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Peat hydraulic properties along the gradient of oil palm ages in the tropical monsoon region

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ABSTRACT

The conversion of vast peatland areas to oil palm plantations in Indonesia may alter hydrological functions under long-term agricultural use. This study aimed to analyze the hydraulic properties of peat soil under oil palm (*Elaeis guineensis* Jacq.) plantations of varying ages (2–5, 6–9, and >10 years) in Ketapang, West Kalimantan, Indonesia, a region with a tropical monsoon climate. There are 27 samples gathered from 3 plantation ages in the 3 peat depths (0-20 cm, 20-40 cm, and 40-60 cm). Hydraulic properties: water holding capacity (WHC), bulk density, particle density, and porosity were analyzed using standard gravimetric, pycnometer, and oven-drying methods. Weather and environmental data from 2013–2022 were used to calculate reference evapotranspiration (ETo), crop evapotranspiration (ETc), and water balance. The results showed that hydraulic properties improved with soil depth and plantation age. WHC ranged from 400% to 850%, increasing significantly in mature plantations. Bulk density declined with depth and age, while porosity significantly increased and reached its maximum at 56.87% in older plantations. Although mature oil palms have high crop water demands (ETc), water availability remains sufficient to meet their needs. However, excess water must be properly managed to avoid reducing oil palm productivity and to preserve peat quality. These findings suggest that as oil palm matures, root development and organic residue accumulation enhance peat's hydrological properties. This study may contribute to understanding peatland behavior under oil palm cultivation and provide crucial insight for improving irrigation and land management practices in tropical peat ecosystems.

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1. INTRODUCTION

Indonesia has vast peatlands, spanning more than 14 million hectares across Sumatra, Kalimantan, and Papua (Osaki et al., 2016). Tropical peatlands are wetland ecosystems that store more than 30% of the soil carbon worldwide, even though they only account for 2%–3% of the soil carbon on the Earth's total surface (Page & Baird, 2016; Xu et al., 2018). These tropical peatlands, although often overlooked, are rich in organic carbon and serve a variety of purposes, including production, water storage, habitat for biodiversity, protection, and economics. It has undergone extensive alterations, primarily due to the rapid expansion of oil palm plantations, driven by both global demand and domestic economic incentives (Carlson et al., 2018; Suwondo et al., 2023).

In Indonesia, domed peatlands have developed naturally over thousands of years, accumulating a great amount of carbon stocks, accounting for more than 70% of the country's soil-based carbon (Page, 2024). Soil moisture content is the amount of water in decomposing organic matter and is expressed in percent (Nasution et al., 2023). However, peat's ability to store water reflects the amount of water the soil (in the root zone) can provide for the plant. Available water content controls plant growth and production and affects nutrient cycling and photosynthesis rates (Minasny & McBratney, 2018). The movement of water and moisture in

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the soil can be considered a function of gravimetric and isothermal conditions and is influenced by several soil properties, such as structure and porosity (Walczak et al., 2002).

Ketapang District, West Kalimantan, is one of Indonesia's largest oil palm-producing regions, with 490,739 hectares of plantations, representing 28% of West Kalimantan's total palm area (Rosyadi, 2023). Ketapang has undergone decades of transformation from secondary peat swamp forests to intensively managed monocultures since oil palm was first introduced there in the late 1970s. Its location within a tropical monsoon climate zone (characterized by distinct wet and dry seasons and influenced by ENSO and Dipole Mode variability) makes it a relevant setting for observing how peat responds hydrologically under prolonged cultivation (Hajrul et al., 2019). The conventional replanting practices and increasing land-use intensity in this region tend to make water management and conservation in this region a significant challenge.

An oil palm plantation will have different water and nutrient requirements throughout its life, which may change the physical state of the soil and its capacity to retain water around the root system. Earlier research has shown the importance of taking plantation longevity into account while managing peatlands. Firdaus (2012) observed a decline in porosity and a rise in bulk density in peatlands that had been planted with oil palm for over a decade. Megayanti et al. (2022) showed that developing oil palm roots also changes the soil structure and increases soil aeration and porosity in the long term. Furthermore, Nasution et al. (2023) demonstrated that bulk density, porosity, and moisture content are crucial factors that vary greatly throughout the plantation ages of oil plum trees.

From a hydrological point of view, peatlands are characterised by a saturated and oxygen-poor water regime. The pile of organic matter in anaerobic environments over thousands of years results in the creation of peat. Systemic drainage in aquaculture activities reduces groundwater levels, increases the oxidation rate, and triggers soil consolidation and subsidence (Hooijer et al., 2012; Menberu et al., 2021). Land function modification causes serious ecological harm, including reduced water storage capacity, heightened land fire danger, and significant greenhouse gas emissions from the aerobic breakdown of organic matter (Word et al., 2022). This hydrological influence directly impacts the soil's water balance and its capacity to retain moisture for plant growth.

