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The Influence of Soil Bearing Capacity on The Application of Agricultural Machinery in Kulon Progo

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Abstract

A critical factor in the enhancement of agricultural productivity is the utilization of agricultural tools and machinery. The challenges posed by reduced labor, narrow rice fields, and deep surface soil layers create significant difficulties for such equipment. Soil penetration resistance refers to the capacity of soil to resist the loads applied to it. The pressure exerted on the soil by agricultural machinery and tools hinders their effective functioning. The present study has been designed to determine the influence of soil evaporation resistance value on the type of agricultural machinery that can be applied. The measurement of soil carrying capacity value is measured in 3 land categories. The analysis was carried out by comparing the value of soil penetration resistance with the tractor's trafficability index. This research was conducted from February to July 2024, and the measured penetration resistance in the sample land was found to be in the range of 0.55–0.90 at a depth of 10 cm and 0.82–1.14 at a depth of 15 cm. A comparison of the penetration resistance values with the trafficability index, which delineates the operational parameters for agricultural machinery, revealed that four-wheel tractors and combine harvesters would be unable to operate on the sample land. The application of these machines will cause sinkage of more than 15 cm for land categories 1 and 2, and will cause sinkage of more than 20 cm for land category 3.

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1. Introduction

The utilization of agricultural tools and machinery constitutes a significant factor in the achievement of increased agricultural production. The role of agricultural tools and machinery in facing the demands of technological development and the scarcity of human resources in the agricultural sector is of great consequence. Moreover, the deployment of agricultural tools and machinery can serve as a technological input in the agricultural sector, thereby enhancing the productivity, production efficiency, processing, quality control, competitiveness, and added value of agricultural products.

Agricultural tools and machinery in Indonesia have historical precedents; however, they have not improved the efficiency or competitiveness of Indonesian agricultural products. Large-scale implementation is necessary considering the environment and local communities (Sulaiman et al. 2018). The development of agricultural mechanization does not require farmers to possess or operate

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their own tools. This involves investment, human resources, management, and technical support. Implementing mechanization empowers farmers to take on challenging tasks, overcoming labor shortages, high costs, and technical or financial constraints associated with traditional farming practices (Gunawan, 2014). Agricultural mechanization can be implemented in two ways. The first is a regional approach, based on a region's readiness for new technology. The second is a technological approach based on ease of use of technology (Pramudya, 1996).

Advancing agricultural mechanization in Indonesia is challenging due to limited farm roads and restricted movement of agricultural machinery in confined paddy fields. Undulating hills and mountains further complicate this situation. Additionally, the potential impact of agricultural machinery on income complicates the situation. The scarcity of skilled farmers and loose layers (hardpans) in Indonesian paddy fields hinders the adoption of mechanization (Prastowo 2010; Aldillah 2016; Priyanto 1997; Jusran et al. 2019). The advancement of agricultural mechanization in Indonesia necessitates the consideration of a multitude of factors, including technical, infrastructural, institutional, socio-cultural, and geographical parameters. This necessity arises from the dynamic nature of agricultural mechanization in developing regions, which is subject to fluctuations triggered by alterations in parameters and specific conditions (Umar, 2013; Mubekti, 2009; Mulyono, 2020). Using information and communication technology, remote sensing, geographic information systems, and navigation systems align with the spatial variability of physical and mechanical conditions that characterize agricultural land (Fountas et al. 2006; Aubert et al. 2012).

One of the factors that determines the suitability of a land area for agricultural machinery is the measurement of the soil's ability to withstand the weight of machinery and equipment (bearing capacity). The resistance of soil to penetration is an important indicator of soil strength, which can affect plant root growth and crop yield, as well as influence the design and selection of agricultural machinery (Jiang et al. 2020). The hardness of a paddy field depends on a number of factors, including the geographical location of the land, intensity of precipitation, water content of the soil, water level in irrigation canals and/or drainage systems, and other environmental conditions (Tanaka 1984). The tillage system has an impact on the value of soil penetration resistance. Wahyunie et al. (2012) indicated that the implementation of intensive tillage systems has the effect of reducing the capacity of soil to absorb water compared to conventional tillage systems. This is evidenced by a reduction in soil moisture content on land utilizing intensive tillage systems. Furthermore, the soil penetration resistance of land utilizing intensive tillage systems was observed to be higher than that of conventional tillage systems.

The influence of pressure, measurement depth, and soil penetration resistance value can be used as a reference in the analysis of the selection of agricultural machinery that can be applied to a particular land. One of the fundamental aspects to consider when assessing a tractor's traffic capability

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is the value of the trafficability index. This study aimed to determine the effect of soil resistance value on the application of agricultural machinery in paddy fields, a case study in the Kulon Progo Regency.

2. Materials and Methods

2.1 Time, Location and Research Instrument

This research was conducted in the paddy field area of the Kulon Progo Regency. Kulon Progo Regency is located between 7°38'42" – 7°59'3" SL and 110°1'37" – 110°16'26" EL. This study was conducted from February to July 2024. The data collected in this study comprised measurements of penetration resistance and daily rainfall. These measurements were taken at the time of harvest during the first planting season (rainy season). The research design is based on Figure 1 and displays layouts in which data collection is based on Figure 2.

