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The Effects of Land Uses on Soil Physical Health in Agricultural Land (Case Study: Kismantoro District, Central Java Province, Indonesia)

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ABSTRACT

Kismantoro district is a karst land with unique characteristics and its physical health is easily influenced by land use. The purpose of this study was to identify the physical health status of soil, and find the influence of land use and parameters that limit soil physical health, which eventually provide appropriate land management strategies and recommendations to improve soil health. The research was conducted using a descriptive explorative approach and a purposive sampling method on the 12 Land Map Units (LMU) with three replications. Data were analysed using Analysis of Variance and Pearson correlation. Results indicated that most soil physical health in agricultural land in Kismantoro District is healthy. The highest soil physical health status was found on plantation agricultural land, with the average of the soil physical health being high status of 63.22%, followed by moor agricultural land at 52.83% and rice fields at 48.2%. The determinant factors of soil physical health were soil porosity, bulk density, and soil texture. To enhance the physical health of agricultural soil in Kismantoro District, it is recommended to apply organic matter, adopt zero or no-tillage practices, and grow cover crops on agricultural land.

INTRODUCTION

Soil health plays an important role in a resilient agricultural system (Chahal et al., 2021). Soil physical health is the ability of soil to provide the needs of plants and ecosystems (Are, 2019). Low soil physical health makes roots it difficult to penetrate the soil, interferes with nutrient absorption, and decreases plant productivity ultimately (Herdiansyah et al., 2024).Soil texture, soil density, and soil porosity altogether affect soil water movement, root growth, and erosion resistance, which are the indicators of soil physical health (Rajput et al., 2023). Fine-textured soils are more resistant to penetration than crumbly-textured soils. Soil compaction is known to limit plant root growth when bulk density reaches a certain level of density (Lyczak et al., 2021).

Soil texture could contribute indirectly to other soil physical properties such as aeration, drainage, root penetration, soil temperature, and decomposition rate (Mustawa et al., 2017) which can also affect soil compaction (Aghhavani

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et al., 2020). Busse et al. (2021) reported that soil compaction increased soil bulk density by 10 to 20% compared to uncompacted soil. Since soil bulk density is the weight of soil dry mass per unit volume (Wang et al., 2024), soils with a high bulk density could reduce drainage and root penetration (Ricky and Rois, 2021). Compacted soil also prevented root system to accessing water and nutrients. These impacts will reduce crop productivity and resulted in a decrease farmers' income and economic welfares.

According to The Regulation of Wonogiri Regency number 23 in 2015, the regional economic structure of Kismantoro district relies heavily on the agricultural sector and influencing the local economy (Purnaningsih and Purnamadewi, 2019). Extensive anthropogenic activities such as land management, including intensive tillage in a long-term could degrades soil structure, porosity and increase soil compaction. Research on soil physical health is very important as it will encourage agricultural productivity through proper, efficient and effective land management. This study aimed to identify the physical health status of the soil, examine the determinants of soil health through the influence of land use and limiting characteristics and provide recommendations for sustainable land management in agricultural land use.

MATERIALS AND METHOD

The research was conducted in Kismantoro District, Wonogiri Regency, Central Java Province, Indonesia, covering an area of 69.86 km2 (Wonogiri Central Bureau of Statistic, 2023), which was located in at an altitude of 348 meters above the sea level and classified as mountain areas (Wonogiri Central Bureau of Statistic, 2022). The soil sampling technique was carried out using a purposive sampling method with 12 Land Map Units (LMUs) with 3 replications and 36 sample points. Soil physical properties were measured both in the field and in the laboratory. Field measurements included soil penetration rate (using the penetrometer method) and root depth (using the soil drilling method). Laboratory analyses included soil porosity (gravimetric method), bulk density (clod method), water content (gravimetric method), and soil texture (pipette method). All methods used for analyzing soil physical properties were based on guidelines from the Indonesian Soil Research Institute (2006). Soil samples from each sample point were collected at a depth of 0-20 cm. The soil samples used in the laboratory were analyzed as disturbed and wind-dried soil without exposure to sunlight as much as 200 g, then sieved using a 200 mm sieve. While for the bulk density parameter using undisturbed soil in the ring sample. The details of LMUs as sampling area areas in this research are listed in Table 1.