The administration of peatland oil palm plantations faces complex challenges related to soil moisture dynamics and changes in soil physical structure. Young plantations, with their small canopies and shallow root systems, consume relatively little water, whereas mature and old plantations exhibit high evapotranspiration rates, which accelerate soil drying and increase the risk of water deficit (Röll et al., 2015). Drainage for maintaining land accessibility exacerbates these conditions, disrupts the water cycle, and accelerates peatland degradation (Barokah et al., 2024; Rahmawati et al., 2022; Word et al., 2022).

Hydraulic properties directly influence peat's ability to absorb, store, and transmit water (Walczak et al., 2002). The hydrological behavior of peat is very dependent on its physical properties, particularly bulk density, porosity, and pore structure, which will affect its water retention and transmission capabilities. Walczak et al. (2002) reported that any significant change in organic matter content will change the characteristics of peat's hydraulics, with higher organic content decreasing bulk density and increasing porosity and microporosity, which are the key determinants of water-holding capacity. That will directly impact the availability of water for plants and the movement of moisture across soil layers, particularly in fluctuating hydrological conditions such as those found in tropical monsoon climates.

Few studies on peatland with palm oil cultivation have directly investigated how peat's hydraulic properties (such as water retention, bulk density, particle density, and porosity) change with plantation age. Studies have shown that oil palm root systems will deepen and expand with age, influencing soil porosity and bulk density (Pérez-Sato et al., 2023; Röll et al., 2015). Firdaus (2012) and Megayanti et al. (2022) reported that long-term cultivation results in both compaction and pore formation, depending on the depth and rate of organic matter decomposition. However, most existing research focuses only on surface layers (Maysarah et al., 2021; Suryadi et al., 2021), with less focus on the vertical distribution of hydraulic functions across peat depth profiles. This has left a critical knowledge gap, particularly in understanding how the hydrophysical structure of peat changes as a response to root compaction, development, and organic matter decomposition. So, this study aims to analyze how peat hydraulic properties (water holding capacity, bulk density, particle density, and porosity) respond to variations in oil palm age and soil depth under tropical monsoon conditions. The findings are expected to support the optimal water and soil management practices based on the oil palm age for maintaining hydrological balance and long-term productivity in peat-based agroecosystems.

2. MATERIAL AND METHODS

2.1. Research location

The research site was located at Ketapang Regency, West Kalimantan, Indonesia (Fig. 1). Ketapang was selected as a location for research due to it has large peatland area that was converted into a palm oil plantation and reflects the general conditions of tropical monsoon peat ecosystems in Indonesia. The research was conducted from September to October 2024, coinciding with the transition season to allow for optimal soil moisture measurement. The analysis of soil hydraulic properties was carried out in the soil laboratory at the STIPER Agricultural Institute (INSTIPER). Ketapang District is a region with a tropical monsoon climate, influenced by both the Australian monsoon and the Asian monsoon. Based on the findings of Setia Budi et al. (2023), using data from 2003–2012, Ketapang has a unimodal precipitation pattern with two peak rainfall months: April (influenced by the Australian monsoon) and November (influenced by the Asian monsoon).

2.1.1. Precipitation

In Figure 2, the precipitation pattern in Ketapang still follows a unimodal trend, but there is a slight shift in the peak

Figure 1. Research location (Ketapang Regency, West Kalimantan Province, Indonesia)

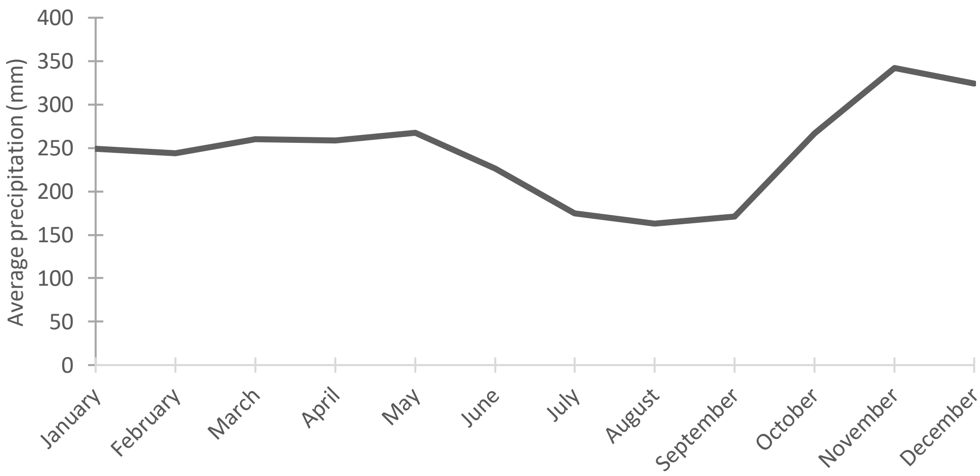

Figure 2. Average monthly precipitation in the research site from 2013-2023

rainy season. The peak associated with the Australian monsoon appears to shift from April to May. In contrast, the November peak remains consistent, with November and December showing the highest monthly rainfall over the 10-year period. Additionally, June to September consistently shows the lowest precipitation, confirming the dry season period in the area. This supports the monsoonal rainfall influence and helps explain seasonal variation in soil moisture and water availability relevant to the study.

