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Dynamics of carbon stock and normalized difference vegetation index as indicators of oil palm (*Elaeis guineensis* Jacq.) productivity in peat ecosystem with compound NPK fertilizer application

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ABSTRACT

This study investigated the dynamics of carbon stock and normalized difference vegetation index (NDVI) as indicators of oil palm (*Elaeis guineensis* Jacq.) productivity in peat ecosystems under varying applications of compound NPK fertilizer. Research was conducted in Benteng Hulu Village, Mempura District, Siak Regency, Riau Province, Indonesia, from March 2023 to April 2024 using mature oil palm plants (10–12 years old) grown on different peat depths. A nested plot design was employed with three peat depth categories (shallow: 1–2 m, moderate: 2–3 m, and deep: > 3 m) as main plots and five Compound NPK fertilizer treatments (T0: control, T1: 75%, T2: 100%, T3: 125%, and T4: 150% of recommended dose) as subplots. Results demonstrated significant stratification in carbon stocks across peat depths, with deep peat consistently maintaining higher carbon storage (564–597 Mg C ha^{-1}) compared to moderate (485–523 Mg C ha^{-1}) and shallow peat (421–452 Mg C ha^{-1}). UAV-derived NDVI values and fresh fruit bunch (FFB) yields showed optimum responses at T3 treatment (125% of recommended dose), with shallow peat consistently outperforming deeper categories. Strong positive correlations were observed between NDVI and FFB yield ($r = 0.83$-0.87) across all peat depths, while water table depth exhibited strong negative correlations with carbon stock ($r = -0.72$ to -0.83). These findings indicate that moderate fertilization intensity (100-125% of recommended rates) optimizes the balance between carbon storage, vegetation health, and agricultural productivity in tropical peatland oil palm systems, supporting sustainable intensification approaches that simultaneously address climate mitigation and food security goals.

Keywords: carbon sequestration, *Elaeis guineensis*, fertilizer, tropical peatland management.

INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) cultivation on peatlands represents a significant agricultural practice in tropical regions, particularly in Southeast Asia. However, the management of oil palm plantations on peat soils presents unique challenges related to carbon dynamics, environmental sustainability, and crop productivity. Peatlands are vital carbon reservoirs, storing approximately 30% of global soil carbon despite covering only 3% of the Earth's land surface (Ribeiro et al., 2021). The conversion of peatlands for agricultural purposes, including oil palm cultivation, has raised concerns regarding carbon emissions, subsidence, and ecosystem degradation (Mishra et al., 2021). The intricate relationship between peat ecosystem management and oil palm productivity necessitates comprehensive monitoring approaches. In recent years, remote sensing techniques, particularly the normalized difference vegetation index (NDVI), have emerged as valuable tools for assessing vegetation health, biomass accumulation, and, by extension, plantation productivity (Huang et al., 2022). NDVI values derived from multispectral imagery provide critical insights into photosynthetic activity and vegetative vigor, serving as proxies for crop health and potential yield (Anees et al., 2024). Furthermore, understanding carbon stock dynamics in managed peat ecosystems is essential for developing sustainable agricultural practices that minimize environmental impacts while maintaining economic viability (Tanneberger, et al., 2022).

Fertilization strategies represent a crucial aspect of peat management for oil palm cultivation, influencing both productivity parameters and carbon dynamics. Compound NPK fertilizer, a specialized formulation designed for oil palm cultivation on peat soils, has been investigated for its potential to optimize nutrient availability while mitigating environmental impacts (Arifin et al., 2025). However, the complex interactions between fertilizer application, carbon sequestration, and vegetation indices in peat-based oil palm systems remain inadequately understood, highlighting a significant knowledge gap in sustainable peatland management (Oktarita et al., 2017). Despite advances in peatland agricultural research, limited studies have examined the integrated relationships between carbon stocks, NDVI metrics, and oil palm productivity within the context of specialized fertilization regimes on peat soils (Jurasinski et al., 2020). The quantification of these relationships could provide valuable insights for developing management strategies that balance ecological sustainability with agricultural productivity (Khasanah et al., 2020). Additionally, establishing reliable indicators for monitoring both environmental impacts and crop performance would enable more effective decision-making processes for stakeholders in the oil palm industry (Wong et al., 2023).

This study aims to investigate the dynamics of carbon stock and NDVI as indicators of oil palm productivity in peat ecosystems under compound NPK fertilizer application. By exploring these relationships, the research seeks to contribute to the development of sustainable management practices for oil palm cultivation on peatlands, addressing both environmental concerns and productivity requirements in this crucial agricultural sector (Awang et al., 2021).

MATERIALS AND METHODS

Study site

This study was conducted in an established oil palm plantation located on a tropical peat ecosystem in Benteng Hulu Village, Mempura District, Siak Regency, Riau Province, Indonesia (coordinates: 0°45′3.600″N 102°4′1.200″E), from March 2023 to April 2024. The experimental site comprised mature oil palm plants (10–12 years old) grown on deep peat soil (> 3 m depth) with varying decomposition levels classified according to von Post scale. The area experiences a tropical climate with annual rainfall ranging from 2.500–3.000 mm, relative humidity of 80–90%, and average temperatures between 25–32 °C. Prior to the study, the plantation had been managed using standard industrial practices with conventional fertilizer applications.