Data Analysis

Soil Physical Health Classification

The physical health status of the soil was determined based on field observations and laboratory analysis results, which were then

Table 1. Characteristic of land mapping units

LMU	Soil Type	Land Use	Rainfall	Slope (%)	Area
1	Alfisols	rice field	1,750	0-8	Gambiranom, Gesing, Kismantoro
2	Alfisols	moor	1,750	0-8	Gedawung, Gesing
3	Inceptisols	plantation	1,750	8-15	Gesing, Kismantoro
4	Inceptisols	plantation	2,250	8-15	Ngroto, Plosorejo, Pucung
5	Inceptisols	plantation	2,250	15-25	Bugelan, Miri, Ngroto
6	Inceptisols	rice field	1,750	0-8	Kismantoro, Lemahbang, Ngroto
7	Inceptisols	rice field	2,250	8-15	Bugelan, Ngroto, Plosorejo
8	Inceptisols	rice field	2,250	15-25	Bugelan, Plosorejo
9	Inceptisols	rice field	2,750	8-15	Bugelan
10	Inceptisols	moor	1,750	15-25	Gedawung, Ngroto, Miri
11	Inceptisols	moor	2,250	15-25	Ngroto, Plosorejo, Pucung
12	Inceptisols	moor	2,250	8-15	Bugelan, Lemahbang, Ngroto

Notes: rainfall (mm/year), area (village)