2.1.2. Air temperature and humidity

Figure 3 shows the average monthly minimum and maximum temperatures in the research site from 2013 to 2022. The temperature in this region remains relatively stable throughout the year, which is typical for tropical monsoon climates. The maximum temperature (T_{max}) consistently ranges between 29–33°C with an average of 31.95°C, while the minimum temperature (T_{min}) fluctuates slightly around 21–24°C with an average of 23.825°C. The hottest period occurs in May, coinciding with the transition between monsoon systems. A noticeable drop in both T_{min} and T_{max} is seen in October (29°C for T_{max} and 21.7°C for T_{min}), which is also a period of low rainfall, possibly influenced by changes in cloud cover and solar radiation.

Figure 4 shows the average monthly humidity in the research site. Humidity remains high throughout the year, ranging from 75% to 85%, with the lowest value in October at 75%. The highest humidity levels are recorded in November and December, possibly due to the increase in rainfall intensity during the late monsoon season. These high-humidity conditions are typical for tropical peatland regions and play a role in regulating evapotranspiration and soil moisture retention.

2.1.3. Oil palm performance

Figure 5 shows oil palm trees of different age classes observed at the research site. In Figure 5a, oil palms aged 2–5 years, or classified as immature, are in a rapid vegetative growth phase, characterized by relatively short fronds. The spacing between trees remains wide, so the shading and organic matter accumulation on the soil surface is categorized as low.

Oil palm trees 6–9 years (Fig. 5b) showed an early productive stage, we can see the tree's canopy is getting wider and usually in this stage, it already starts yielding fruit. In the > 10-year-old plantations (Fig. 5c), palms are fully mature with tall trunks, dense canopies, and accumulated frond bases, significantly influencing ground shading and under-canopy microclimate.

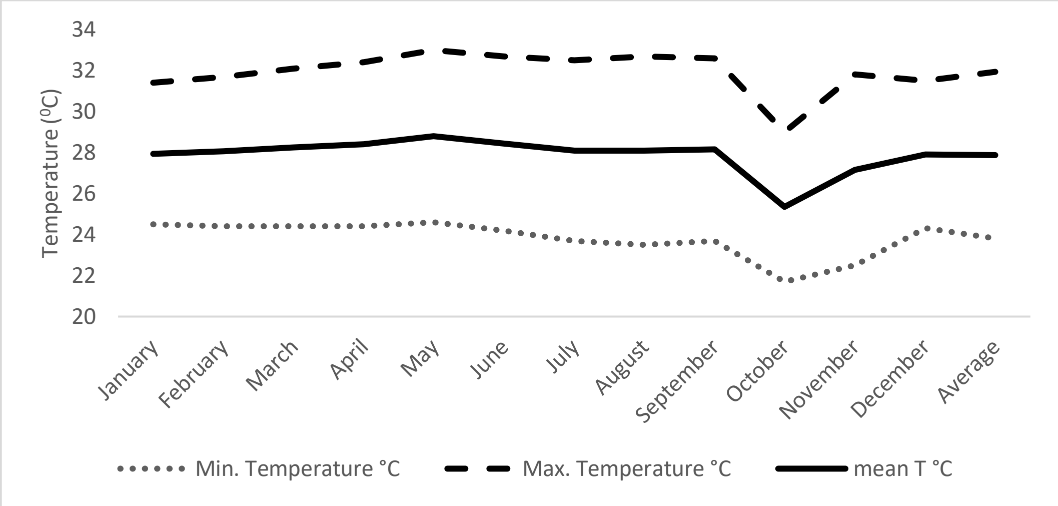

Figure 3. Average monthly minimum and maximum temperatures at the research site from 2013 to 2022