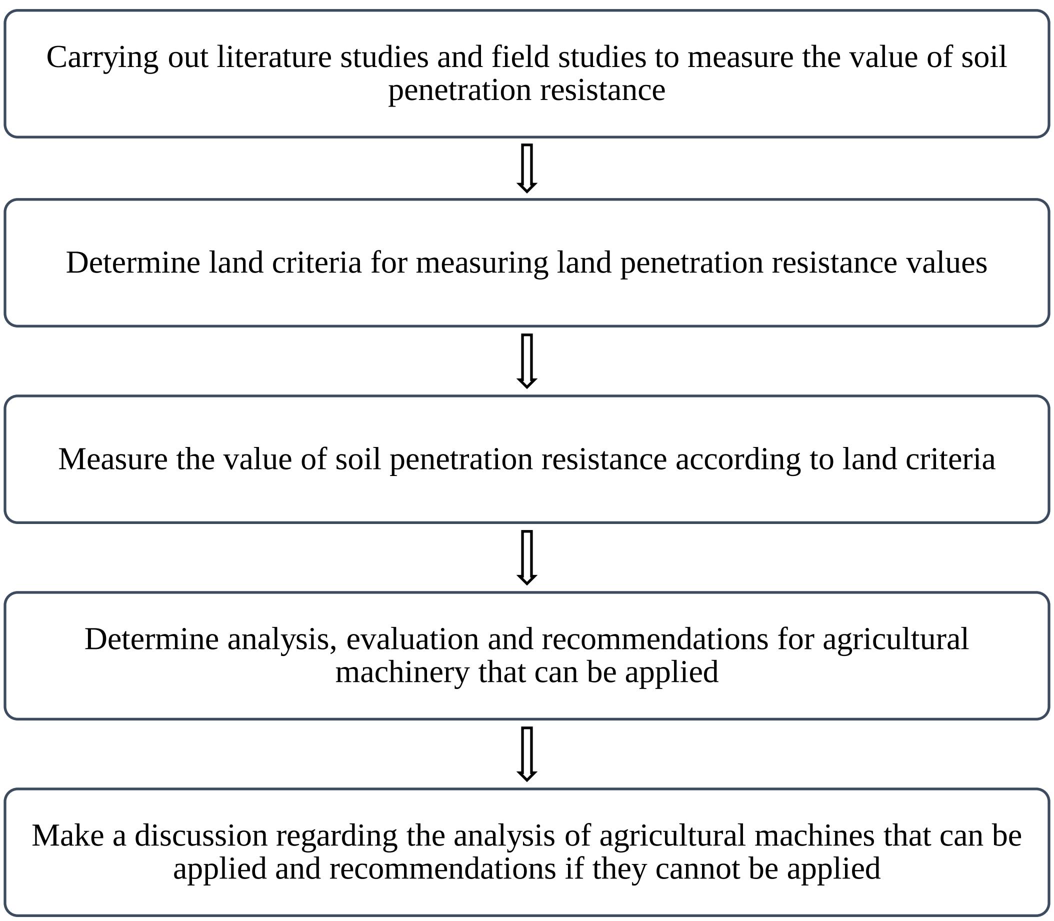

Figure 1. Research design

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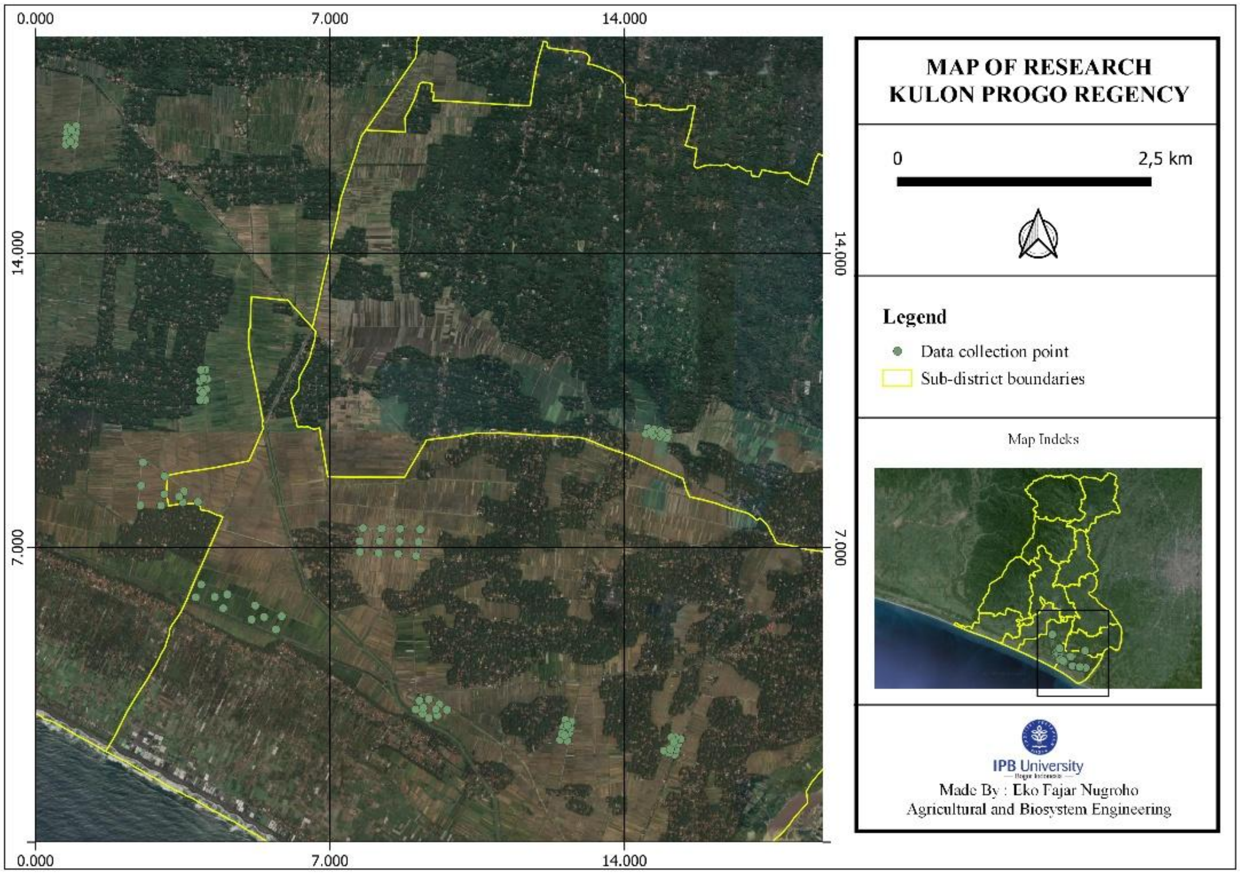