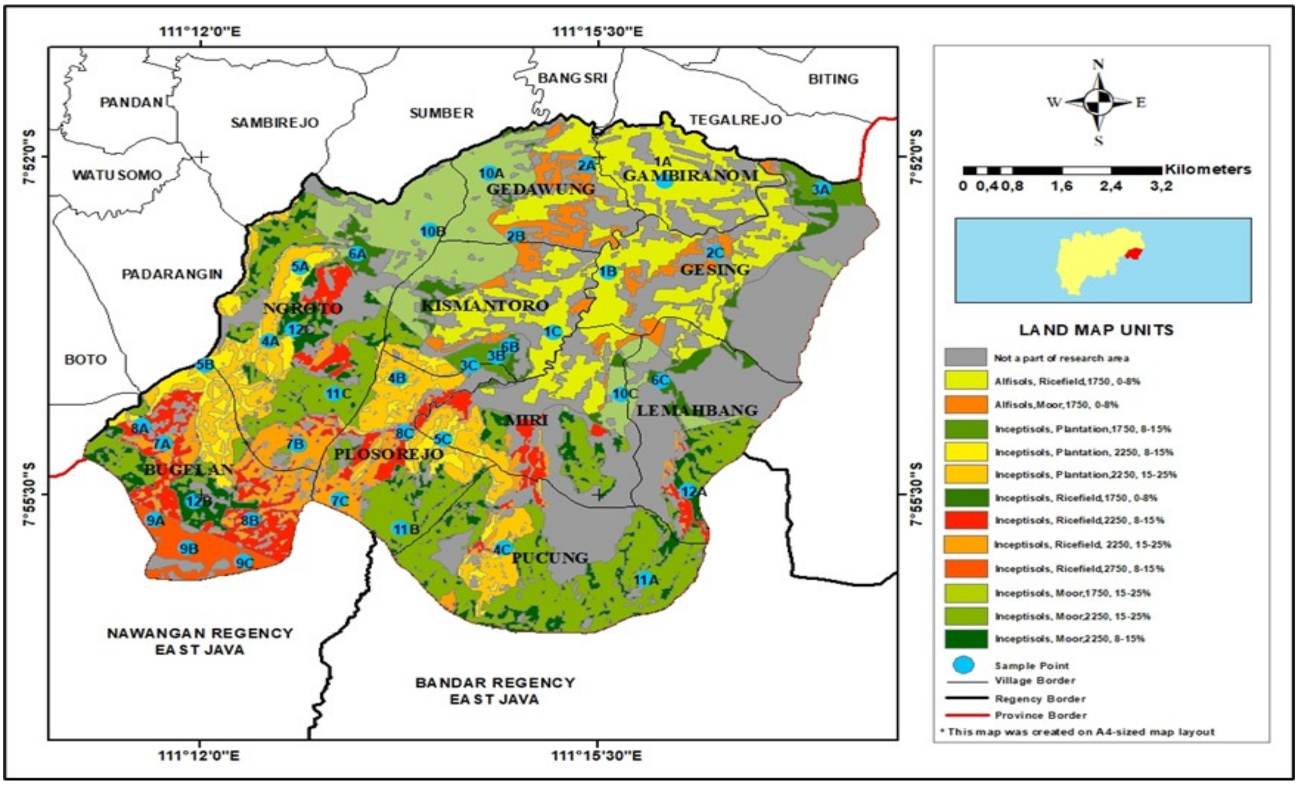


Figure 1. Soil observation and sampling points

compared to Table 2 to assign a corresponding score. Each property received a score on a scale from 1 to 5, with a maximum possible total score of 30. Variations in the scores for each property were influenced by differences in the environmental factors associated with the soil samples.

The total scores of soil properties gained were calculated with Equation 1 (Moebius-Clune et al., 2016) to classify the soil physical health status as classified in Table 3. The value of soil physical heath is shown in percentage. The differences in soil physical health status could be the result of environmental factors, which affect soil physical properties score.

Determinant Factor

A determinant factor is a factor that significantly influences and affects the research results. This study used an ANOVA (Analysis of Variance) test to evaluate the effects of environmental factors, including land use, rainfall, soil type, and slope, primarily agricultural land use, on the limiting factors of soil physical health status. If it is significant (P-value

Table 2. Assessment of Soil Physical Health Properties

Parameters	Very Low	Low	Moderate	High	Very High
	Score 1	Score 2	Score 3	Score 4	Score 5
Porosity (%)	<30; >70	30-34; 65-69	35-39; 60-64	40-49	50-59
Bulk Density (g/cm^3)	>1.6	>1.5-1.6	>1.4-1.5	1.3-1.4	<1.3
Penetration Rate (kg/cm^2)	>1.5	1.4-1.5	1.2-1.3	1-1.1	<1
Root Depth (cm)	<30	30-60	60-90	90-150	>150
Texture	S,C	LS, Si	SCL, SL, SC	SiC, CL, SiCL, SiL	L
Water Content (%)	31-40	1-3	4-9	10-18	19-30

Source: (Riwandi and Handajaningsih, 2011), (Lucky and Suratman, 2018), (PermenLH, 2006), (Alan, 2005).
Remark: S = sand, C = clay, LS = loamy sand, Si = silt, SCL = sandy clay loam, SL = sandy loam, SC = sandy clay, SiC = silty clay, CL = clay loam, SiCL = silty clay loam, SiL = silty loam, L = loam.

Table 3. Soil physical health status

No.	Value (%)	Category
1	0-20	Very Low
2	20-40	Low
3	40-60	Moderate
4	60-80	High
5	80-100	Very High

Source : (Moebius-Clune et al., 2016)

<0,05) a further test was carried out with DMRT (Duncan's Multiple Range Test) to determine the difference among the environmental factors. A correlation test was also conducted to determine the relationship between soil physical properties and soil physical health to find which one of the soil properties acts as a limiting factor in soil physical health. The sources of environmental diversity and determining factor parameters found in the results of ANOVA and correlation analyses are the basis for determining recommendations for land management strategies to improve soil physical health, which is supported by references from previous research.

$$\text{Soil physical health} = \frac{\text{Total Score Gained}}{\text{Maximum Score}} \times 100\%$$

RESULTS AND DISCUSSION

Soil Physical Health

This study investigated the soil's physical properties to determine the soil physical health status of various agricultural lands in the Kismantoro regency, including rice fields, moor, and plantations. The rice field was a rainfed agricultural land, heavily depending on rainfall before tillage operation can be carried out. Moorland was cultivated with secondary crops like corn (*Zea mays*) and cassava (*Manihot esculenta*), while plantation areas were planted with perennial trees, such as rubber (*Hevea brasiliensis*). The highest soil physical health status was 68%, categorized as "High," (at LMU 5) and was observed in plantations. In contrast, the lowest soil physical health status was 41%, categorized as "Moderate" (at LMU 6), and was found in rice fields (Table 4).

