.05	49.35	35.60	SCL
3	45 years	0-20	4.81	1.13	2.00	42.89	0.40	14.94	45.81	39.25	SCL
		20-40	4.86	1.20	2.00	39.74	0.41	14.38	42.77	42.85	SC
		40-60	4.51	1.16	1.90	39.27	0.37	14.02	42.95	43.04	SC
4	30 years	0-20	5.11	1.43	2.09	31.21	0.33	17.72	45.73	36.55	SCL
		20-40	4.79	1.33	1.99	32.98	0.31	17.26	43.41	39.33	SCL
		40-60	5.06	1.31	2.11	37.57	0.28	15.15	44.00	40.85	SC
5	7 years	0-20	5.02	1.37	2.04	32.73	0.22	11.19	38.66	50.15	C
		20-40	4.99	1.14	2.00	42.73	0.21	18.37	42.80	38.83	SCL
		40-60	4.80	1.25	2.01	37.78	0.24	20.92	46.22	32.86	CL

Remarks: AS: Aggregate Stability; BD: Bulk density; PD: Particle density; Por. : Porosity; WC: Water Content; C: Clay; SC: Silty Clay; SCL: Silty Clay Loam; CL: Clay Loam

Soil penetration resistance at LU2 with an average plant age of 56 years is classified in moderate to high class. The highest penetration resistance value was 2.25 MPa, and the lowest was 1.42 MPa. The decrease in soil penetration resistance occurred at a depth of 20-40 cm compared to at a depth of 0-20 cm. This is caused by several physical characteristics of the soil in the form of soil density, porosity, and water content (Table 2). The soil at a depth of 20-40 cm illustrates the soil condition with more pore space so that the penetrometer more easily penetrates it. This is in accordance with [Silalahi & Nelvia \(2017\)](#), mentioning that the density and total soil pore space can affect the value of soil penetration resistance. In addition, soil water content also affects soil penetration resistance. According to [Azzuhra et al., \(2019\)](#), when the soil is dry or the soil moisture content is low, it is more difficult for plant roots to penetrate the soil because the bond (cohesion force) between soil particles is very strong.

LU3 is land with an average coffee plant age of 45 years. The highest soil penetration resistance value was 2.18 MPa, and the lowest was 1.34 MPa, categorized into the Moderate to High penetration resistance class. At LU 3, the value of soil penetration resistance at a depth of 20-40 cm was higher than at other depths. This condition can occur allegedly due to aggregate stability and soil density (Table 2). According to [Landsberg et al., \(2003\)](#), the penetration resistance is influenced by the density of the soil and the stability of the soil structure (aggregate).

The average age of coffee plants in LU 4 is 30 years, and the value of soil penetration resistance is classified in the high class. The highest soil penetration resistance value was 2.48 MPa, and the lowest was 2.08 MPa. Soil penetration resistance was lower at a depth of 20-60 cm compared to that at a depth of 0-20 cm. The difference in the

value of soil penetration resistance is caused by the decreased soil density (Table 2). This soil condition is in accordance with the results of research by [Silalahi & Nelvia \(2017\)](#), stating that the factor that affects soil penetration resistance is density. The higher value of soil density in the 0-20 cm layer indicates the effect of soil compaction due to coffee plantation management activities that take place on the soil surface.

In LU5, with the youngest plant age, which is about 7 years, the soil penetration resistance value is classified in the high class, which is thought to be due to the influence of the aggregate stability value and soil texture in the form of sand, dust, and clay (Table 2). The highest soil penetration resistance value at LU5 was 3.35 MPa, and the lowest was 2.43 MPa. The high value of soil penetration resistance at a depth of 0-20 cm is thought to be due to the high clay fraction content (50.15%) and high aggregate stability. In addition, the effect of soil compaction also occurs due to the influence of coffee plantation management activities ([Sitania et al., 2018](#)).

The results of the T-test of two unpaired samples showed a significant difference in soil penetration resistance between LU2 and LU5 at a depth of 20-40 cm and 40-60 cm, and between LU3 and LU5 at a depth of 0-20 cm (Table 3). This difference is thought to have something to do with the age of the coffee plantation. Routine plantation management activities carried out every year can cause compaction of the topsoil (0-20 cm). In addition, older plants (coffee and shade trees) have more root systems, which directly and indirectly affect the physical characteristics of the soil (soil aggregation, soil porosity).