Figure 2. Map of the research location

The tools used in this study included digital penetrometers, stationery, and computer sets equipped with ArcGIS, QGIS, and Microsoft Office (Microsoft Word and Excel).

2.2 Measurement of Soil Penetration Resistance With Plates

The measurement of soil resistance with plate penetration was conducted using a digital penetrometer equipped with a flat plate measuring 2.5 x 10 cm. The penetrometer was attached to a plate at the end and pressed to a depth of 10 cm and 20 cm. The measured loading value was recorded, and the value of soil resistance was calculated using Equation 1 (Mudzakir 2013).

$$T_p = \frac{F_p + m_p}{A_k} \quad (1)$$

Description

T_p : Penetration resistance (kg/cm2)

F_p : Penetration force (kgf)

m_p : Weight of the penetroemeter (kgf)

A_k : Plate cross-sectional area (cm2)

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The measurements were conducted through random sampling, with three land criteria considered. Data collection was performed in triplicate for each land criterion, as shown in Table 1.

Table 1. Land criteria for collecting data on land carrying capacity

Land	Criteria
Land 1	1. Near irrigation network 2. Near natural drainage network
Land 2	1. Has an irrigation network 2. Has a natural drainage network
Land 3	1. Far from the main irrigation network 2. Far or have no natural drainage network

2.3 Rainfall Data

Daily rainfall data were obtained from the Meteorology, Climatology, and Geophysics Agency website at the Yogyakarta Meteorological Station in April and May of 2024. The objective was to determine the effect of rainfall on the penetration resistance value.

2.4 Data Analysis

The influence of the measured penetration values on the applicable agricultural machinery was evaluated using a trafficability index. This trafficability index measures the extent of a soil's capabilities before being applied to agricultural machinery. This index was initially developed by Kokubun (1970) for tractors with a power output between 30 and 40 PS, with both wheel and crawler types included. The trafficability index values are presented in Table 2.

Table 2. Determination standards for tractor traffic

Instrument	Types of tractors	Operating Method	Trafficability
Cone index (kg/cm^2)	Wheel tractor (tire)	Rotary tilling	> 5,0 *
			2,5 – 5,0 **
			< 2,5 ***
		Plowing	> 6,5 *
			4,0 – 6,5 **
			< 4,0 ***
	Crawler tractor		> 3 *
			1,5 – 3 **
			< 1,5 ***

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Instrument	Types of tractors	Operating Method	Trafficability
Plate sinkage (cm)	Wheel tractor (tire)	Rotary tilling	< 6,0 *
			6,0 – 10,5 **
			> 10,5 ***
		Plowing	< 3,0 *
			0 – 3,0 **
	Crawler tractor		< 5,0 *
			5,0 – 15,0 **
			> 15,0 ***

Note :1) *(easy to operate), ** (able to operate), *** (unable to operate)
2) *Cone index* measured at an average depth of 0 – 15cm (cone angle 30^{o} and cone area 2 cm^2)
3) *Rectangular plate singkage* 2,5 × 10 cm size plate is used, with pressure of 30kgf (1,2 kg/cm^2)

Plate sinkage is used to determine the maximum depth to the point of tractor sinkage when operating in paddy fields. A crawler type tractor specification is employed to estimate the traffic capability of the combine harvester. And for 4-wheeled tractors it is assumed that a tractor with wheel tractor specifications is used.

Pearson correlation statistical analysis was carried out to determine whether there was a relationship between the measured land criteria and the measured soil penetration resistance values. This analysis was performed using the SPSS 25.

3 Results and Discussion

3.1 Soil and Land Use Characteristics

As illustrated on the map (Figure 3), the soil types in the Kulon Progo Regency are diverse, with the widest type of soil, lithosol, totaling 13,807 ha, and the narrowest type of soil, Mediterranean Haplik, totaling only 105 ha. Paddy fields in the Kulon Progo Regency are widely dispersed, particularly in lowlands and watersheds, with the highest concentrations observed in Temon, Wates, and Sentolo Districts. This evidence suggests that the presence of irrigation plays a crucial role in shaping the quality and characteristics of the soil in the Kulon Progo Regency.