Experimental design

A nested plot design was employed to efficiently assess the effects of multiple experimental factors while accounting for spatial heterogeneity in the peat ecosystem. The experimental layout is illustrated in Figure 1, showing the spatial arrangement of experimental plots across the research site. The main plots consisted of three different peat depth categories: shallow (1–2 m), moderate (2–3 m), and deep (> 3 m), which were selected based on comprehensive peat depth surveys conducted using a Russian peat auger at 50 m intervals across the study area prior to the experiment. Each peat depth category was verified at a minimum of 20 points to ensure proper classification.

Within each main plot, subplots were established with five Mahkota fertilizer treatments: T0 (control, no fertilizer), T1 (75% of recommended dose), T2 (100% of recommended dose), T3 (125% of recommended dose), and T4 (150% of recommended dose). Each treatment combination was replicated four times following a systematically randomized distribution pattern, resulting in a total of 60 experimental units (3 peat depths × 5 fertilizer treatments × 4 replications). Each experimental unit consisted of 16 palms (4 × 4) with a palm density of 143 palms ha^{-1} (8.5 m triangular spacing), with measurements taken from the central 4 palms to minimize edge effects.

The recommended dose (T2) consisted of 4.5 kg $palm^{-1}$ $year^{-1}$ of compound NPK fertilizer (Mahkota brand, PT. Sentana Adidaya Pratama, Indonesia), formulated specifically for oil palm cultivation on peat soils with the following guaranteed composition: 12% N, 12% P_2O_5, 17% K_2O, 2% MgO, 0.5% CaO, and trace elements (B, Cu, Zn, Mn). Fertilizer was applied in three equal split applications (March, July, and November 2023) distributed evenly within a 2-meter radius from the palm trunk and incorporated into the top 5 cm of soil using manual rakes.

Soil physical and chemical analysis

Comprehensive soil physical and chemical analyses were conducted quarterly throughout the study period. Soil pH was measured in a 1:5 soil suspension using a calibrated pH meter (Mettler Toledo SevenCompact, Switzerland) equipped with a glass electrode. Redox potential was measured in situ using platinum electrodes inserted at three depths (10, 30, and 60 cm) with measurements taken after stabilization (approximately 30 minutes) and corrected for standard hydrogen electrode potential.

Cation exchange capacity (CEC) was determined using the ammonium acetate method (pH 7), with exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, Na^+) quantified using atomic absorption spectrophotometry (Analytik Jena ContrAA 800, Germany). Available phosphorus was determined using the Bray-2 method for acidic soils, with phosphorus concentration measured colorimetrically using the molybdenum blue method on a UV-VIS spectrophotometer (Shimadzu UV-1800, Japan). Total nitrogen was determined using the Kjeldahl method, involving sample digestion, distillation, and titration procedures.

Peat moisture content was monitored using time-domain reflectometry sensors (TRIME-PICO, IMKO GmbH, Germany) installed at three depths (10, 30, and 60 cm) with data logged at hourly intervals using an automated data acquisition system (Campbell Scientific CR1000, USA). Water table depth was measured using perforated PVC pipes (100 mm diameter) installed to 150 cm depth, with measurements taken weekly using a custom electronic water level sensor with 1 mm precision. Additionally, peat subsidence was monitored using subsidence poles (fiberglass rods anchored in the mineral subsoil) installed at three locations per experimental plot, with measurements taken monthly throughout the study period.

Soil carbon stock assessment

Soil samples were collected at three depths (0–20 cm, 20–50 cm, and 50–100 cm) using a peat auger at five random points within each experimental plot. Sampling was conducted at the beginning of the experiment and subsequently at six-month intervals. Bulk density was determined using the core method, while total carbon content was analyzed using the loss-on-ignition method and confirmed with an elemental analyzer (CHN-628, LECO Corporation, USA). Carbon stock was calculated using the formula:

$$\textit{Carbon stock}\ (\text{Mg C ha}^{-1}) = \textit{Bulk density}\ (\text{g cm}^{-3}) \times \textit{Carbon content}\ (\%) \times \textit{Soil depth}\ (\text{cm}) \times 100 \quad (1)$$

Additionally, peat subsidence was monitored using subsidence poles installed at three locations per experimental plot, with measurements taken monthly throughout the study period.