Soil penetration resistance obtained from each LU and depth in the field also did not always increase but also decreased with increasing soil depth. According to [Oduma et al., \(2017\)](#), the increase

Table 3. T-Test of two unpaired samples

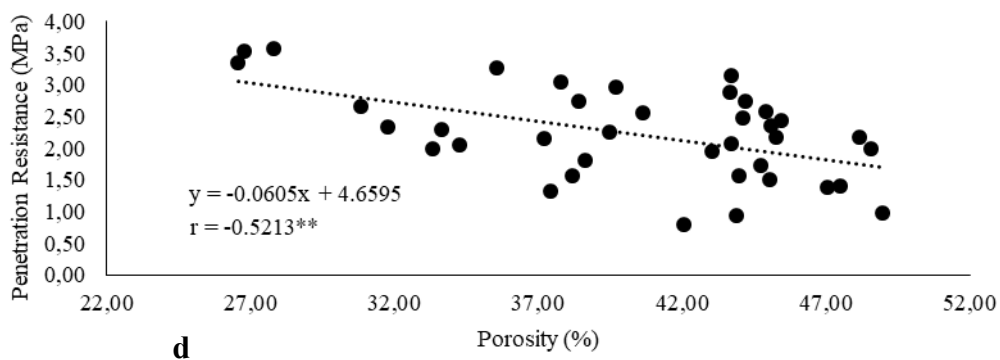
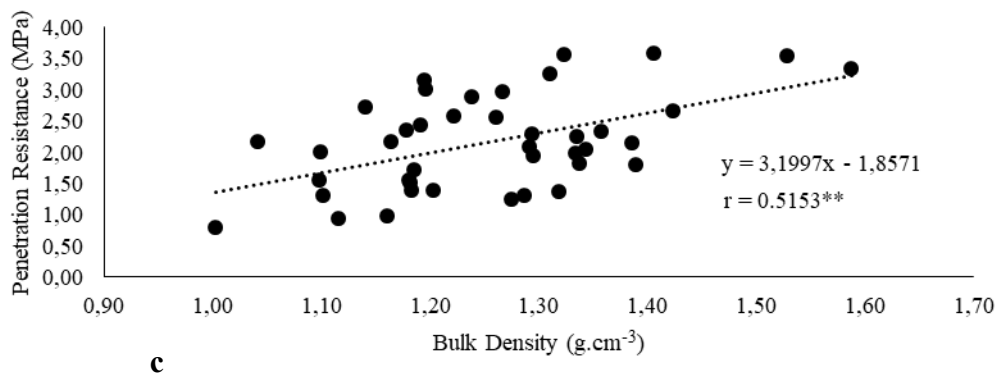
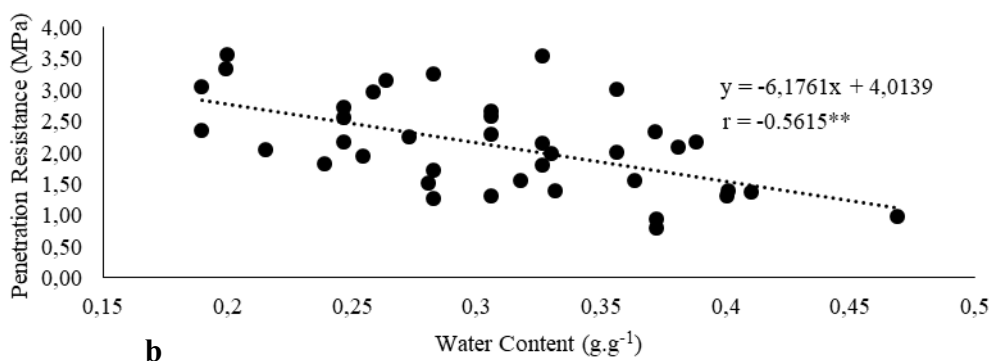
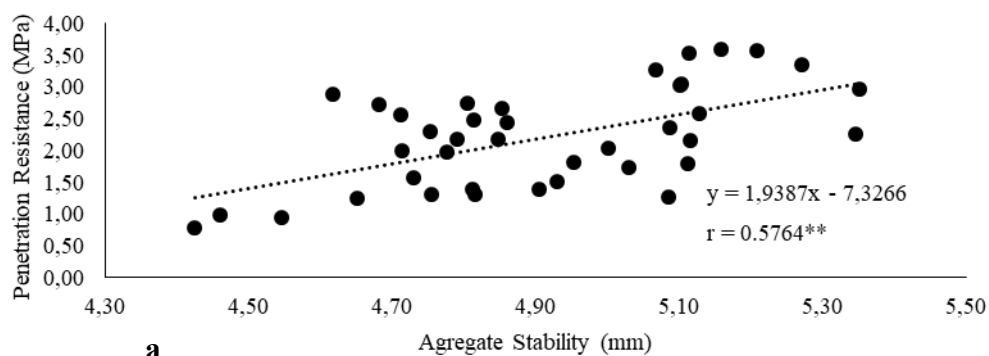
LU	Soil Depth (cm)	T Stat	T-table	T-test result
1 : 2	0-20	0.7384		NS
	20-40	2.3665	2.7764	NS
	40-60	1.5184		NS
1 : 3	0-20	1.6396		
	20-40	0.2653	2.7764	NS
	40-60	1.3856		NS
1 : 4	0-20	0.3195		
	20-40	0.4651	2.7764	NS
	40-60	0.2254		NS
1 : 5	0-20	-1.3115		
	20-40	-0.5341	2.7764	NS
	40-60	-0.4060		NS
2 : 3	0-20	0.9628		
	20-40	-1.5666	2.7764	NS
	40-60	0.3364		NS
2 : 4	0-20	-0.3457		
	20-40	-1.3970	2.7764	NS
	40-60	-0.8629		NS
2 : 5	0-20	-2.6005		
	20-40	-3.0215	2.7764	S
	40-60	-3.0738		S
3 : 4	0-20	-1.1692		
	20-40	0.1658	2.7764	NS
	40-60	-0.9406		NS
3 : 5	0-20	-4.0952		
	20-40	-0.6921	2.7764	NS
	40-60	-2.0435		NS
4 : 5	0-20	-1.5840		
	20-40	-0.9045	2.7764	NS
	40-60	-0.5597		NS