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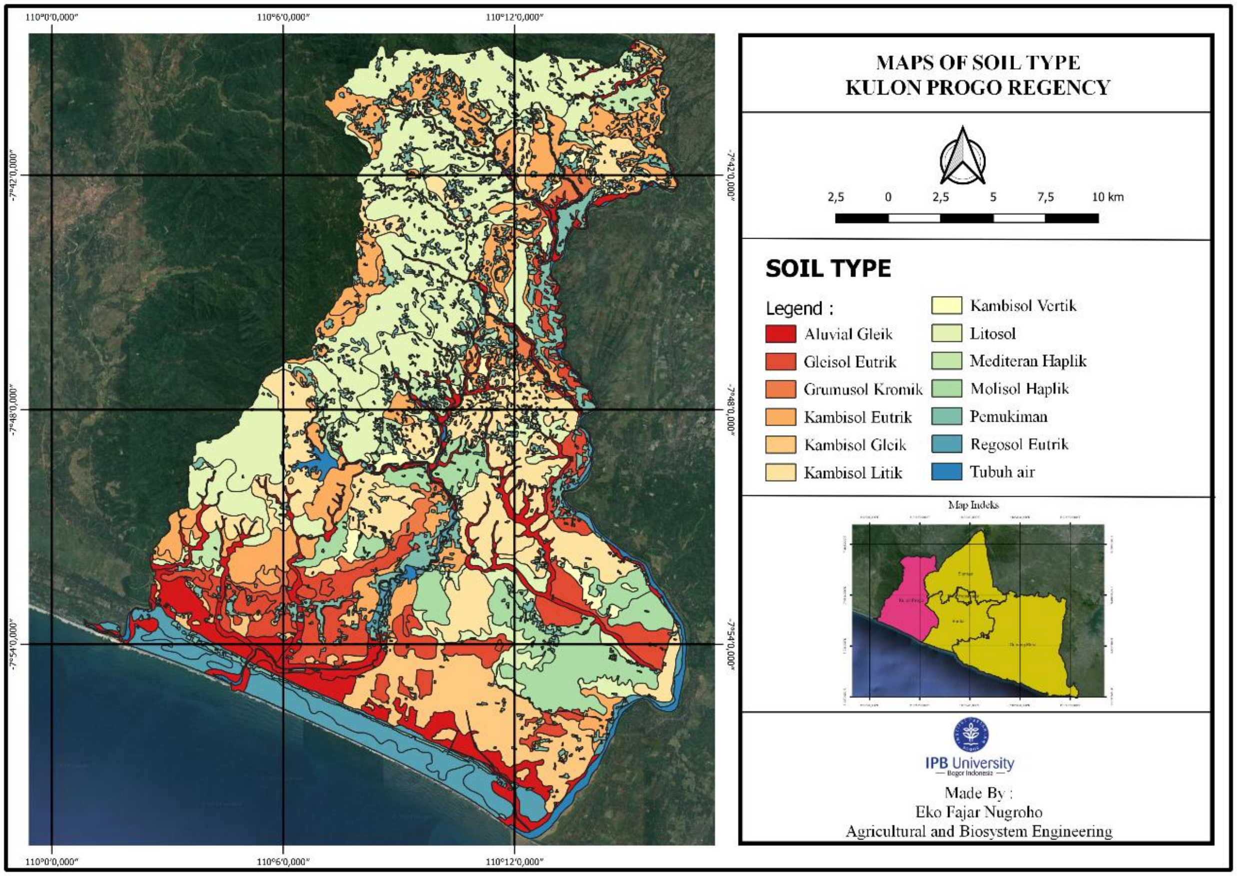

Figure 3. Map of soil types in Kulon Progo Regency (Source: Agricultural Land Resources Research and Development Center (BBPSDLP) Ministry of Agriculture)

The characteristics of the soil type have a significant impact on the hydrological processes of water absorption into the soil. The location, structure, and texture of the soil are essential factors in the process of water absorption into the soil. The physical properties of soil are generally characterized because soil samples are not collected. The physical characteristics of the soils are listed in Table 3.

Table 3. Characteristics of soil type and drainage

No	Soil Types	Textures	Structures	Drainage characteristics
1	Litosol	Sandy or gravelly	Not dense or gravelly	Good to very good
2	Regosol eutrik	Sandy to loamy	Loose	Good
3	Mediteran haplik	Sandy to loamy	Loose	Good in dry season
4	Molisol haplik	Sandy loam to dusty loam	Crumb	Good to very good

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No	Soil Types	Textures	Structures	Drainage characteristics
5	Kambisol litik	Sandy to loamy	Granular to dense	Good to medium
6	Kambisol eutrik	Sandy to loamy	Granular to dense	Good to medium
7	Kambisol vertik	Very loamy	Granular to dense	Good to bad
8	Grumusol kromik	Loamy	Granular to dense	Medium to bad
9	Aluvial gleik	Very loamy	Water saturation in the soil tends to be high	Bad to very bad
10	Kambisol gleik	Sandy to loamy	Granular to dense	Bad to very bad
11	Gleisol eutrik	Sandy to loamy	Granular to dense	Bad to very bad

Source: Subardja *et al*. 2016

The sample soil type on the property has a muddy texture with poor drainage characteristics. When the soil is saturated with air, it becomes softer. This will affect the soil pressure and the response of the soil, including sinkage. This penetration resistance is a measure of the ability of the soil to withstand pressure. Resistance is influenced by soil properties, such as consistency, mineral composition, air content, and density. Settling is a change that occurs in the soil as a result of the pressure applied to the soil surface. Increased soil pressure can increase the possibility of sinking, especially if it exceeds the bearing capacity of the soil. The influencing factors include soil type (sand, clay, silt), water content, and pressure distribution from the load. The physical properties of the soil can determine its response to pressure, penetration, and cooling; therefore, this is important in determining interactions with agricultural machinery.