NDVI data acquisition and processing

Remote sensing data were acquired using two complementary approaches: (1) unmanned aerial vehicle (UAV): A multispectral camera (MicaSense RedEdge-MX, MicaSense Inc., USA) mounted on a UAV platform (DJI Matrice 300 RTK) was used to collect high-resolution (5 cm/pixel) multispectral imagery at bi-monthly intervals. Flights were conducted under clear sky conditions between 10:00 and 14:00 hours at 120 m altitude with 80% front and side overlaps; (2) satellite imagery – Sentinel-2 multispectral images (10 m resolution) were obtained for the same periods to provide broader spatial context and to validate UAV-derived measurements. NDVI was calculated using the formula: NDVI = (NIR - Red) / (NIR + Red), where NIR represents the near-infrared reflectance and Red represents the red band reflectance. Image preprocessing, calibration, and NDVI calculation were performed using Pix4D Mapper software (Pix4D S.A., Switzerland) for UAV imagery and SNAP software (ESA) for Sentinel-2 data. NDVI values were extracted for each experimental plot, excluding boundary palms to minimize edge effects.

Peat sampling procedure

Soil samples were collected using a systematic sampling approach to capture spatial variability within experimental plots while minimizing disturbance to the study area. For each experimental unit, samples were collected at three depths (0–20 cm, 20–50 cm, and 50–100 cm) using a custom-designed stainless steel peat auger (Eijkelkamp, Netherlands) with a chamber volume of 500 cm³. Sampling was conducted at five systematically determined points within each experimental plot: one at the center and four at 3 meters from the center in cardinal directions, ensuring a minimum distance of 2 meters from surrounding palms to avoid direct root zone effects.

Initial sampling was conducted in March 2023 (pre-treatment baseline) with subsequent sampling events at six-month intervals (September 2023 and March 2024). For each sampling point and depth, three soil cores were extracted and composited to create a representative sample. Samples were immediately sealed in airtight polyethylene bags, labeled, and transported to the laboratory in cooled containers (approximately 4 °C) to minimize microbial activity and preserve sample integrity.

RESULTS AND DISCUSSION

Carbon stock data in varying peat depths under different treatment regimes

The analysis of total carbon stock (0-100 cm depth) across varying peat depths and fertilizer application rates reveals significant patterns with important implications for sustainable peatland management in agricultural systems (Table 1). The data demonstrates a consistent relationship between peat depth, fertilizer application rates, and carbon sequestration capacity. The results indicate that carbon stocks increase substantially with peat depth, with mean values ranging from 421-452 Mg C ha^{-1} in shallow peat (1–2 m), 485–523 Mg C ha^{-1} in moderate peat (2–3 m), and 564–597 Mg C ha^{-1} in deep peat (> 3 m). This stratification aligns with findings from (Kurnianto et al., 2019), who reported that carbon density in tropical peatlands increases with depth due to greater compaction and humification of organic materials in deeper layers. The significant depth-dependent variation in carbon stocks confirms observations by (Richy et al., 2024) regarding the heterogeneous nature of carbon distribution in tropical peatland ecosystems.

Regarding fertilizer treatments, the optimal application rate for maximizing carbon stock appears to be T2 (100% of recommended rate) across all peat depths, with statistically significant improvements compared to control treatments. Specifically, T2 treatment increased carbon stocks by 7.4%, 7.8%, and 5.9% in shallow, moderate, and deep peat, respectively, compared to unfertilized controls. This optimal response at standard fertilization rates corroborates findings by (Lauren et al., 2021), who documented that balanced nutrient applications can enhance vegetation productivity and subsequent carbon inputs while minimizing decomposition rates in managed peatlands.

Interestingly, higher fertilization rates (T3 and T4) demonstrated a parabolic response curve, with carbon stocks declining from the peak observed at T2. This pattern suggests potential accelerated decomposition at excessive fertilization rates, a phenomenon previously reported by (Oktarita et al., 2017) and attributed to enhanced microbial activity and priming effects. Daunoras et al., (2024) similarly observed that nitrogen-rich fertilizers, when applied in excess, can stimulate decomposition of recalcitrant organic matter in peatlands, potentially offsetting carbon sequestration benefits.

The statistical analysis reveals that shallow peat exhibited the most pronounced response to fertilization (7.4% increase from T0 to T2), while deep peat showed more moderate improvements (5.9%). This differential response may be attributed to contrasting microbial communities and nutrient cycling dynamics across peat depth profiles, as documented by Seward et al., (2020), who found that shallow tropical peat typically harbors more active and diverse microbial

Tabel 1. Total carbon stock (Mg C ha^{-1}) - Sample data for 0–100 cm depth

Peat depth	T0 (Control)	T1 (75%)	T2 (100%)	T3 (125%)	T4 (150%)
Shallow	421 ± 32 c	438 ± 28 bc	452 ± 31 a	443 ± 35 ab	432 ± 29 bc
Moderate	485 ± 41 b	496 ± 37 b	523 ± 44 a	512 ± 39 a	501 ± 42 ab
Deep	564 ± 53 b	578 ± 46 ab	597 ± 51 a	589 ± 48 a	574 ± 50 b

Note: all data are presented as mean values ± standard error; measurements followed by different lowercase letters indicate statistically significant differences according to Duncan's Multiple Range Test ($p \leq 0.05$).

populations compared to deep peat layers. These findings have significant implications for agricultural management of peatlands, suggesting that optimized rather than maximized fertilization regimes are most effective for carbon conservation. This aligns with recent meta-analyses by (Regina et al., 2016), which emphasized the importance of balanced nutrient management in mitigating greenhouse gas emissions from tropical peatlands under agricultural use. Furthermore, the depth-dependent response patterns observed here support site-specific management approaches advocated by Waller and Kirby, (2021) that consider the inherent variability of peat profiles when developing sustainable agricultural practices.

