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Effects of Land and Water Management on Bulk Density of Peat Soils in Coconut Plantations

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Abstract. Peatlands, which cover approximately 7% of Indonesia's land surface, hold significant agricultural potential but require careful management for sustainability. The objective of this research is to assess the effects of land and water management on peat soil bulk density (BD) and subsidence in agricultural practices employing integrated water management. The study was conducted in Pulau Burung District, Riau Province, which is the only Nucleus and Smallholder Estate Scheme of coconut plantation in Indonesia. The plantation applied and managed an integrated water management technique called "Water Management Trinity" to regulate water levels during rainy and dry spells, ensuring optimal growth conditions and maintaining peat soil wetness. The results show no pattern differences in BD between the nucleus estate and smallholder estate, with values ranging from 0.10–0.19 g/cm³. It was observed that peat soil BD decreases with increasing depth. The annual subsidence rate is -1.56 cm. However, the BD has increased by 136% relative to the initial measurements in 1986, contributing to a slowdown in the progression of subsidence rates in recent years. The adoption of cover crop management, which enhances nutrient cycling processes in peat soil on the nucleus estate, and the transformation of farmers from conventional practices to apply cover crop management, have shown positive impacts on productivity. The application of sustainable management practices in coconut plantations demonstrates the potential for the sustainable use of peatlands, particularly in mitigating the high subsidence rates that are a primary concern in peatland agriculture.

1. INTRODUCTION

Peatlands in Indonesia cover approximately 13.43 million hectares (Mha), about 7% of the country's total land area, with significant areas located in Sumatra (5.85 Mha), Kalimantan (4.54 Mha), Papua (3.01 Mha), and Sulawesi (0.024 Mha) [1]. In Sumatra, peatlands are especially prevalent along the eastern coast, with Riau Province having the largest extent, covering around 3.85 million hectares [2]. These peatlands have long been vital for the agriculture of the people in Riau, emphasizing the province's key role in both local and global environmental contexts. Therefore, the promotion of sustainable management practices for peatlands in Riau is essential for benefiting both local and international ecological context [3].

Peatlands have been utilized for agriculture in Indonesia by indigenous people for centuries, proving successful for cultivating traditional food crops, fruits, and spices [4]. During the 1970s and 1980s, the transmigration program expanded to include peatlands, recognizing their potential, particularly given that by the 1990s, peatland areas were estimated to comprise 20.6 million hectares (Mha), or 10.8% of Indonesia's land surface. The program aimed to enhance the production of non-oil and gas commodities, support farmers' incomes, and promote regional development. Under Presidential Instruction Number 1 of 1986 regarding the Development of Plantations with the Nucleus Estate and Smallholder (NES) Scheme Linked to the Transmigration Program, Riau Province, which has the largest peatland area, became a focal point for these transmigration program.

The selection of coconut as a commodity was based on its historical significance as the main livelihood for the people of Indragiri Hilir, leading to the development of coconut plantations through the NES Scheme. In 1986, the Sambu Group was chosen as the lead company to design and develop large-scale coconut agriculture and its processing industry. Sustainable peatland management in this context requires appropriate water management practices [5]. Consequently, the development of these plantations incorporated an integrated water management approach known as the "Water Management Trinity," which regulates water to prevent flooding during the rainy season and mitigate drought during the dry season for coconut productivity and peat soil preservation [6]. This trinity in water management consists of canals, dikes, and dams with water gates. This development marked the first large-scale utilization of peatlands using integrated water management in Indonesia.

The development of a comprehensive coconut industry ecosystem, ranging from upstream to downstream, substantially influences socio-economic dimensions [7]. However, evaluations of the impact of integrated water management applied since 1986—spanning nearly four decades—remain inadequate. This knowledge limitation is significant, considering that understanding the characteristics of peat soil under integrated water management is essential for successful agricultural practices on peatlands. An assessment of physical changes, particularly in terms of bulk density (BD) and the relationship between subsidence and integrated water management, is necessary. These evaluations are essential to address the risk of irreversible drying during peatland utilization [8].