3.2 Measurement of Soil Penetration Resistance

The results of the penetration resistance measurements are shown in Figure 4 (a)–(c). The average value of the penetration resistance at several depths (15 cm depth is taken from the middle value between 10 cm and 20 cm depth) is shown in Figure 5. The condition of the land at the time of data collection was in the post-harvest period with minimal waterlogging because in the month of data collection, rainfall began to decrease.

The results of the measurements indicate that the greater the penetration depth, the higher the penetration resistance value is. This was due to the influence of soil moisture content and the variability of soil textures. Research conducted by Mudzakir (2013) shows that the value of penetration resistance increases as the depth of plate pressing increases linearly. The penetrating power of the soil increased if the moisture content decreased and the depth increased. As stated by Suparding *et al.* (2018), penetration resistance is influenced by a number of factors, including soil moisture content, sand fraction, cross-sectional area of the tool, and ballast weight. A reduction in the cross-sectional

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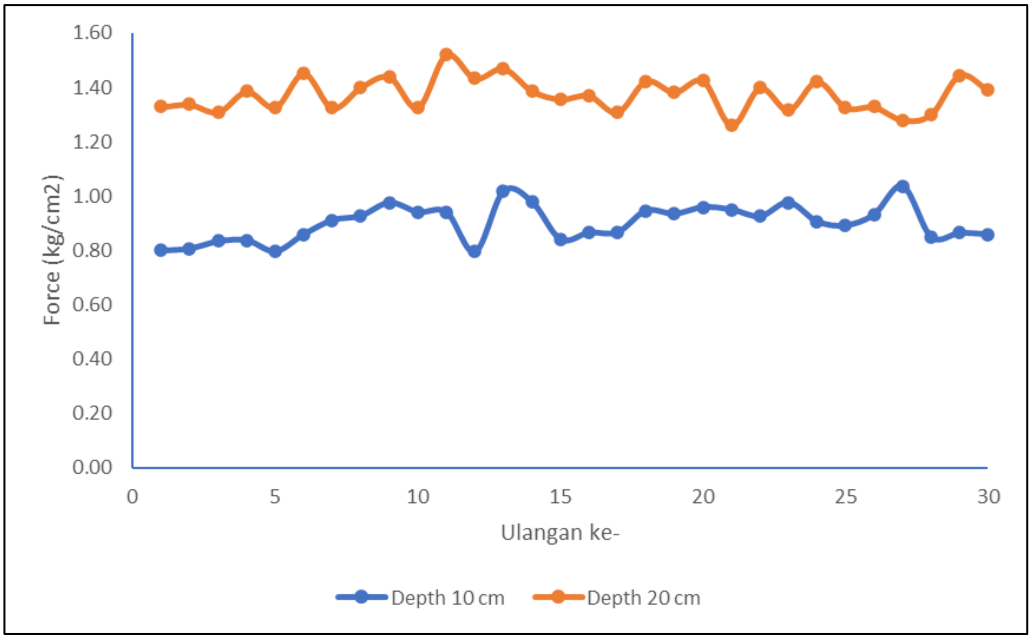
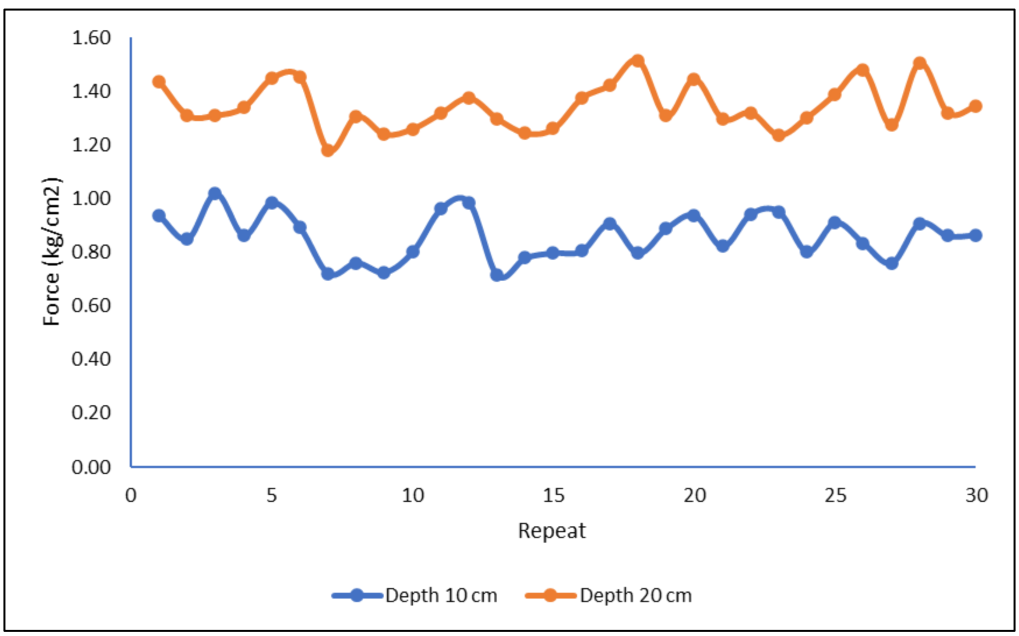
area of the tool and weight of the test equipment employed resulted in an increase in the tool depth. This is because a decrease in the area of the compressive field and an increase in the weight of the test equipment lead to a higher value of ground pressure than penetration resistance, thus causing the tool to sink into the ground.