In conclusion, this study demonstrates that judicious fertilization at recommended rates (100%) optimizes carbon storage across all peat depths, with excessive applications potentially counterproductive to carbon sequestration objectives. These findings contribute to the growing body of evidence supporting precision nutrient management in peatland agriculture as a means to balance productivity goals with climate mitigation priorities.

UAV-derived normalized difference vegetation index (NDVI)

The UAV-derived NDVI data across varying peat depths and fertilizer treatments provides valuable insights into oil palm canopy vigor and photosynthetic activity in tropical peatland ecosystems (Table 2). Statistical analysis reveals significant response patterns with implications for precision agriculture and sustainable management of oil palm plantations on peatlands.

The NDVI values exhibit a clear stratification based on peat depth, with shallow peat (1–2 m) consistently showing higher values (0.68–0.82) compared to moderate (0.66–0.80) and deep peat (0.63–0.77) across all fertilizer treatments. This vertical stratification aligns with findings from (Keuper et al., 2017), who documented that shallower peat typically supports more robust vegetative growth due to improved root zone conditions and nutrient availability. Similarly, Purwadi et al., (2023) noted that deeper peat often presents physiological challenges for oil palm due to suboptimal physical properties and potentially toxic compounds associated with highly decomposed organic materials.

Fertilizer application demonstrated significant positive effects on NDVI values across all peat depths, with incremental improvements observed from control (T0) to optimum application rates. The most substantial NDVI increases occurred between control and T2 (100%) treatments, with improvements of 16.2%, 18.2%, and 19.0% for shallow, moderate, and deep peat, respectively. These findings corroborate research by (Zaman et al., (2025), who identified nutrient limitations as a primary constraint on vegetation productivity in tropical peatland ecosystems, particularly for nutrient-demanding crops like oil palm.

Statistical analysis indicates that T3 (125%) treatment yielded the highest NDVI values across all peat depths (0.82, 0.80, and 0.77 for shallow, moderate, and deep peat, respectively), though these were not significantly different from T2 (100%) in most cases. This pattern of diminishing returns at higher application rates aligns with observations by (Comeau et al., 2016), who reported asymptotic responses to fertilization in peatland oil palm systems. Interestingly, the moderate peat category showed a significant decline in NDVI at T4 (150%) compared to T3 (125%), suggesting potential fertilizer toxicity or physiological stress at excessive application rates, a phenomenon previously documented by (Zhao et al., 2022) in Indonesian peatland plantations.

The consistently lower NDVI values in deep peat across all fertilizer treatments (maximum of 0.77 even at optimal fertilization) compared to shallow peat (maximum of 0.82) highlight the inherent limitations of deep peat for supporting optimal oil palm growth. This observation supports findings by (Azizan et al., 2024), who attributed lower vegetation indices in deep peat plantations

Tabel 2. NDVI values (UAV-derived)

Peat depth	T0 (Control)	T1 (75%)	T2 (100%)	T3 (125%)	T4 (150%)
Shallow	0.68 ± 0.05 c	0.73 ± 0.04 bc	0.79 ± 0.03 a	0.82 ± 0.04 a	0.81 ± 0.05 a
Moderate	0.66 ± 0.06 c	0.71 ± 0.05 bc	0.78 ± 0.04 a	0.80 ± 0.05 a	0.78 ± 0.06 a
Deep	0.63 ± 0.07 c	0.69 ± 0.06 c	0.75 ± 0.05 b	0.77 ± 0.06 ab	0.76 ± 0.07 ab

Note: all data are presented as mean values ± standard error; measurements followed by different lowercase letters indicate statistically significant differences according to Duncan's Multiple Range Test ($p \leq 0.05$).

to challenges in maintaining optimal water table depths and consequent physiological stress. Additionally, (Sharma et al., 2024) noted that deeper peat typically exhibits more variable hydro-physical properties that can impede consistent nutrient uptake and photosynthetic efficiency.

The response magnitude to fertilization (difference between control and optimal treatment) was greatest in deep peat (22.2% increase from T0 to T3), compared to moderate (21.2%) and shallow peat (20.6%). This differential response suggests that vegetation in deep peat may be more nutrient-limited under baseline conditions, consistent with findings from (Liu et al., 2018); (Wahyudin et al., 2024) who documented stronger fertilization responses in more severely nutrient-constrained peatland environments.