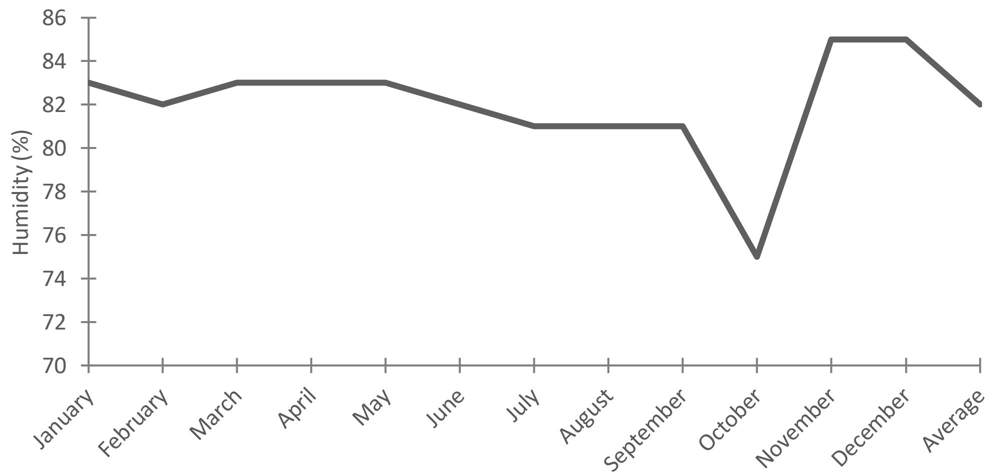

Figure 4. Average monthly humidity in the research site from 2013-2022

These characteristics (such as canopy size, frond density, and root development) of the oil palm at different stages need to be studied, as they are expected to influence soil compaction, surface organic matter accumulation, and evapotranspiration, all of which affect the hydraulic behaviour of peat soils. Corley and Tinker (2015) study has noted that oil palm root systems deepen and expand with age, so there is a huge change in modifying peat porosity and water retention properties.

2.2. Research design and sampling technique

The research design was a descriptive quantitative approach with a field survey method for soil sampling. The observation units were divided into three groups in accordance with the age of the oil palm plantations: young (ages 2–5 years), mature (ages 6–9 years), and elderly (ages >10 years). For each age group, three representative blocks were chosen for replication. Sampling in each block was carried out with three soil layer depths, namely, 0–20, 20–40, and 40–60 cm. Thus, the total number of samples obtained was 27 soil samples (3 ages × 3 blocks × 3 depths). Purposive random sampling based on the requirements of uniform land cover, flat terrain, and low levels of disturbance was adopted. Soil samples were taken using a 5 cm diameter cylindrical peat drill to maintain the integrity of the vertical soil structure (Menberu et al., 2021).

Four primary parameters of soil hydraulic properties (maximum water content, bulk density, particle density, and total porosity) representing the physical and hydrological characteristics of peat soil were the focus of the laboratory analysis. Soil water content was ascertained using the oven method at 105 °C for 24 hours in accordance with ASTM D2216-19 standard procedure. Bulk density was computed from the ratio of dry soil mass to cylinder volume. Particle density was measured using the pycnometer method. Total porosity was determined from the ratio between bulk density and particle density using the porosity formula = [1 – (BD/PD)] × 100% (Firdaus, 2012; Xu et al., 2018).

2.3. Data analysis

Mean and standard deviation were calculated for each hydraulic parameter (water holding capacity, bulk density, particle density, and porosity) across plantation age and soil depth. One-way analysis of variance (ANOVA) was performed to determine the significance of differences between age groups and depth layers at a 95% confidence level (α = 0.05). Post-hoc tests (LSD) were applied to compare means where significant effects were found. The statistical software used for analysis was SPSS version 26.0.

Figure 5. Oil palm group ages (a) 2-5 years; (b) age 6-9 years; and (c) >10 years on the research

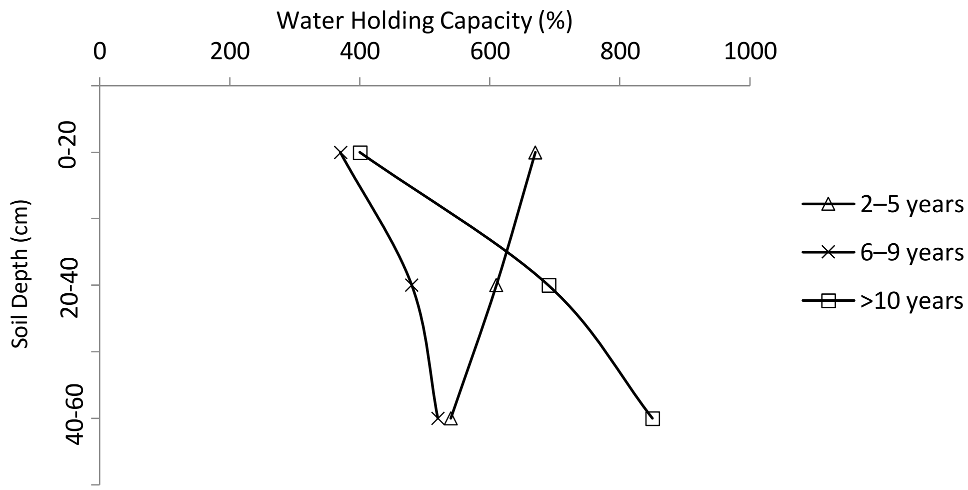

Figure 6. Water Holding Capacity profile in peat soil at various depths and oil palm ages

We also analyzed the environmental conditions, which were then used to calculate ET_o, ET_c, and the water balance. This was aimed at gaining a better understanding of the actual changes occurring in the hydraulic properties of the peat soil itself. To calculate ET_0, the FAO Penman–Monteith method was used, based on average monthly climate data from 2013 to 2022 (Eq. 1). The equation used is as follows:

$$ETo = \frac{0.408\Delta(R_n)+\gamma\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.34u_2)} \text{ .... [1]}$$