Peat soil that is excessively dry or overly moist can compromise the stability of soil structure and its nutrient retention capacity. Liu et al. (2021) indicated that the available water capacity (AWC) of peat increases with soil bulk density up to 0.2 g cm^{-3}, beyond which AWC notably declines [9]. Therefore, maintaining an optimal soil bulk density is essential to preserve AWC and promote plant growth. Additionally, effective water management markedly influences nutrient cycling and microbial activity, which are vital for maintaining nutrient availability and fostering plant growth [10]. Consequently, the objectives of this research are to assess the effects of land and water management on peat soil BD and subsidence in agricultural practices employing integrated water management. The findings aim to bridge the knowledge gap in peatland research and augment understanding of the advantages of water management application in peatland agriculture.

2. RESEARCH METHODS

2.1 Study Area

The study was carried out at a coconut plantation operating under a NES Scheme in Pulau Burung District, Indragiri Hilir Regency, Riau Province, in October 2022 (Figure 1). The plantation is positioned within the Sungai Gaung Sungai Kampar Peatland Hydrological Unit. The elevation of the plantation varies between 1.8 and 6.2 meters above sea level, and it experiences an average annual rainfall of 1875 mm, which follows a bimodal distribution with rainfall peaks in April and November. This plantation implements a closed-system integrated water management approach, involving primary, secondary, and tertiary canal systems to regulate the water table [7]. The canals also serve as the primary transportation routes within the plantation, facilitating the movement of harvested coconuts to processing facilities and supporting the mobility of people. Since the initiation of operations in 1986, these management systems have consistently maintained the water table at an average depth of approximately 40 cm to ensure adequate wetness levels in the peat soil.

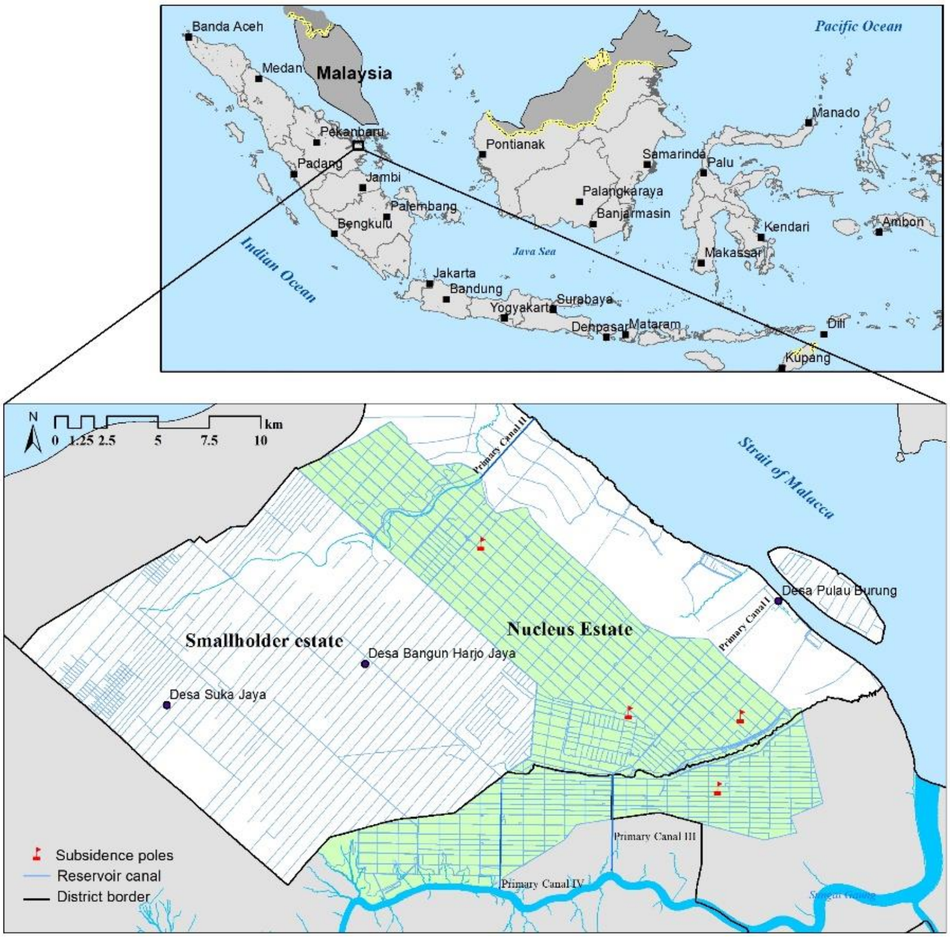

Figure 1. The map of study area

2.2 Data and Analysis

Peat soil samples were systematically collected from four distinct locations: two from a nucleus estate in planting blocks 09.08 and K3.01, and two from smallholder estates located in the villages of Suka Jaya and Bangun Harjo Jaya. These locations were selected because they all employ integrated water management systems, albeit with significant differences in agricultural practices. Specifically, the nucleus estate practices cover crop management as a strategy to maintain soil health and moisture, whereas the smallholder estates apply a combination of herbicide treatments and controlled burning to eradicate unwanted vegetation.