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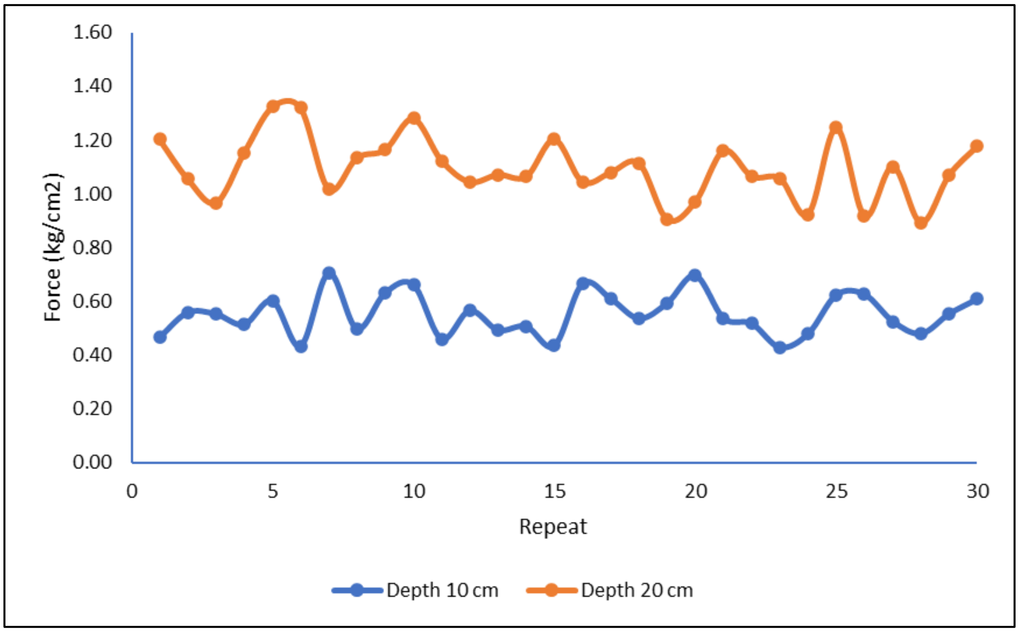

Figure 4. The value of penetration resistance on land category 1 (a); land category 2 (b); land category 3 (c)

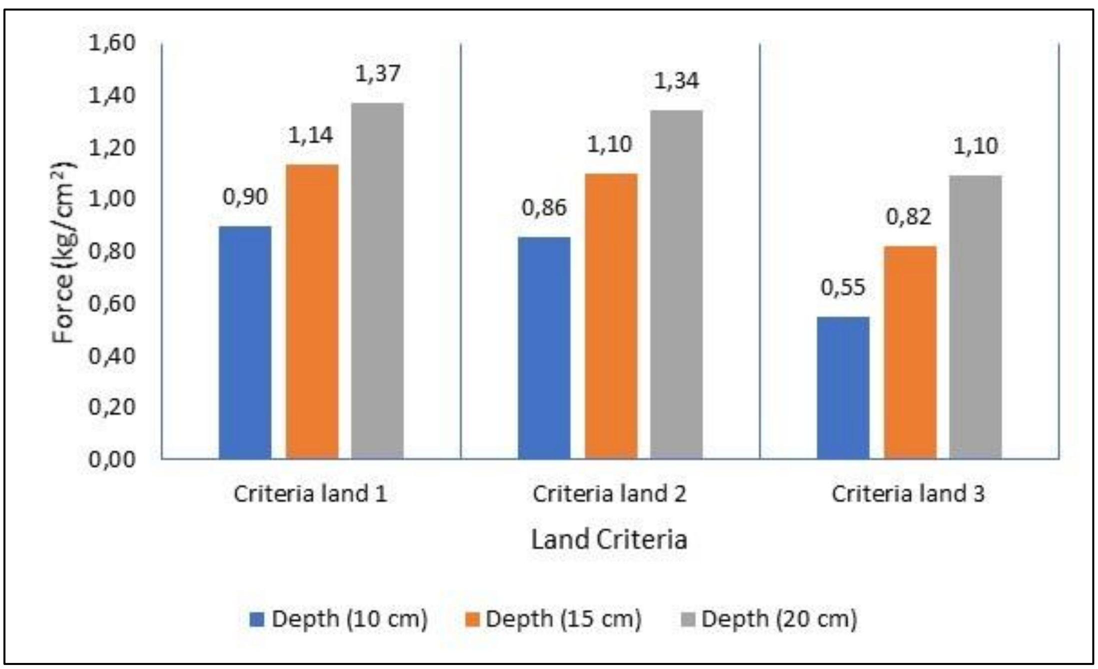

Figure 5. Average value of penetration resistance at several depths (15 cm depth is taken from the middle value between 10 cm and 20 cm depth)