Remarks: NS: No Significant; S: Significant

and decrease in the value of soil penetration resistance can occur due to soil and plant management activities, such as land sanitation, plant care, such as pruning, fertilization, weed control, pest and disease control and harvesting of produce, which are carried out annually. Meanwhile, according to [Landsberg et al., \(2003\)](#), several soil characteristics that affect penetration resistance are bulk density, soil structure, soil texture (content of sand, silt, clay fraction), and soil organic matter content.

The Relationship between Soil Penetration Resistance and Soil Physical Characteristics

The correlation between penetration resistance and aggregate stability shows a value of $r=0.5764^{**}$ (Figure 1a), which means an increase in soil aggregate stability results in an increase in soil penetration resistance. In soils with a high clay fraction, the stability of the aggregate is related to the adhesive function of clay particles in the soil aggregation process ([Brady & Weil, 2009](#)). Increasing the stability of the aggregate means the



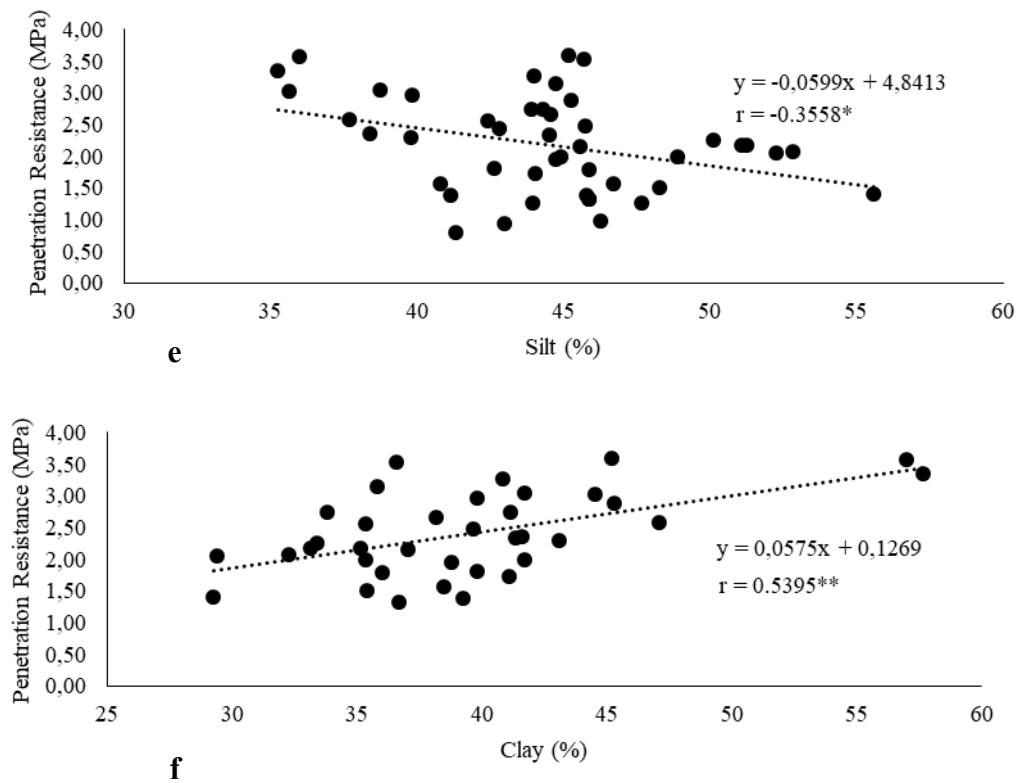


Figure 1. The relationship between soil penetration resistance with soil physical characteristics:
a. Aggregate stability, b. Water content, c. Bulk density, d. Porosity, e. Silt, f. clay

greater the bond strength between soil particles so that the soil is more difficult to penetrate by roots or by penetrometers. According to [Haridjaja et al., \(2010\)](#), the value of soil penetration resistance increases when soil compaction occurs. Meanwhile, the results of the study by [Catania et al., \(2018\)](#) showed that tillage to overcome soil compaction was related to soil penetration resistance and soil aggregate stability.

The results of the correlation test between penetration resistance and water content at depths of 0-20 cm, 20-40 cm, and 40-60 cm showed a negative relationship with the calculated r-value of -0.5615 (Figure 1b). The negative direction in the correlation test results means that any increase in water content will decrease soil penetration resistance. The decrease in soil penetration resistance is thought to be due to an increase in the number of water particles in the soil so that the density decreases, and the distance between soil particles

increases, which causes a decrease in the attractive force between soil particles, causing the soil to become less hard, making it easier for plant roots to penetrate. According to [Azzuhra et al., \(2019\)](#), plant roots will find it difficult to penetrate the soil when the soil water content is low because the soil has a strong particle bond that makes the soil hard, whereas if the soil water content is high, the soil will be slippery, thereby making it easier for roots to penetrate the soil.