The soil sampling process utilized a ring sampler method, which was carefully connected to a PVC pipe to preserve the integrity of the soil structure during collection (Figure 2a). The soil was collected at six stratified depth intervals: 0-5 cm, 5-15 cm, 15-25 cm, 25-35 cm, 35-50 cm, and 50-70 cm. This structured approach allowed for a comprehensive soil profile from the surface to the deeper peat layers. In total, 24 soil samples were collected from these stratified depths across all four locations, with each specific depth sampled three times to ensure data reliability and reproducibility. Bulk density were quantitatively assessed using the gravimetric method. This involved measuring the dry weight of the soil, which was facilitated by a three-phase meter to ensure accurate and consistent results (Figure 2b). Additionally, the water table depths were precisely measured using a Dipwell instrument, providing critical data on the hydrological status of the peat soil at each site (Figure 2c). Furthermore, long-term subsidence data, which are important for understanding the changes within the peatlands, were obtained from the Sambu Group. These data have been systematically recorded since 1986 using subsidence poles strategically placed at each of the four locations.

(a) (b) (c)

Figure 2. (a) Peat soil sampling using a PVC pipe, (b) a three-phase meter, and (c) a dipwell instrument for measuring water table level.

3. RESULTS AND DISCUSSIONS

3.1 Agriculture Management Practices

Table 1 shows the differences in management practices within the NES Scheme. Peatland management significantly impacts the physical characteristics of peat soil due to agricultural activities. In the nucleus estate, management is directly overseen by the Sambu Group, which adheres to a standardized industrial management and complies with several certifications, including the Rainforest Alliance Certification, SEDEX Certification, and organic certifications from USDA Organic, EU Organic, and Ecocert. These practices incorporate cover crop management, which serves as a natural fertilizer for coconut trees by facilitating the nutrient cycling process. This method promotes the recycling of decomposed organic matter, enriching the soil with essential nutrients, and fostering a healthy ecosystem conducive to the growth of coconut trees. Ashton-Butt et al. (2018) found that enhancing understory vegetation can increase soil macrofauna diversity and maintain stable soil nutrient levels [11]. Additionally, the presence of tall trees in the nucleus plantation contributes to high productivity and optimal coconut yield.

In smallholder estates, management is less regulated compared to industrial plantations. Smallholder farmers, part of the Indonesian government's transmigration program, are allocated 2 hectares for coconut plantations and 0.5 hectares for their homes and gardens. The planting space in smallholder estates is larger compared to nucleus estates, resulting in lower coconut density as it is designed for intercropping, especially with pineapples. The demand for pineapples remains constant due to processing by the Sambu Group, providing farmers with an opportunity for additional income.

Table 1. Comparison of land management practices between nucleus and plasma coconut plantations

Parameter	Nucleus estate	Smallholder estate
Management	Directly managed by Sambu Group.	Managed by farmers from the transmigration program.
Agriculture practices	Implements cover crop management to enhance the nutrient cycling process.	Utilizes conventional methods involving herbicides and synthetic fertilizers, accompanied by controlled burning.

Coconut	PB 121	PB 121
Density	173 trees/ha	136 trees/ha
Planting year	1988	1995 – 1997
Fertilizer usage	Organic fertilizer (resulting from vegetation decomposition)	Ash from burned undergrowth vegetation and synthetic fertilizers
Productivity	2,000 - 4,000 coconut nuts per hectare per harvest.	1,500 – 3,000 coconut nuts per hectare per harvest.

However, these farmers often lack access to education on sustainable agriculture practices on peatland. This is exacerbated by their limited capital and input, as their remote location makes it difficult to manage their land effectively. Consequently, they resort to using herbicides to clear the land of cover crops by burning them, an efficient but environmentally harmful method. This practice renders the peat topsoil highly susceptible to burning, adversely affecting macro and micro fauna populations and disrupting long-term ecosystem functionality [12].