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Pearson correlation analysis was conducted to ascertain the relationship between the sample land criteria and penetration resistance values at depths of 10 cm and 20 cm. The results of the analysis in Table 4 indicate that the Sig. (2-tailed) between the criteria of the sample land (X) and the value of penetration resistance at a depth of 10 cm (Y) is 0.000 < 0.05, which indicates that there is a significant correlation between the land criteria and the value of land penetration resistance at a depth of 10 cm. Additionally, it was established that the r-calculated value for the relationship between the land criteria (X) and the penetration resistance value at a depth of 10 cm (Y) was 0.824. This indicates a relationship or correlation between the land criteria and penetration resistance value at a depth of 10 cm. The relationship between the land criteria and the penetration resistance value at a depth of 20 cm is illustrated in Table 5. It has been established that Sig. (2-tailed) value between the sample land criteria (X) and the penetration resistance value at a depth of 20 cm (Y) is 0.000 < 0.05, which indicates a significant correlation between the land criteria and the land penetration resistance value at a depth of 20 cm. Additionally, it was established that the r-calculated value for the relationship between the land criteria (X) and the penetration resistance value at a depth of 20 cm (Y) is 0.741. This indicates a relationship or correlation between the land criteria and penetration resistance value at a depth of 20 cm. A positive value of the r calculation, or Pearson Correlation, in this analysis indicates a positive relationship between the two variables. This suggests that an improvement in the quality of the sample land criteria results in an enhancement of the measurable penetration resistance value.

Table 4. Pearson correlation of land criteria and penetration resistance value (10 centimeters)

		Land criteria	Penetration resistance value (10 cm)
Land category	Pearson Correlation	1	0,824**
	Sig. (2-tailed)		0,000
	N	90	90
Penetration resistance value (10 cm)	Pearson Correlation	0,824**	1
	Sig. (2-tailed)	0,000	
	N	90	90

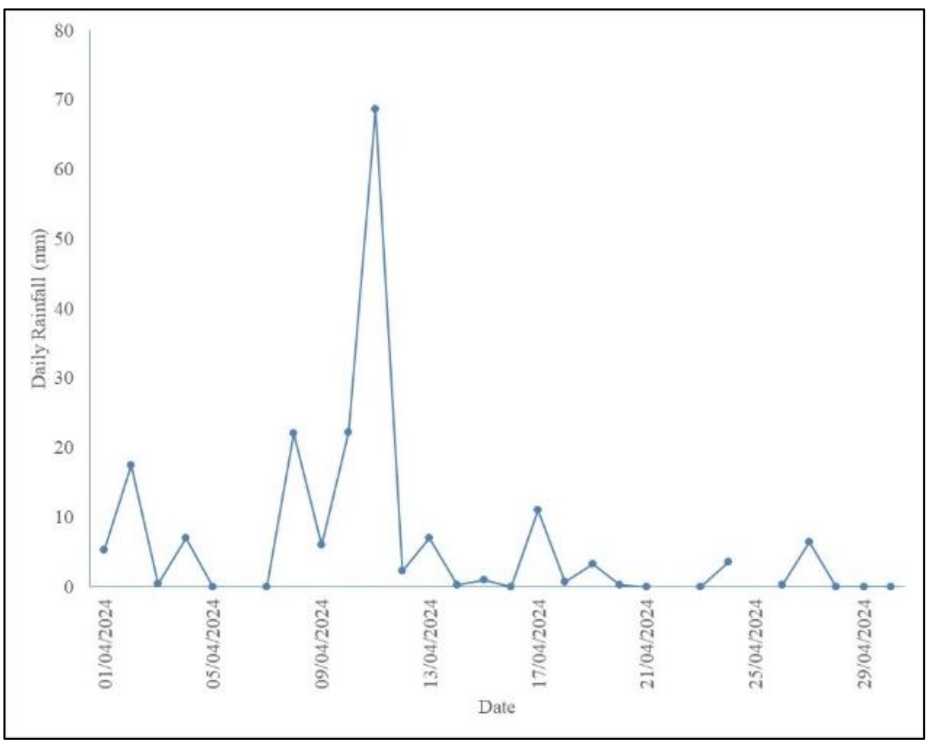
**Correlation is significant at the 0.01 level (2-tailed)

Table 1. Pearson correlation of land criteria and penetration resistance value (20 centimeters)

		Land criteria	Penetration resistance value (20 cm)
Land category	Pearson Correlation	1	0,741**
	Sig. (2-tailed)		0,000
	N	90	90
Penetration resistance value (10 cm)	Pearson Correlation	0,741**	1
	Sig. (2-tailed)	0,000	
	N	90	90

3.3 Effect of Rainfall on Penetration Resistance Value

The daily rainfall during the data collection period for penetration resistance values ranged from cloudy to moderate rain. This is evidenced by the daily rainfall data measured at the Yogyakarta Meteorological Station (Figure 6a). Throughout April 2024, only two days in the Kulon Progo Regency area experienced moderate intensity rainfall. In contrast, other days in April 2024 were characterized by low-intensity rainfall, with some days experiencing no rainfall accumulation. The daily rainfall data for May 2024 (Figure 6b) demonstrated that there was no precipitation throughout the entire month.