Where T: Mean air temperature = $(T_{max} + T_{min})/2$; u_2: Wind speed at 2 meters ($m.s^{-1}$); Δ: Slope of vapor pressure curve ($kPa.°C^{-1}$), calculated from T; e_s : Saturation vapor pressure (kPa), from T_{max} and T_{min}; e_a: Actual vapor pressure (kPa), calculated using RH and es; γ: Psychrometric constant ($kPa.°C^{-1}$); assume standard pressure = 101.3 kPa → γ ≈ 0.0673; Rn: Net radiation, simplified as Rn=(1−α)·Rs ; α=0.23

Crop evapotranspiration (ETc) was calculated using Equation 2, where ETc represents the evapotranspiration of oil palm (*Elaeis guineensis* Jacq.) and Eto denotes the reference evapotranspiration. The crop coefficient (Kc) was applied according to plant age: 0.82 for 2–5 years, 0.92 for 6–9 years, and 0.93 for plants older than 10 years (Harahap & Darmosarkoro, 1999). Following the estimation of ETc, water surplus was determined using the equation: Water surplus (mm) = Effective precipitation (Pe) − ETc, in which Pe was calculated using the FAO standard method.

$$ETc = Kc \times ETo \text{ ....[2]}$$

Table 1. Bulk density, particle density and porosity at various depths and oil palm ages

Depth / Properties	0-20 cm			20-40 cm			40-60 cm		
	Age (years)								
	2-5	6-9	>10	2-5	6-9	>10	2-5	6-9	>10
Bulk Density (g cm^{-3})	0.236^{ab}	0.227^{ab}	0.218^{b}	0.274^{a}	0.253^{ab}	0.209^{b}	0.266^{a}	0.258^{ab}	0.217^{b}
Particle Density (g cm^{-3})	0.427^{b}	0.413^{bc}	0.429^{b}	0.519^{ab}	0.459^{b}	0.382^{c}	0.547^{a}	0.518^{ab}	0.503^{ab}
Porosity (%)	44.68^{c}	45.10^{c}	49.22^{b}	47.24^{bc}	44.9^{c}	45.28^{c}	51.34^{b}	50.21^{b}	56.87^{a}

Note: Numbers followed by different letters on the same line are significantly different at the 5% level.

3. RESULTS

3.1. Water holding capacity, bulk density, particle density, and porosity of oil palm at different depths

Figure 6 shows water holding capacity (WHC) in the study site at different ages and soil depths. WHC in oil palm ages 2-5 years decreased relatively with soil depth, starting from 670% at a 0-20 cm depth, declining to 610% at a 20-40 cm depth, and 540% at a 40-60 cm depth. For the plantation ages 6-9 years, a different pattern is shown, which tends to increase with the soil depth. The WHC for 0-20 cm depth noted in 370%, increases to 480% in 20-40 cm depth, and increases again to 520% at 40-60 cm depth. Lastly, WHC in the oil palm ages >10 years shows significantly increased values, from the lower to deeper soil depth, starting from 400% at 0-20 cm depth, followed by 690% at 20-40 cm depth and 850% at 40-60cm depth. So, with the increase of oil palm ages and depth, the WHC value is getting bigger. If the WHC graph is looked at by the age of the oil palm plantation, it starts with a high remark in the young stage (2-5 years), declines at the early-mature stage (6-9 years), and increases significantly at the mature stage (>10 years).

The peat's bulk density, particle density, and porosity at different depths and oil palm age stages are shown in Table 1. In the 0–20 cm soil depth, bulk density value decreased with the ages of the oil palm, highest at the ages 2-5 years with a value of 0.236 g cm^{-3}, followed by 0.227 g cm^{-3} at 6-9 years, and lowest at >10 years with a value of 0.218 g cm^{-3}. This pattern was also applied at the 20–40 cm depth, bulk density varied from 0.209 to 0.274 g cm^{-3}, with the highest value observed in the 2–5 years group and the lowest found again in the >10 years group. A similar pattern was also seen in the 40–60 cm layer, where bulk density reached its lowest value of 0.217 g cm^{-3} in the >10 years group, and the highest (0.266 g cm^{-3}) in the 2–5 years group.

For particle density, the oil palm with early stages/young plantation (2-5 years) was set at the highest value in every soil depth, 0.427 g cm^{-3} for 0-20 cm, 0.519 for 20-40 cm, and 0.547 for 40-60 cm. Regarding the ages, at 0-20 cm depth, the particle density tends to look stable and does not significantly change over time, 0.427 g cm^{-3} at ages 2-5 years, followed by 0.413 g cm^{-3} and 0.429 g cm^{-3} at ages >10 years. The second depth (20-40 cm) shows a significant decline from the young stage group to the mature group. Different patterns are shown by the 40-60 depth, decreased slightly with age, starting from 0.547 g cm^{-3} at ages 2-5 years to the point 0.503 g cm^{-3} at ages >10 years. Generally, particle density tended to increase with the increase in oil palm age.