The correlation test results between penetration resistance and soil density at a depth of 0-20 cm, 20-40 cm, and 40-60 cm showed a positive relationship with the r-value of 0.5153 (Figure 1c). These results mean that any increase in the soil's density will increase the soil's penetration resistance. [Prasetyo et al., \(2014\)](#) reported a negative relationship between soil density and plant roots with an r value of -0.728, which means that an increase in soil density will cause the total length of plant roots to

decrease because plant roots are difficult to penetrate. [Panayiotopoulos et al., \(1994\)](#) also showed a positive relationship between soil penetration resistance and soil density ($r = 0.64$).

The correlation test between penetration resistance and soil porosity at depths of 0-20 cm, 20-40 cm, and 40-60 cm resulted in an r-value of -0.5213 (Figure 1d), which means that the relationship between penetration resistance and soil porosity has the same direction. The direction of the negative relationship means that any increase in soil porosity will decrease soil penetration resistance. According to [Colombi & Walter \(2016\)](#), macro pores and meso pores will disappear when soil compaction causes a decrease in soil porosity ([Cannell, 1977](#)). Furthermore, the denser the soil, the higher the soil penetration resistance and the more difficult it is for plant roots to penetrate the soil ([Refliaty & Endriani, 2018](#)).

The results of the correlation test between penetration resistance and dust content at depths of 0-20 cm, 20-40 cm, and 40-60 cm showed a negative relationship with the calculated r-value of -0.3558 (Figure 1e). These results mean that any dust content increase will decrease the soil's penetration resistance. According to [Zhang et al., \(2017\)](#), dust positively correlates with macroporosity with an R-value of 0.709. High macroporosity conditions make soil penetration resistance decrease, which causes the soil to be more easily penetrated by plant roots.

The correlation test results between soil penetration resistance and clay fraction content at a depth of 0-20 cm, 20-40 cm, and 40-60 cm resulted in a value of $r=0.5395^{**}$ (Figure 1f). This means that an increase in the content of the clay fraction results in an increase in the penetration resistance of the soil. The results of [Suprayogo et al., \(2004\)](#) showed that an increase in the content of the clay fraction resulted in a decrease in soil macro-porosity caused

by the blockage of soil pores by clay particles of small size and resulted in increased soil penetration resistance. This is in line with the results of research by [Wahyunie et al., \(2012\)](#), reporting that high clay fraction content will reduce soil macroporosity and can have an impact on increasing soil penetration resistance due to blockage of macro soil pores.