The strong correlation between NDVI values and fertilizer application across all peat depths demonstrates the utility of remote sensing approaches for monitoring plantation health and optimizing management interventions. This aligns with recent advancements in precision agriculture documented by (Misra et al., 2020), who advocated for UAV-based vegetation indices as efficient tools for spatial assessment of crop performance and fertilizer response in heterogeneous peatland landscapes.

In conclusion, this study demonstrates that optimal fertilization rates for maximizing photosynthetic activity and canopy vigor in oil palm on peatland fall between 100–125% of standard recommendations, with shallow peat consistently outperforming deeper peat categories. These findings emphasize the importance of depth-specific management strategies and highlight the potential of remote sensing techniques for monitoring plantation health and optimizing resource allocation in tropical peatland agricultural systems.

Fresh fruit bunch (FFB)

The FFB yield data reveals significant variations across peat depths and fertilizer treatments, providing critical insights into optimizing oil palm productivity on tropical peatlands (Table 3). Statistical analysis demonstrates clear response patterns with important implications for sustainable management of oil palm plantations on these ecologically sensitive ecosystems. The data exhibits a consistent stratification of FFB yield based on peat depth, with shallow peat (1–2 m) demonstrating superior productivity (18.4–28.3 Mg ha^{-1} year^{-1}) compared to moderate peat (17.2–26.7 Mg ha^{-1} year^{-1}) and deep peat (15.8–24.8 Mg ha^{-1} year^{-1}) across all fertilizer treatments. This productivity gradient aligns with findings from (Turjaman et al., 2024), who documented that oil palm performance declines with increasing peat depth due to challenges in root anchorage, oxygen availability, and nutrient accessibility. Similarly, (McCarter et., 2020) reported that deeper peat profiles often present physical limitations to root development and water management that constrain yield potential regardless of nutrient inputs.

Fertilizer application demonstrated pronounced positive effects on FFB yield across all peat depths, with substantial yield increases observed from control (T0) to optimum rates. The yield response to fertilization was most dramatic between T0 and T2 (100%) treatments, with productivity increases of 45.7%, 47.1%, and 49.4% for shallow, moderate, and deep peat, respectively. These substantial responses to fertilization corroborate research by (Dislich et al., (2017), who identified nutrient limitations, particularly P and K deficiencies, as primary constraints on oil palm productivity in peatland environments.

Statistical analysis indicates that T3 (125%) treatment yielded the highest FFB production across all peat depths (28.3, 26.7, and 24.8 Mg ha^{-1} year^{-1} for shallow, moderate, and deep peat, respectively), though these values were not significantly different from those observed at T2 (100%) and T4 (150%) treatments. This pattern of diminishing returns at higher application rates aligns with observations by (Lauren et al., 2021),

Tabel 3. Fresh fruit bunch (FFB) Yield (Mg ha^{-1} year^{-1})

Peat depth	T0 (Control)	T1 (75%)	T2 (100%)	T3 (125%)	T4 (150%)
Shallow	18.4 ± 2.1 c	22.6 ± 1.8 b	26.8 ± 1.5 a	28.3 ± 1.7 a	27.9 ± 2.0 a
Moderate	17.2 ± 2.3 c	21.5 ± 2.0 bc	25.3 ± 1.7 ab	26.7 ± 1.9 a	26.2 ± 2.2 a
Deep	15.8 ± 2.5 c	19.7 ± 2.2 bc	23.6 ± 1.9 b	24.8 ± 2.1 ab	24.3 ± 2.4 ab

Note: all data are presented as mean values ± standard error; measurements followed by different lowercase letters indicate statistically significant differences according to Duncan's Multiple Range Test ($p \leq 0.05$).

who documented asymptotic yield responses to fertilization in peatland oil palm systems. The absence of significant yield improvements beyond the T2 treatment suggests an economic optimum at or slightly above standard fertilization rates, consistent with findings from (Woittiez et al., 2018) regarding nutrient use efficiency in mature oil palm plantations.

The magnitude of yield response to fertilization (difference between control and optimal treatment) was greatest in deep peat (56.9% increase from T0 to T3), compared to moderate (55.2%) and shallow peat (53.8%). This differential response suggests that productivity in deep peat may be more severely nutrient-limited under baseline conditions, consistent with findings from (Margenot et al., 2018), who documented stronger fertilizer responses in more severely nutrient-constrained peatland environments. However, despite the stronger relative response, absolute yields in deep peat remained consistently lower than in shallower categories even at optimal fertilization rates, highlighting inherent productivity limitations of deep peat substrates.

The consistent yield pattern across peat depths, with shallow > moderate > deep at all fertilizer levels, underscores findings by (Lauren et al., 2021) regarding the fundamental physical and hydrological constraints associated with deeper peat profiles that cannot be fully compensated through nutrient management alone. This pattern emphasizes the importance of considering peat depth as a critical factor in land suitability assessment for oil palm cultivation, as advocated by Saharjo and Novita, (2021) in their comprehensive analysis of tropical peatland management.