The application of cover crop management has a significant impact on soil nutrient availability over time [13]. This strategy is essential for maintaining soil fertility and retaining vital nutrients within the vegetation. In the Nucleus estate, cover crops, predominantly ferns of the *Nephrolepis* sp. species, are manually cut every four months and left to decompose naturally under the coconut trees. The decomposition of these cut cover crops releases nutrients into the soil, facilitating nutrient cycling and contributing to the growth and productivity of the coconut trees. Sumawinata et al. (2019) demonstrated that the nutrient cycling process significantly influences the growth and production of peatlands [14]. This underscores the importance of preserving vegetation through cutting rather than burning to ensure the health of the soil and the broader ecosystem.

In terms of coconut trees, specifically the PB 121 variety, the application of cover crop management that incorporates nutrient cycling processes helps maintain high productivity. However, productivity per coconut tree can vary between the Nucleus estate and smallholder estates, despite using the same coconut variety and a unified system of integrated water management, due to differences in management practices.

3.2 Water Management

Ochs et al. (1992) described the development of the "Water Management Trinity" (WMT), an integrated water management system designed with a hierarchical canal structure [15]. The system is supported by three primary components: canals, which serve as reservoirs, dikes, and dams with water gates. The primary canal, equipped with water gates at its terminus, serves as the central axis, controlling water levels and functioning both as a transportation route and an overflow reservoir. Perpendicular to the primary canal are secondary canals, which regulate water levels and maintain groundwater for plant root systems, encompassing planting blocks measuring 1000 x 500 meters. Tertiary canals run perpendicular to the secondary canals.

Dikes, constructed from excavated material during canal digging and sometimes reinforced with natural materials like soil, coconut shells, and coconut tree trunks, strengthen the banks of water bodies and provide stability. The water gates at the end of the primary canal manage the flow of water, ensuring a consistent water supply necessary for coconut production and maintaining ecological water balance in peatlands [6]. This water management strategy stabilizes groundwater levels year-round, preventing flooding during the rainy season and mitigating drought during prolonged dry spells. Figure 3 shows the average water table depth, which ranges from -51 to -45 cm below the surface.

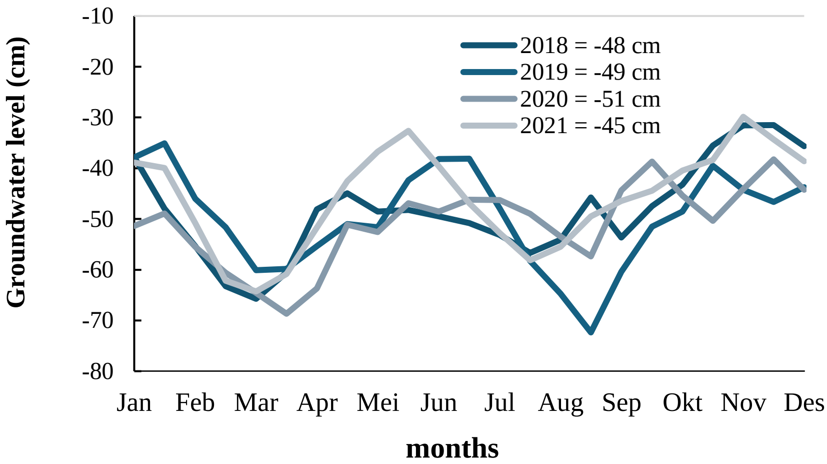

Figure 3. The graph of monthly average water table depth

3.3 Bulk Density

Table 2 presents the bulk density (BD) of peat soil at various depths within both nucleus and smallholder estates. In the nucleus estate, the BD ranges from 0.10 to 0.16 g/cm³, while in the smallholder estate, it varies between 0.10 to 0.18 g/cm³ across different depths. The data generally indicate a decrease in BD with increasing soil depth. This trend reflects the general characteristic of peat soil, where the surface layer is more sapric (well-decomposed) compared to the subsurface layer. This pattern is influenced by climate conditions and water table depth, which affect the decomposition rates of organic peat material.

This trend aligns with studies showing that peat soil BD decreases as depth increases, with the lowest values observed in the deepest layers [16]. Ochs et al. (1992) documented an initial BD of 0.072 g/cm³ at depths of 0-20 cm within plantation areas, suggesting that the BD has more than doubled since then [15]. This increase contributes to soil compaction and consolidation, indicating that the peat soil is in a sapric category or well-decomposed. This increase in BD leads to reduced soil porosity and permeability, which can impact agriculture management due to changes in water retention and root penetration. Despite these findings, the patterns of BD across different depths do not vary significantly between the nucleus and smallholder estates. However, at depths greater than 35 cm, the smallholder estate exhibits a higher BD. Understanding these changes is important for developing effective land management strategies to ensure sustainable agricultural practices on peatlands.