Relationship of Plant Productivity with Soil Penetration Resistance

The productivity of the coffee plant is influenced by one of the physical characteristics of the soil, namely soil penetration resistance. The average productivity in LU1, LU2, LU3, LU4, and LU5 was 2535, 1617, 5232, 10433, and 2498 kg/ha, respectively. Thus, it is necessary to do a correlation test to determine the relationship between coffee plant productivity and soil penetration resistance. The correlation test between soil penetration resistance at a depth of 0-20 cm, 20-40 cm, and 40-60 cm with the productivity of coffee plants in 2019 resulted in a value of $r = -0.5936^{**}$ (Figure 2). This means that increasing soil penetration resistance can reduce the productivity of coffee plants. Increased soil penetration resistance can cause decreased root growth, thereby decreasing plant productivity.

The relationship between penetration resistance and productivity is inversely proportional. There is a decrease in plant productivity with an increase in soil penetration resistance ([Colombi & Walter, 2016](#)). Increased soil penetration resistance is related to the effect of soil compaction, resulting in disturbances in plant root growth, thereby decreasing plant productivity ([Carmi et al., 1983](#); [Bartzen et al., 2019](#)).

The difference in the value of soil penetration resistance between LUs is related to three things: the age of the coffee plantation, the technology of coffee plantation management, and the soil characteristics. According to [Mechram et al., \(2013\)](#),

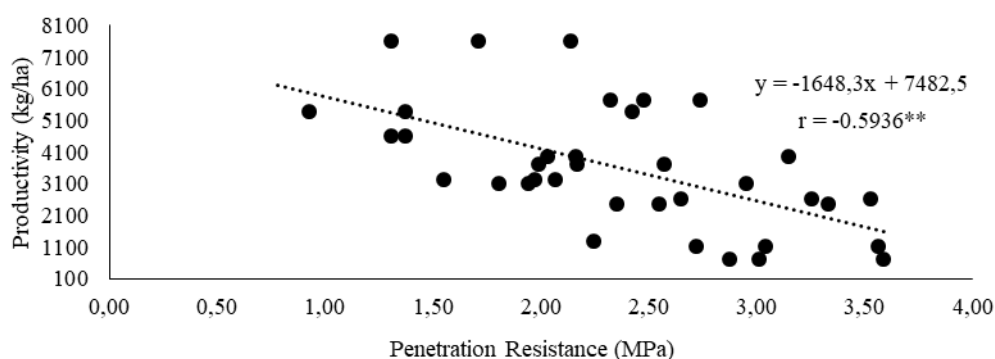


Figure 2. Relationship between coffee productivity in 2019 and penetration resistance

the value of soil penetration resistance increases or decreases with soil depth, presumably due to the soil compaction resulting from coffee plantation management activities. This compaction effect is more pronounced in the topsoil (0-20cm). Soil physical characteristics that can affect the value of soil penetration resistance include aggregate stability, water content, bulk density, porosity, dust fraction content, and clay fraction content (Assouline et al., 1997).

Aggregate stability is closely related to soil penetration resistance value, and every 0.1 mm increase in aggregate stability will increase soil penetration resistance by 0.19 MPa. This is presumably because the Robusta coffee area, Bangelan Plantation, has dominant clay soil, so the attractive force between soil particles (cohesion) becomes strong. The value of soil aggregate stability in Robusta coffee land, Bangelan Plantations, is classified into a very stable class and causes the value of soil penetration resistance to be high because the soil is difficult to destroy. This is supported by Serosero et al., (2016), stating that clay is a particle that can form a bond, so soils containing a lot of clay can form stable aggregates.

Soil water content has a significant negative relationship with soil penetration resistance, and an increase in water content results in a decrease in soil penetration resistance. This has something to do with the stability of the aggregate and the

strength of the attractive forces between soil particles. When the soil water content is low, the soil has strong cohesion between particles and makes the soil dense and hard, whereas if the soil moisture content is high, the cohesion force between soil particles becomes weaker, and the penetration resistance is lower (Azzuhra et al., 2019).