The average soil porosity in plantation land (45.93 %) was similar to dry land (37.44 %), while highly significant differences with rice fields (28.84 %). The highest soil porosity was found in plantation land, while the lowest was found in rice fields. Low soil porosity in rice fields was presumably due to the clay soil texture (Sukartono et al., 2023) as well as soil processing, drainage, and soil eluviation which affect soil particles and change the physical properties of the soil (Jayawora and Mutiara, 2021). Low soil porosity makes water difficult to enter and exit the soil. The higher the soil porosity, the easier for water to enter the soil. Soil porosity could be increased by adding organic matter available in the land, such as fallen leaf litter from vegetation around the land. In addition, the amount of vegetation on plantation land plays important roles in strengthening soil aggregates and accelerating the reduction of soil erosion (Wang et al., 2022).

The average soil bulk density on plantation is (1.05 g/cm^3) did not different to moor's (1.20 g/cm^3), but significantly different with that of in rice field (1.30 g/cm^3). Soil with bulk density below 1.4 g/cm^3 is better for soil physical health, because bulk density that is too high reduces the percentage of soil pores. High soil density prevents water circulation to enter the soil and reduces root penetration into the soil (Zainuddin et al., 2020). According to Darmanto and Setiawan, (2021), bulk density and soil porosity have an inverse relationship, meaning that a decrease in soil bulk density is directly proportional to an increase in soil porosity.

The highest average of water content was recorded on rice field (10.96 %) which was significantly different than those in moor (8.49 %) and plantation (7.25 %). The highest average water content on rice fields could also result from its clay-textured soil with a strong water-holding capacity. The rice field soil has an impermeable layer formed by plowing and tillage, resulting in higher water content and greater water saturation compared to other land uses (Yunagardasari et al., 2017). Meanwhile, lower ground cover plants in peatlands and higher evaporation surfaces in plantations causes high evaporation in plants indicating high water loss. Indis et al., (2022) suggested that soil porosity, texture, and the amount of soil organic matter could affect soil water con-

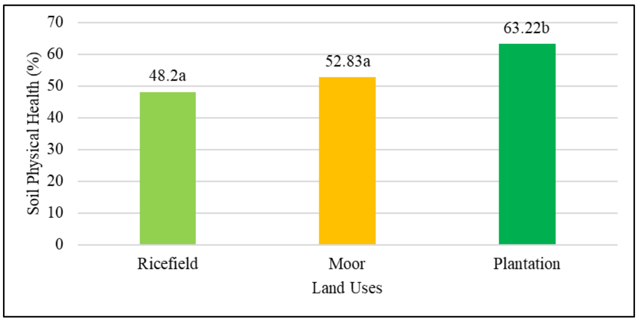
Table 4. Scoring of soil physical health