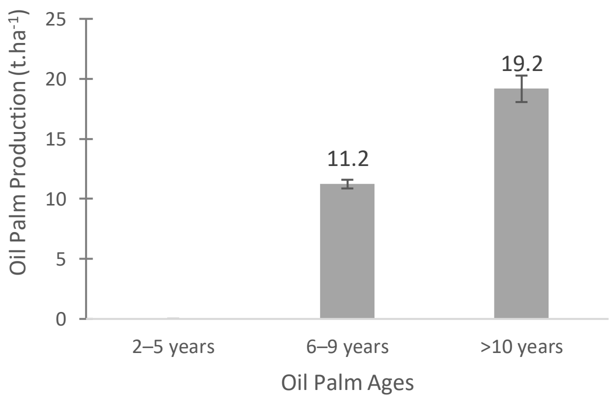

Figure 7. Average oil palm production at different age stages

Regarding porosity, an increasing trend with depth and plantation age is observed. At 0–20 cm, porosity ranged from 44.68% to 49.22%, while in the 40–60 cm layer, it increased significantly, reaching up to 56.87% under >10-year-old palms. This pattern suggests that older plantations and deeper peat layers tend to have higher porosity. Overall, the data indicate that peat's physical properties are influenced by both soil depth and plantation age, where older plantations tend to have lower bulk density and higher porosity.

3.2. Oil palm productivity

The oil palm plantation is at the age of 2-5 years (immature), so there is no yield record yet (Fig. 7). This is because the oil palm was still in the vegetative stage. The plant starts to record yield at 6-9 years old plantation with an average yield of 11.23 t ha^{-1} and increases to 19.17 t ha^{-1} at >10 years old plantation.

3.3. Oil palm evapotranspiration (ETc) at various ages

Figure 8 shows monthly oil palm evapotranspiration (ETc) at various ages, reference evapotranspiration (ETo), and effective precipitation. The climatic information used as an analyzed instrument was from 2013-2023. The ETo pattern is very similar to the ETc pattern of all the oil palm age stages; the difference is in their value. Oil palm aged 2-5 years has the lowest ETc value, followed by 6-9 years, and the highest is found at age >10 years. The highest ETo occurred in September at 114 mm, we can say this is the driest day, and the lowest 94.2 mm occurred in October, when the wet season is at its peak.

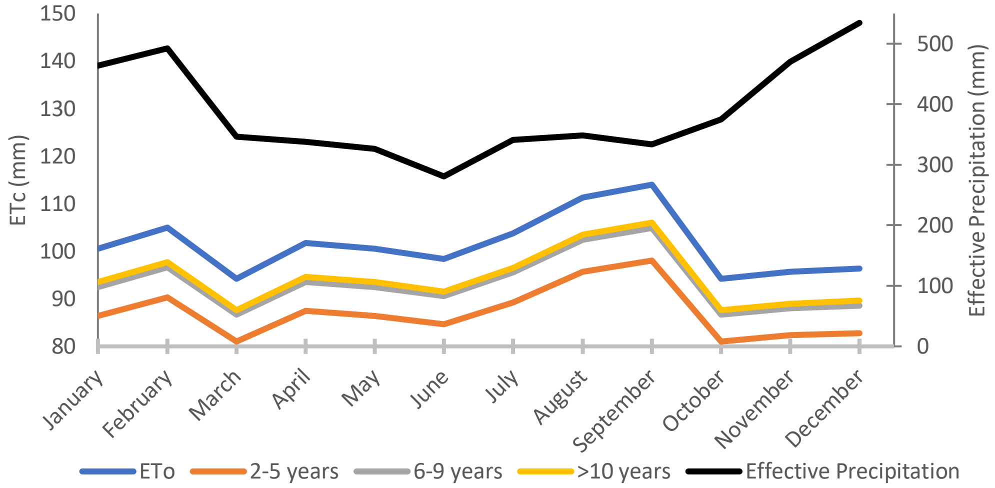

Figure 8. Oil palm evapotranspiration (ETc) at various ages in 2023 using climatic information of 2013-2023

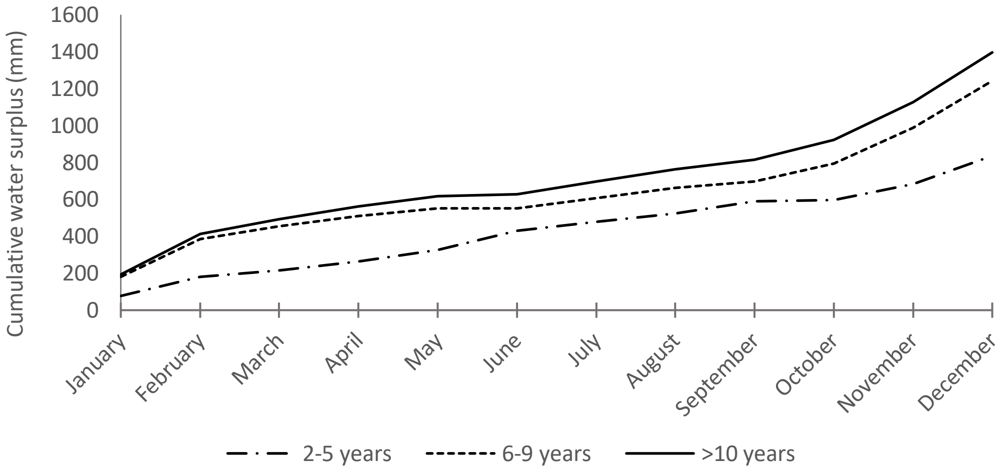

Figure 9. Cumulative water surplus under various oil palm ages in 2023 using climatic information of 2013-2023