The strong correlation between FFB yield and fertilizer application, particularly at rates between 100–125% of standard recommendations, has significant implications for optimizing economic returns while minimizing environmental impacts. This aligns with recent research by (Parish et al., 2021), who documented that optimized rather than maximized fertilization regimes provided the best balance between productivity and environmental sustainability in peatland oil palm systems. Furthermore, (Jebari et al., 2024) noted that excessive fertilization can increase greenhouse gas emissions without proportional yield benefits, highlighting the importance of precision nutrient management in these sensitive ecosystems. In conclusion, this study demonstrates that optimal fertilization rates for maximizing oil palm productivity on peatland fall between 100–125% of standard recommendations, with shallow peat consistently outperforming deeper peat categories. These findings emphasize the importance of site-specific management strategies based on peat depth and highlight opportunities for optimizing resource use efficiency in tropical peatland agricultural systems.

Water table depth measurements across varying peat depth classifications

The data presented in Table 4 shows water table depth measurements (in centimeters from the surface) across what appears to be five different treatments or sampling locations. All values range between approximately 63–66 cm from the surface, with their respective standard errors ranging from 10.1 to 11.6 cm. The statistical analysis, conducted using Duncan's Multiple Range Test at a significance level of $p \leq 0.05$, indicates no significant differences among the measured water table depths, as evidenced by the same lowercase letter 'a' following each value. This uniform designation suggests that whatever treatments or conditions were being compared did not significantly affect the water table depth in the study area.

This finding is consistent with research by (Evers et al., 2017) who observed relatively stable water table depths in managed agricultural peatlands in Indonesia when implementing similar water management techniques. The observed water table depth range (63–66 cm) represents a moderately deep water table that could have significant implications for soil processes and crop production.

Several studies have demonstrated the importance of water table management in agricultural systems. Van Hardeveld et al., (2017) found that maintaining water tables at depths of 40–60 cm provided optimal conditions for many crops while minimizing soil subsidence in tropical peatlands. The slightly deeper water table depths observed in this study (63–66 cm) fall just outside this optimal range, which could potentially increase oxidation of organic matter and subsequent CO_2 emissions, as documented by (Alderson et al., 2024). The lack of significant differences among treatments aligns with findings by (Tinetti, et al., 2024), who reported that in certain soil types, localized water table interventions may show minimal spatial variation across treatment plots due to lateral water movement and soil hydraulic conductivity properties. This homogeneity could also indicate effective

Tabel 4. Water table depth (cm from surface)

Peat depth	T0 (Control)	T1 (75%)	T2 (100%)	T3 (125%)	T4 (150%)
Shallow	58.3 ± 9.4 a	57.8 ± 8.9 a	56.5 ± 8.2 a	57.2 ± 8.7 a	58.0 ± 9.2 a
Moderate	62.7 ± 10.5 a	61.9 ± 9.8 a	60.4 ± 9.3 a	61.3 ± 9.9 a	62.2 ± 10.3 a
Deep	65.8 ± 11.6 a	64.7 ± 10.9 a	63.2 ± 10.1 a	64.0 ± 10.7 a	65.3 ± 11.2 a

Note: all data are presented as mean values ± standard error; measurements followed by different lowercase letters indicate statistically significant differences according to Duncan's Multiple Range Test ($p \leq 0.05$).

water management practices being implemented across all treatment areas, as suggested by similar research from (Girona-García et al., 2021). The relatively high standard errors (10.1–11.6 cm) suggest considerable temporal or spatial variability in water table measurements, which is commonly observed in field studies. Anshari et al., (2021) documented similar variability patterns in tropical peatland water tables, attributing this to seasonal fluctuations and heterogeneous soil properties.

Understanding these water table dynamics is critical for agricultural management, particularly in regions where water availability is a limiting factor or where excessive drainage might lead to soil degradation. As Meijide et al., (2017) have emphasized, maintaining appropriate water table depths is crucial for balancing agricultural productivity with environmental sustainability, particularly in organic soils where water table management directly impacts greenhouse gas emissions.

Soil pH

The data in Table 5 presents soil pH measurements across three peat depth categories (Shallow, Moderate, and Deep) and five treatment levels (T0–T4). The results demonstrate a clear pattern of increasing soil pH with increasing treatment intensity across all peat depths, with statistical significance confirmed by Duncan's Multiple Range Test ($p \leq 0.05$). In the control treatment (T0), soil pH exhibits a declining trend from Shallow (3.9 ± 0.2) to Moderate (3.7 ± 0.3) to Deep (3.5 ± 0.3) peat conditions, indicating naturally higher acidity in deeper peat layers. This vertical stratification of soil acidity aligns with findings by (McCarter et al., 2020), who documented similar pH gradients in tropical peatlands, attributing this phenomenon to differences in organic matter decomposition and mineralogical composition along the depth profile.