Sample Points	Porosity	Bulk density	Soil penetration rate	Root depth	Texture	Soil water content	Total score	Value (%)	Status classification
1A	3	5	1	2	4	3	60		
1B	4	5	1	2	3	3	60	59	Moderate
1C	2	5	1	2	3	4	57		
2A	3	5	1	1	3	3	53		
2B	4	5	1	3	3	3	63	54	Moderate
2C	1	4	1	2	3	3	47		
3A	3	5	1	3	3	3	60		
3B	4	5	1	2	3	3	60	63	High
3C	4	5	5	1	3	3	70		
4A	2	4	3	2	1	3	50		
4B	2	5	5	2	4	4	73	59	Moderate
4C	4	5	1	2	1	3	53		
5A	5	5	4	2	1	4	70		
5B	3	5	2	2	1	3	53	68	High
5C	5	5	5	2	4	3	80		
6A	1	3	1	1	1	4	37		
6B	1	3	4	1	1	3	43	41	Moderate
6C	3	3	1	2	1	3	43		
7A	1	5	2	2	4	4	60		
7B	1	3	2	2	1	4	43	48	Moderate
7C	1	3	3	1	1	3	40		
8A	1	2	1	2	1	3	33		
8B	1	3	1	2	1	4	40		
8C	3	4	4	2	1	4	60	44	Moderate
9A	1	2	1	2	1	4	37		
9B	3	5	1	2	3	4	60	49	Moderate
9C	2	5	1	2	1	4	50		
10A	4	5	3	1	4	3	67		
10B	5	5	4	2	1	3	67	62	High
10C	3	5	1	3	1	3	53		
11A	1	3	2	2	3	3	47		
11B	1	4	1	1	3	3	43	49	Moderate
11C	2	5	2	2	3	3	57		
12A	3	4	1	2	1	3	47		
12B	2	5	1	2	1	4	50	46	Moderate
12C	1	4	1	1	1	4	40		

tent. When organic matter is high, the percentage of soil pores increase, eventually improving soil texture's ability to support plant growth.

The sources of diversity in each LMU indicated the conditions of the landscape and environment (land use, slope, rainfall, and soil type), that affect soil characteristics, especially physical characteristics such as porosity, texture and soil structure (Bakri et al., 2022). According to Akinola et al., (2023) these soil properties had an impact on food security, groundwater quality, soil carbon absorption and erosion disasters.

It appeared that plantation land had the highest soil physical health status (63.22 %) in compared to other land uses. This status was also significantly different from rice field and moor lands. The soil physical properties could be influenced by vegetation and soil texture which caused differences in soil looseness, bulk density, and porosity (Naharuddin et al., 2020). Soils under tree canopies generally ex-



Remarks: different letter shows different values in the 5% level of DMRT

Figure 2 The distribution of soil physical health status under various land uses

hibit better physical and chemical properties including higher nitrogen, phosphorus and sulfur nutrient contents as well as lower concentration of clay and silt particles. Fallen leaves on plantation land could also contribute soil organic matter and hence improved soil physical properties (Rahmayuni and Rosneti, 2017). In addition, soil organic matter and the soil's physical properties determine the land's suitability for crop cultivation (Roy et al., 2024).

Moorland had the second highest soil physical health status with 52.83 (moderate status), while rice field had the lowest soil physical health status 48.2 (moderate category). Statistical analysis indicated no significant differences between these two types of land. On moor agricultural land, decreased in soil physical health could be resulted from the lack of land cover, causing soil aggregates to be disrupted by raindrops. Clay-textured soil directly exposed to raindrops is more easily broken apart than crumb-textured soil. The rupture of soil aggregates occurred when the soil became water clogged, forcing air from the soil and leading to aggregate rupture. This process was related to soil texture, water content and soil mineral types (Gauthier et al., 2023). Good soil aggregates can increase soil erosion resistance and prevent a decline in soil health (Sianipar et al., 2024). In rice field, tillage and plowing frequency could also degraded soil structure and aggregation by causing smaller soil particles to form strong bonds, resulting in soil compaction (Gunadi et al., 2020). The research results of Gunadi et al., (2020) show that rubber plantations have a higher soil density, reaching 1.03 g/cm^3 compared to rice fields which are only 0.94 g/cm^3, due to the low organic matter and minimum tillage due to being on a steep slope, while rice fields have sufficient organic matter input and management before and after planting.

Determinant Factor

The identified determinants should be enhanced through targeted land management to ensure effectiveness and efficiency, as outlined in the forthcoming land management strategy recommendations. Table 5 shows the soil physical parameters that determines the high and low soil health classes called determinant factors. In the research area, the identified determinant factors included soil porosity and soil bulk density. An increase in soil bulk density could occur as a result of the reduced pore space in the soil. Soil with a high bulk density face difficulties to facilitating water circulation and hardly allowing the roots penetrating the soil (Zainuddin et al., 2020). Relatively high soil porosity with low bulk density represents good physical conditions of agricultural soil (Nuraida et al., 2021).