Meanwhile, the pattern is different for effective precipitation (EP). The lowest EP occurred in June at 281 mm, and higher PE occurred from October to December, with the highest in December at 535 mm. The gap between effective precipitation and ETc is smallest in the dry months and widest in the wetter months. There is no water deficit in August and September (dry months) because effective precipitation still meets the ETc requirements, but both are at their lowest points of the year.

3.4. Water balance surplus on oil palm ages

Figure 9 shows the cumulative monthly water surplus throughout the year based on oil palm ages. The data were derived from the difference between effective precipitation and ETc using climatic records from 2013–2023. Water surplus increases progressively from January to December at all oil palm age stages. Oil palm aged 2–4 years has the lowest surplus, followed by 5–9 years, and the highest surplus was found in oil palm aged > 10 years. Although the pattern for all age stages is similar, the gap between them becomes more visible in the second half of the year. The water surplus gradually increases from January to August and starts to increase greatly from October to December. All age stages have the highest water surplus in December, 836 mm for age 2-5 years, 1,242 mm for age 6-9 years, and 1,396 mm for ages >10 years.

4. DISCUSSION

In monsoon climate regions with peat-based soils, ensuring oil palm plantation productivity, sustainability, and the preservation of soil conditions requires appropriate and optimal management. One key aspect is proper water management, as water can be considered one of the most essential factors for plant growth, for vegetative and productivity matters (Afandi et al., 2022). By studying the hydraulic properties of peat, namely water holding capacity, bulk density, particle density, and porosity, we can determine the most effective ways to manage water in oil palm plantations.

Based on the results presented in Figure 6 and Table 1, it is evident that both plant age and soil depth influence hydraulic properties. The deeper the soil and the older the oil palm, the better the hydraulic properties become. These findings support the observation that peat soils in the study area have strong water retention capabilities, especially at greater depths (40–60 cm) and under older oil palms (>10 years), as reflected in the WHC graph (Fig. 6). This finding is similar with the report of (Abd. Rashid, 2019), which states that soil bulk density decreased with increasing age of oil palm tree, but vice versa for total porosity. Tao et al. (2023) findings also support this statement, where their research shows that larger root diameters in older palms correlate with higher hydraulic conductivity. Implies that older palms have more effective water uptake systems, reflecting improved soil–plant hydraulic integration with age.

In oil palms aged >10 years, the WHC rises consistently—from around 400% in the 0-20 cm depth, to 680% in the 20-40 cm depth, and reaching approximately 850% in the 40-60 cm depth. However, this upward pattern is only seen between ages 6–9 and >10 years. In contrast, the younger age group (2–5 years) shows a consistent decline in WHC with depth, from 670% at 0–20 cm to 540% at 40–60 cm. This may happen due to the natural WHC of peat, as we already know, which has a large WHC of over 500%, influencing soil water retention characteristics at different depths and stages of oil palm development. The organic matter content and soil structure changes with palm age and soil depth contribute to this variation in WHC (Safitri et al., 2018). The younger oil palm group (2-5 years) has not yet developed a great root system, so biological activity in the deeper rhizosphere layer is still limited, and its original hydraulic properties are still maintained. The limited biological activity in younger compared to the mature oil palm was also reported by Melling et al. (2014) and Hergoualc'h et al. (2017), who observed the soil CO_2 activity from oil palm of different ages in peatland.

In contrast to the WHC value in the mature stage, a noticeable decrease is observed in the 6–9-year age group. This may reflect a transitional phase, during which the root system development, organic residue accumulation, and the coverage from the fronds and leaves, begin to change the peat's structure. During this adjustment period, there is supposed to be an increase in soil compaction and a reduction in soil porosity due to densifying roots (Nasution et al., 2023), which will reduce the peat's holding capacity temporarily.

When the oil palm reaches mature age (>10 years), WHC increases again significantly, from 400% at the lowest (0-20 cm) layer to 850% at the deepest (40-60 cm) layer of peat. This indicates that there were some changes in structural and physical properties. From the results, a change is suspected to have occurred due to root systems and surface vegetation development, which has a positive effect on the peat's hydraulic properties over time. The dense canopy, stable litter layer, and deep root penetration likely contribute to improved porosity and organic matter incorporation, enhancing the peat's ability to store and retain water effectively. Utami et al. (2021) reported strong correlations between litter thickness, coarse root mass, and macroporosity, while Cannavo et al. (2011) demonstrated experimentally that root development in peat substrates has consequences for the modification of the total porosity of growing media, pore size distribution, and pore connectivity. The increase in porosity (the lowest 44.7% at 2-5 years in the 0-20 cm depth and gradually increase with age and depth to the highest 56.9% at >10 years in the 40-60 cm dept) and the decrease in bulk density (especially compared to younger plantations) are also contributing factors to the improved peat's hydraulic properties.