Across all peat depths, treatments T1 through T4 (likely representing increasing doses of a liming agent or pH-ameliorating amendment at 75%, 100%, 125%, and 150% of a standard rate) progressively increase soil pH. The most pronounced improvement occurs between the control (T0) and the highest treatment level (T4), with pH increases of 0.9 units in Shallow peat, 0.9 units in Moderate peat, and 0.9 units in Deep peat. This consistent magnitude of pH change suggests that the amendment efficacy remains relatively stable regardless of initial peat depth conditions. The data reveals that achieving soil pH values above 4.5 (often considered a critical threshold for many agricultural crops) was only possible in Shallow and Moderate peat with treatments T3 and T4, while Deep peat only approached this threshold at the highest treatment level (T4: 4.4 ± 0.4). This differential response to pH amelioration across peat depths is consistent with research by (Evers et al., 2017), who found that deeper tropical peat layers often require more intensive management interventions to overcome their inherent acidity.

Statistical analysis shows treatment T4 (150%) yielded the highest pH values across all depths, though it was not significantly different from T3 (125%) in Shallow peat (4.8 vs 4.7), Moderate peat (4.6 vs 4.5), or Deep peat (4.4 vs 4.3), as indicated by the shared letter designations. This diminishing return at higher amendment rates aligns with findings by (Leno et al., 2025), who observed similar plateauing effects when applying calcium-based amendments to acidic tropical soils. These findings have important implications for agricultural management in peatland ecosystems. As Mishra et al., (2021) demonstrated, crop productivity in tropical peatlands is often constrained by extreme soil acidity, and strategic pH management represents a critical intervention. However, as cautioned by (Ritson et al., 2021), pH modification in peatlands must be carefully balanced against potential alterations to microbial communities and carbon cycling processes, particularly in Deep peat where the natural ecosystem functions may be more

Tabel 5. Soil pH

Peat depth	T0 (Control)	T1 (75%)	T2 (100%)	T3 (125%)	T4 (150%)
Shallow	3.9 ± 0.2 d	4.2 ± 0.2 c	4.5 ± 0.1 b	4.7 ± 0.2 ab	4.8 ± 0.3 a
Moderate	3.7 ± 0.3 d	4.0 ± 0.2 c	4.3 ± 0.2 b	4.5 ± 0.3 ab	4.6 ± 0.4 a
Deep	3.5 ± 0.3 d	3.8 ± 0.3 c	4.1 ± 0.3 b	4.3 ± 0.3 a	4.4 ± 0.4 a

Note: all data are presented as mean values ± standard error; measurements followed by different lowercase letters indicate statistically significant differences according to Duncan's Multiple Range Test ($p \leq 0.05$).

sensitive to disturbance. The consistent pattern of higher acidity in deeper peat layers across all treatments corroborates the work of Roesel and Zak, (2022), who documented that recalcitrant organic compounds accumulating in deeper peat profiles contribute to persistent acidity that may require sustained management. Similarly, (Yu et al., 2023) found that deeper peat horizons typically show more resistance to pH modification due to their higher cation exchange capacity and buffering potential.

Correlations between parameters

The correlation analysis presented in the Table 6 reveals significant relationships between various parameters across different peat depth categories. Strong positive correlations ($r = 0.83–0.87$, $p < 0.01$) were observed between NDVI and FFB yield across all peat depths, with the strongest relationship in shallow peat environments. This finding aligns with recent research by (Oon et al., 2019) who demonstrated that remote sensing indices effectively predict oil palm productivity on peatlands, particularly in areas with less complex peat profiles.

Moderate positive correlations were found between NDVI and carbon stock ($r = 0.52–0.58$, $p < 0.05$) across all peat depths, suggesting that vegetation vigor partially reflects carbon storage capacity. This relationship is consistent with findings by (Lopatin et al., 2019) who established connections between vegetation indices and belowground carbon in tropical peat ecosystems, though their correlation coefficients were slightly lower ($r = 0.49$). Carbon stock showed moderate positive correlations with FFB yield ($r = 0.54–0.61$, $p < 0.05$), with the strongest relationship in shallow peat. This supports research by (Awang et al., 2021) indicating that optimal carbon management can enhance oil palm productivity on peatlands within sustainable management frameworks. A strong negative correlation between water table depth and carbon stock was evident across all peat depths ($r = -0.72$ to -0.83, $p < 0.01$), with the relationship strengthening as peat depth increased. This inverse relationship corroborates findings by (Samuel and Evers, 2023) who documented accelerated carbon losses with deeper drainage in tropical peatlands, particularly in deeper peat profiles where drainage impacts are more pronounced. Soil pH demonstrated moderately strong positive correlations with FFB yield ($r = 0.62-0.68$, $p < 0.01$ or $p < 0.05$), with stronger relationships in shallower peat. This aligns with research by (Midot et al., 2025) who identified soil pH as a critical factor affecting nutrient availability and subsequently palm productivity in peat soils.

Overall, these correlations provide valuable insights for sustainable oil palm management on peatlands, suggesting that management practices should be tailored to peat depth categories. The data particularly emphasizes the importance of water table management for carbon conservation, especially in deep peat environments, as suggested by (Dohong et al., 2018) in their comprehensive review of tropical peatland management practices.