Soil density and penetration resistance have a significant positive correlation, where an increase in soil density results in an increase in soil penetration resistance. This happens because the bulk density of the soil is an illustration of the solid composition and pore space of the soil. According to Panayiotopoulos et al., (1994), soil penetration resistance and soil density have a positive relationship, meaning that when the soil density is high, the soil penetration resistance value will also be high.

Soil porosity has a significant negative correlation with soil penetration resistance. A large number of pore spaces in the soil makes the soil less dense, and the penetration resistance of the soil is lower. This is in accordance with the results of research by Colombi & Walter (2016), reporting that a number of soil pores disappear when soil compaction occurs and soil porosity decreases. Soil compaction like this has an impact on decreasing soil porosity and increasing soil penetration resistance (Kooistra & Trovey, 1994; Carducci et al., 2014).

The content of dust fraction has a negative effect on the value of soil penetration resistance. This is because the dust particles have a larger size than clay so in the process of soil aggregation, it produces meso and macro pores, and the penetration resistance of the soil becomes lower. This is supported by [Serosero et al., \(2016\)](#), stating that dust particle has a size of 0.05 mm to 0.002 mm, but the surface of dust particles is not electrically charged, so it cannot form bonds and does not act as an adhesive in the aggregation process ([Kemper, & Rosenau, 1986](#); [Amezketta, 1999](#); [Bronick & Lal, 2005](#)).

The content of clay fraction has a significant positive relationship with soil penetration resistance. This has something to do with the very small size of clay particles, and clay can act as an adhesive in the soil aggregation process. The more clay particles, the more stable and stronger the soil aggregates, and the pores formed are mostly micro pores, so the penetration resistance of the soil becomes greater. The results of [Suprayogo et al., \(2004\)](#) showed that the increase in clay fraction content was followed by a decrease in soil macropores and an increase in micropores, which resulted in increased soil penetration resistance. Other factors that may affect the value of penetration resistance are soil organic matter content, aeration pores, and soil aggregation ([Day et al., 1995](#); [Carducci et al., 2015](#)).

Penetration resistance and soil compaction have a significant relationship with crop productivity. If the value of soil penetration resistance is high, then plant root growth and development will be disrupted, which can inhibit plant growth and decrease plant productivity ([Gilman et al., 1987](#); [Bengough & Mullins, 1990](#); [Ehlers et al., 1983](#); [Kozłowski, 1999](#); [Masaka & Khumbula, 2007](#)). This is also in accordance with the results of research by [Colombi & Walter \(2016\)](#), reporting that increased

soil penetration resistance causes plant root growth to decrease, thereby reducing plant productivity. The results also showed a decrease in productivity by 27%, along with an increase in soil penetration resistance from T0 (0.32 MPa) to T4 (1.83 MPa).

Soil penetration resistance in the root zone of coffee plants is, directly and indirectly, related to the age of the coffee plantation and its management ([dos Santos et al., 2009](#); [Martins et al., 2012](#); [Refliaty & Endriani, 2018](#)). Information related to the distribution of soil penetration resistance at various ages of coffee plantations is very important to support efforts to manage coffee plantations more sustainably.

CONCLUSION

Soil penetration is an essential soil quality indicator in agricultural evaluation that directly affects root growth and coffee production. The research on soil penetration resistance conducted at various ages of coffee plantations (7-78 years) and soil depth (0-60 cm) showed a reasonably significant variation, but overall, it was classified into the “Moderate” to “High” soil penetration resistance class (1.34 MPa to 3.35 MPa). Differences in plant age cause this difference in soil penetration resistance. Age differences cause additional soil compaction depending on plant growth conditions. Older tree plants have more roots and are more actively growing, which indirectly affects the density of the soil. Soil physical characteristics that have a significant correlation with soil penetration resistance are aggregate stability, water content, bulk density, soil porosity, dust fraction content, and clay fraction content. The value of soil penetration resistance (at a depth of 0-60 cm) has a significant negative correlation with the average productivity of coffee plantations ($r=-0.5936^{**}$). Therefore, increased soil penetration resistance can cause decreased root growth, thereby reducing plant productivity.

Soil penetration resistance has a close relationship with plant productivity and has an effect of 35.24% ($R^2 = 0.3524$) with the equation of $y = -1648.3x + 7482.5$. This equation means that every 1 MPa increase in soil penetration resistance will reduce plant productivity by 1.64 tons/ha. If the value of soil penetration resistance is high, then plant roots will be disturbed in their growth and development, which causes plant productivity to decrease.

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