Table 2. Peat Soil Bulk Density at Different Depths in Nucleus and Plasma Plantations

Sampling Location		Depth (cm)	Bulk Density (g/cm³)
Nucleus Estate	Planting Block 09.08	0-5	0.16
		5-15	0.13
		15-25	0.12
		25-35	0.10
		35-50	0.13
		50-70	0.11
	Planting Block K3.01	0-5	0.19
		5-15	0.14
		15-25	0.14
		25-35	0.13
		35-50	0.11
		50-70	0.11
Smallholder Estate	Suka Jaya Village	0-5	0.17
		5-15	0.18
		15-25	0.13
		25-35	0.13
		35-50	0.15
		50-70	0.10
	Bangun Jaya Harjo Village	0-5	0.16
		5-15	0.13
		15-25	0.12
		25-35	0.12
		35-50	0.12
		50-70	0.10

3.4 Subsidence

The implementation of WMT in coconut agriculture contributes to the retention of moisture in peat soils and prevents drying. Table 3 shows subsidence monitoring data indicating a total subsidence of -56.3 cm from 1986 to 2022 (36 years), equivalent to an annual rate of -1.56 cm. With an average bulk density (BD) in the 0-5 cm layer of 0.17 g/cm³, the peat soil undergoes compaction and consolidation, resulting in a volume increase of 136%. This suggests that subsidence can occur rapidly when groundwater levels decrease due to peat consolidation or water extraction, rather than from carbon loss through decomposition [17].

This subsidence rate is lower compared to previous studies [18, 19], suggesting that the implementation of water management practices has helped mitigate subsidence. This is due to the swelling and shrinking process depending on the rate of decomposition and peat water content. Table 3 shows a slower progression of subsidence rates in recent years. Positive values in Table 3 represent an increase in peat subsidence, indicating further compaction and reduction in surface elevation. The findings also indicate that different management practices between nucleus and smallholder estates affect the surface condition of peat soil. Although there are no differences in BD, visible differences in the surface are evident. Recently, following interventions by IPB University and the Sambu Group, farmers have transitioned from conventional practices to cover crop management. This shift has shown productivity improvements compared to the outcomes under conventional management.

Table 3. Peat Soil Subsidence in PT RSUP's Nucleus Plantation at 10-Year Observation (2013-2022)

Year of Observation	Planting Year				Accumulated Subsidence	Average Subsidence
	1987	1988	1989	1990		
	----------------------------------(cm)---------------------------					(cm/year)
2013	-39,1	-40,8	-46,4	-40,6	-41,7	3,2
2014	-41,5	-43,8	-48,3	-42,8	-22,7	-2,4
2015	-44,7	-47,2	-51,9	-46,6	-24,3	-3,5
2016	-46,0	-48,8	-54,2	-49,5	-49,6	-2,0
2017	-46,0	-50,0	-54,5	-49,5	-50,0	-0,4
2018	-46,5	-50,0	-56,0	-49,5	-50,5	-0,5
2019	-51,0	-51,5	-62,0	-52,0	-54,1	-3,6
2020	-53,0	-51,5	-63,0	-53,0	-55,1	-1,0
2021	-55,0	-53,3	-65,0	-55,0	-57,1	-2,0
2022	-53,5	-52,0	-65,5	-54,3	-56,3	0,8

4. CONCLUSION

The implementation of integrated water management, as outlined in the Water Management Trinity, positively impacts the preservation of peat soil within coconut plantations. The bulk density (BD) has increased by 136% relative to the initial measurements in 1986, indicating that the peat soil has transformed into a well-decomposed (sapric) state and undergone significant compaction and consolidation. As a result, the subsidence rate has decreased to an annual rate of -1.56 cm, demonstrating a slowdown in progression. Additionally, the adoption of cover crop management has improved the soil nutrient cycling processes, maintaining optimal productivity for coconut cultivation. The combined application of integrated water management and cover crop management in coconut plantations demonstrates the potential for sustainable use of peatland, particularly in mitigating high subsidence rates that are a primary concern in peatland agriculture.

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