These favourable hydraulic properties help the plant retain water in the root zone and reduce the risk of water deficiency during dry periods. This is clearly illustrated in Figures 8 and 9, where, even during the driest months (August and September), the water surplus continues to increase. Interestingly, this applies to all observed plant age groups, including oil palms aged >10 years, which, according to ETc data, have the highest water demand. Mathematically, this group should have the lowest water surplus; yet the findings show it has the highest surplus, reaching its peak at the end of the year with approximately 1,396 mm in December. Under certain conditions, the existence of water surplus can be beneficial to the oil palm, especially in the dry season, by providing a buffer against future water deficits, but when surplus water exceeds the soil's infiltration capacity, it can lead to surface ponding or waterlogging. Henson and Mohd Tayeb (2004) emphasized that although oil palms are adapted to high rainfall environments, they are sensitive to extended periods of root zone saturation. Therefore, water surplus stored in a reservoir or other water-saving instrument can effectively offset dry-season deficits (Sutikno et al., 2023) or prevent the soil from degradation.

This suggests that the plant root system actively influences and improves the hydraulic properties of peat soil as the plantation matures. Although many reports conclude that the conversion of peatland into an oil palm plantation results in an increase in bulk density and a lowering of porosity (Guillaume et al., 2016; Kunarso et al., 2022; Pérez-Sato et al., 2023), over time, this condition can be improved due to the optimal activity of the rhizosphere. Moreover, root-mediated increases in soil organic carbon and microbial activity can further improve rhizosphere porosity and hydraulic retention in peat substrates (Batista et al., 2024). Old roots can create small channels and pathways in the soil, which may increase porosity and improve water movement. These claims are similar to Bodner et al. (2014), who report that Coarse root systems increased macroporosity by 30 %. Martinez et al. (2021) also reported that tree roots can modify soil structure (porosity and permeability). These biological activities also tend to contribute organic matter that helps hold water and support microbial life. In this way, the physical changes in the soil are not only a result of age but also a result of the plant's interaction with its growing environment.

These results are consistent with several previous studies that found long-term cultivation of oil palm could change the hydraulic behaviour of soil. For instance, increased porosity and better water retention were reported under mature plantations due to deeper rooting and organic residue accumulation (Utami et al., 2021). Tinuntun et al. (2025) found similar results where soil organic carbon and porosity improve under certain textures and biological conditions. Ratai et al. (2024) also found that the second generation of oil palm plantations has a higher humification degree compared to the forest area and the first generation of oil palm plantations.

Oil palm production increases in line with the trees' physiological age, from 0 t ha^{-1} in young plantations (2–5 years), to 11.23 t ha^{-1} in young mature plantations (6–9 years), and reaching 19.17 t ha^{-1} in mature plantations (>10 years). This trend reflects that plantation conditions are sufficiently meeting the crop's growth requirements, indicating the absence of limiting factors that could cause yield anomalies. A similar pattern was also reported by Gromikora et al. (2015), whose study observed an increase in oil palm productivity consistent with the findings of this research.

In tropical peatlands, such changes become even more important because of the natural waterlogging risk. Therefore, understanding how oil palm age affects the hydraulic properties of peat soils is important not just for productivity but also for land management in peat areas. These findings also reinforce the idea that mature plantations play an active role in shaping the condition of their own rooting medium. The implications of these findings can be useful for future peatland management strategies. In areas where irrigation or water control is planned, knowing the pattern of water surplus and soil hydraulic response may help reduce excessive drainage or overwatering. Planting distance, timing of fertilizer or compost application, and even decisions about replanting may need to consider how root age interacts with soil water movement. Although this study does not yet look at root biomass or root-soil interaction in detail, it can be used as a base for further research in this field. More in-depth measurements, such as infiltration rate, soil moisture fluctuation, or soil biological activity, might be useful in the next study.

5. CONCLUSION

The peat hydraulic properties of the oil palm plantation, the tropical monsoon, are affected by soil depth and the age of the oil palm, which significantly influence water holding capacity, porosity, and bulk density. Mature oil palm plantations (>10 years) show improvement in hydraulic properties, with consistently higher water holding capacity and porosity, especially in deeper peat layers (40–60 cm). This improvement appears due to root development, canopy closure, and organic residue accumulation, which contribute to the structural enhancement of peat soils over time. The improved peat hydraulic properties can buffer the land event in the driest months with sufficient water availability. That makes the productivity of oil palm still follow its potential and physiological cycle. These insights are crucial for peatland management, particularly in guiding irrigation strategies, replanting decisions, and efforts to reduce degradation. Future studies are encouraged to explore root–soil interactions in more detail, including root biomass quantification, infiltration dynamics, and microbial contributions, to maintain and optimize the productivity of oil palm and reduce the peatland negative effects due to the conversion.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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