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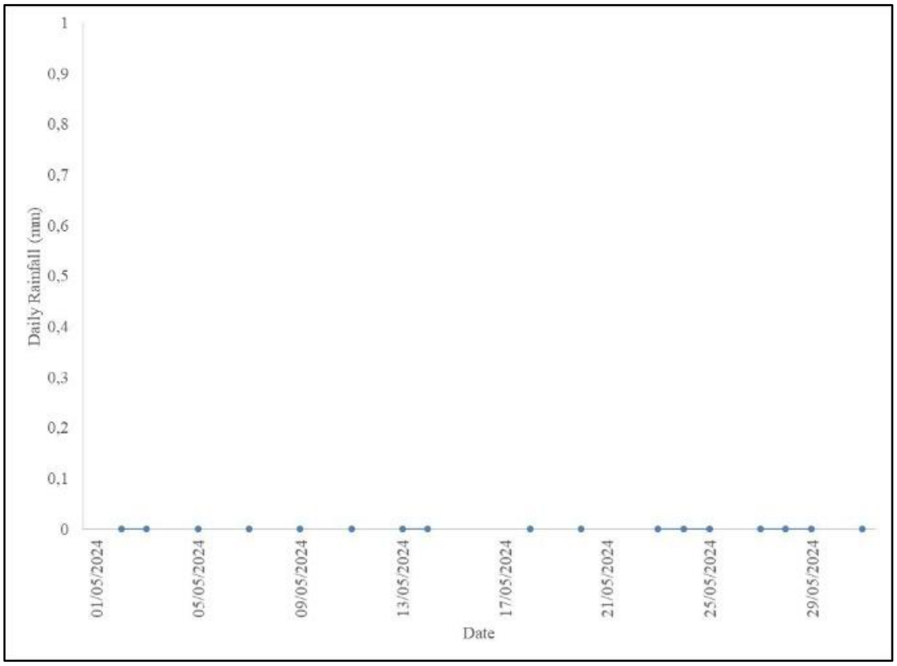

Figure 6. Daily rainfall: April 2024 (a) and May 2024 (b) in Kulon Progo Regency

The relationships between rainfall, soil moisture content, and penetration resistance are complex. Furthermore, the physical properties of the soil influence its capacity to store water. Kurnia (2019) observed that open land will experience a rapid decrease in moisture content in the absence of additional precipitation. Bujung et al. (2019) stated that the addition of high rainfall will result in an increase in the value of soil shear strength. As the soil moisture content increased, the cohesion value, shear angle value, and weight of soil content decreased, resulting in a reduction in the penetration resistance value. The difference in measurement time has a significant impact on the measured puncture resistance value, particularly when assessments are conducted on land with varied soil types and rainfall levels.

3.4 Effect of penetration resistance on agricultural machinery application

The ground pressure of the four-wheel tractors and combine harvesters is determined by the weight and type of wheels or tires used. In the case of a combine harvester equipped with a crowler, ground pressure calculation is performed by determining the area of the wheel tread that makes contact with the ground. This was achieved by first measuring the width and length of the wheel tread and then calculating the area of contact between the tread and the ground. For four-wheel tractors, it is essential to determine the dimensions of the tires used and the angle of contact between the tires and the ground.

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Table 2 indicates that, for optimal performance in paddy fields, the combine harvester must have a maximum sinkage value of 15 cm at a pressure of 1.2 kg/cm². A comparison of the results of measuring the penetration resistance value with the requirements for applying a combine harvester indicated that the sample land failed to meet these criteria. If the machine is operated under these conditions, it will sink by more than 15 cm in land categories 1 and 2, and by more than 20 cm in land category 3.

Table 2 provides information regarding the requirements for a four-wheel tractor to operate effectively. For a four-wheel tractor to be effective in plowing work, it must have a maximum sinkage value of 3 cm at a pressure of 1.2 kg/cm². To perform scraping using a four-wheel tractor, it is necessary that the maximum sinkage value is 10.5 cm at a pressure of 1.2 kg/cm². A comparison of the measured penetration resistance values indicates that the sample land fails to meet the criteria for the application of a four-wheel tractor in both plowing and scraping processes. This is due to the fact that the measured penetration pressure at a depth of 10 cm shows a maximum value of 1.0 kg/cm². Consequently, if it is still necessary to apply the four-wheeled tractor, it can sink by 15-20 cm for land categories 1 and 2, and by more than 20 cm for land category 3.

As demonstrated by Handaka *et al.* (2007), the implementation of agricultural machinery in Indonesia is feasible when the land is in dry or humid conditions with a moisture content of 27-40%. This indicates that the paddy field did not experience waterlogged conditions. It is essential to achieve these conditions if a drainage channel is available for dry paddy fields. Furthermore, modifications can be made to the agricultural machinery. The combine harvester can be modified to reduce the risk of becoming stuck in mud. There are two well-known approaches to increasing the contact area of the machine. In track harvesters, the contact area can be increased by increasing the track width. In wheel harvesters, the contact area can be increased by reducing the air pressure in the tires. However, harvesters with larger track widths must be mindful of the additional weight, which may reduce the benefit of the increased contact area. It is very important to choose the right track when making or buying a product. The air pressure in tires can also be reduced to improve traction in off-road situations such as sandy soil, snow, or dirt (Colton et al. 2021). Modifications that can be made for four-wheel tractors include installing cage wheels or floating wheels to improve grip on the ground.

4. Conclusion

The soil type on the sample land exhibited substandard drainage characteristics, which can result in muddy and soft soil conditions. Soil penetration resistance quantifies the capacity of the soil to withstand the pressure imposed on the soil surface. The soil penetration resistance value is associated with the use of agricultural machinery. The penetration resistance measurements taken on the sample land ranged from 0.55 to 0.90 at a depth of 10 centimeters (cm) and from 0.82 to 1.14 at a depth of 15 cm. When evaluated against the trafficability index, which delineates the operational parameters for agricultural machinery, it was determined that the sample land does not meet the requirements for the use of agricultural machines such as 4-wheeled tractors and combine harvesters. The application of these machines will cause sinkage of more than 15 cm for land categories 1 and 2, and will cause sinkage of more than 20 cm for land category 3.

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