Soil texture significantly contributes to resisting disturbance (Perron et al., 2022). Soil texture determines root activity in the soil, includes the ability to absorb water and soil nutrients for plants and carry out plant metabolism (Tamimi, 2024). Soil texture was also related to dust and clay content which is correlated with the diversity of soil fungi and bacteria in the rhizosphere (Oliveira et al., 2024) that helps organic matter decomposition and increases soil aggregation. Clay textured soil with a good bulk density would generally be more suitable for agricultural land than sandy soils ((Fadel et al., 2021).

Land Management Strategy

The recommended land management strategy aims to enhance soil health based on its current characteristics, ensuring it is managed effectively and efficiently to support plant productivity. The limiting factors of soil physical health can be improved by targeted soil processing for soil physical problems. One of them is reducing the use of chemical fertilizers, because the impacts of long-term use of chemical fertilizers could reduce soil root depth, disrupt water storage and gas exchange in the soil,

Table 5 The correlation between parameter and class of soil physical health

Parameter	PR	BD	PNT	RD	Texture	WC	SPH
PR	1						
BD	-.849**	1					
	0						
PNT	-0.007	-0.031	1				
	0.966	0.857					
RD	.353*	-0.308	0.264	1			
	0.035	0.067	0.12				
Texture	0.154	-0.277	0.015	0.256	1		
	0.371	0.101	0.929	0.132			
WC	-0.316	0.068	-0.136	-0.13	-0.036	1	
	0.06	0.693	0.428	0.449	0.834		
SPH	.650**	-.600**	-0.326	0.271	.600**	-0.103	1
	0	0	0.052	0.109	0	0.552	

Remark: PR=porosity, BD=bulk density, PNT=soil penetration rate, RD=relative density, WC=water content, SPH=soil physical health; *) Pearson correlation Sig. (2-tailed) < 0.05 (significant); **) Sig. (2-tailed) < 0.01 (highly significant).

and increase plant stress which could reduce plant productivity (Temegne et al., 2024). The combination of organic and chemical fertilizers could improve soil structure (Supriatna et al., 2024) and soil health (Mossie et al., 2024). In addition, the use of waste for fertilizer such as paper pulp waste can reduce soil density, increase the number of micro and meso pores, and increase water holding capacity to help plants cope with drought (Räty et al., 2023).

In order to replace the use of chemical fertilizers in the soil, many sources of organic fertilizers are needed (Lal, 2020) and soil conditioners from around the land. Plant residues or harvest residues such as straw are included in soil conditioners (Fagodiya et al., 2024), which could act as mulch to prevent soil aggregates from breaking (Toth et al., 2024). Soil organic matter used in agricultural management activities improve soil porosity and soil bulk density (Gurmu, 2019). Soil organic matter around the plants, such as dry leaves and dry twigs could be used as ground cover (Penhen et al., 2022). This role will improve the physical, chemical, and biological properties of the soil (Wulanningtyas et al., 2021), including improving aggregate bonds between soil particles, and reduce specific gravity and increase soil pore space (Marlina and Satriawan, 2014). In addition, according to Yang et al., (2024), low soil density and soil porosity can be overcome by applying soil minimum tillage and *Arbuscular mycorrhizal* fungi.

CONCLUSION

The soil physical health status of agricultural land in Kismantoro is predominantly classified as moderate. The highest soil physical health was recorded at 68% (LMU 5), while the lowest was 41% (LMU 6). Overall, the soil physical health status ranked from highest to lowest as follows: plantation, moor, and rice field. The main limiting factors affecting soil physical health were soil porosity and bulk density. Implementing practices such as adding soil organic matter (SOM), using cover crops, and adopting no-tillage methods could enhance soil physical health. The implications of this study suggest the need for improved land management practices to enhance soil characteristics and boost the physical health of the soil, ultimately supporting agricultural productivity.

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