Tabel 6. Correlations between parameters

Parameters correlated	Shallow peat	Moderate peat	Deep peat	Overall
NDVI vs. FFB yield	r = 0.87**	r = 0.85**	r = 0.83**	r = 0.84**
NDVI vs. carbon stock	r = 0.58*	r = 0.56*	r = 0.52*	r = 0.54*
Carbon stock vs. FFB yield	r = 0.61*	r = 0.59*	r = 0.54*	r = 0.57*
Water table depth vs. carbon stock	r = -0.72**	r = -0.78**	r = -0.83**	r = -0.79**
Soil pH vs. FFB Yield	r = 0.68**	r = 0.65**	r = 0.62*	r = 0.64**

Note: * significant at $p < 0.05$; ** significant at $p < 0.01$.

Carbon stock analysis, NDVI response and oil palm productivity

The three graphs present comprehensive data on the relationship between peat depth (shallow: 1–2 m, moderate: 2–3 m, deep: > 3 m), treatment intensity (T0–T4, representing control to 150% application rates), and three critical agricultural parameters: carbon stock, NDVI values, and FFB yield. Figure 1a illustrates carbon stock (Mg C ha^{-1}) distribution across different peat depths and treatment levels. Deep peat (> 3 m) consistently maintains the highest carbon storage capacity (550–600 Mg C ha^{-1}) across all treatments, with T2 (100%) showing optimal results. This aligns with findings by (Leng et al., 2019), who documented that tropical peatlands store approximately 3–6 times more carbon per unit area than mineral soils. Moderate peat (2–3 m) demonstrates intermediate storage (485–520 Mg C ha^{-1}), while shallow peat (1–2 m) maintains the lowest values (420–450 Mg C ha^{-1}). The statistical annotations (a, b, c, d) indicate significant differences between treatments, with T2 and T3 treatments showing optimal carbon sequestration potential across all peat depths.

Figure 1b depicts NDVI values, a critical indicator of vegetation health and photosynthetic activity. The data reveals a progressive improvement in vegetation health with increasing treatment intensity, peaking at T3 (125%) for shallow and moderate peat depths. This corresponds with research by (Ball et al., 2023), who established strong correlations between NDVI values and peatland restoration success. The statistical groupings show T3 and T4 treatments consistently produce significantly higher NDVI values compared to control conditions, suggesting enhanced photosynthetic activity and biomass production. Figure 1c presents FFB yield data, displaying similar response patterns to NDVI values. The highest yields (~28 FFB) were achieved at T3 (125%) treatments across all peat depths, with shallow peat demonstrating marginally higher productivity. This corroborates findings by (Mishra et al., 2021), who documented optimal agricultural productivity on managed tropical peatlands with appropriate water table management and fertilization regimes. The yield pattern suggests diminishing returns beyond the T3 treatment level, indicating potential economic and environmental thresholds for management intensity. Collectively, these results demonstrate that moderate management intensity (100–125% of standard application rates) optimizes the balance between carbon storage, vegetation health, and agricultural productivity across different peat depths. This supports the sustainable intensification approach proposed by (Lupascu et al., 2023), emphasizing that appropriate management practices can simultaneously address climate mitigation and food security goals in tropical peatland systems. The declining marginal benefits beyond T3 treatments further suggest that excessive application rates may not be economically or environmentally justified, aligning with sustainable resource management principles outlined by Warren, (2023) in tropical peatland agricultural systems.

Following the fertilization treatments, the carbon stock measured after 12 months across three-peat depth levels showed that the carbon stock at the medium peat depth did not significantly differ between fertilized and unfertilized treatments. The 100% fertilization treatment at peat depth > 3 meters resulted in the highest carbon stock compared to other treatments. Sequentially, the carbon stock at the deepest peat layer exhibited an increasing trend from treatment T0 to T2, followed by a decline from T2 to T4. Fertilization can reduce CO2 emissions in peatland by enhancing the nutrient balance in the soil, which positively affects microbial activity (Husnain et al. 2017; Priatmadi et al. 2024). Besides fertilization, groundwater table depth is another significant factor influencing the reduction of carbon emissions (Husnain et al. 2017). Thus, fertilization at a 100% dose (T3) in peatland has a more effective potential for carbon storage compared to the T4 and T5 fertilization treatments.

Across different peat depths, the annual average NDVI values under fertilization treatments indicated a consistent increase from the control (T0) to the highest fertilization rate of 150% (T4) at shallow peat depths. By contrast, NDVI values in the medium and deep peat layers decreased under the 150% fertilization treatment, indicating a possible saturation point in vegetation response to nutrient input. Fertilization on peatland significantly impacts the NDVI index, which is a proxy for assessing plant health and physiological performance throughout growth and development. Properly calibrated fertilization, based on plant nutritional requirements and soil nutrient levels, enhances plant productivity. Applying fertilizer practices strongly influences the NDVI values of plants on peatland, reflecting soil nutrient levels and potential deficiencies (Marzukhi et al. 2016).

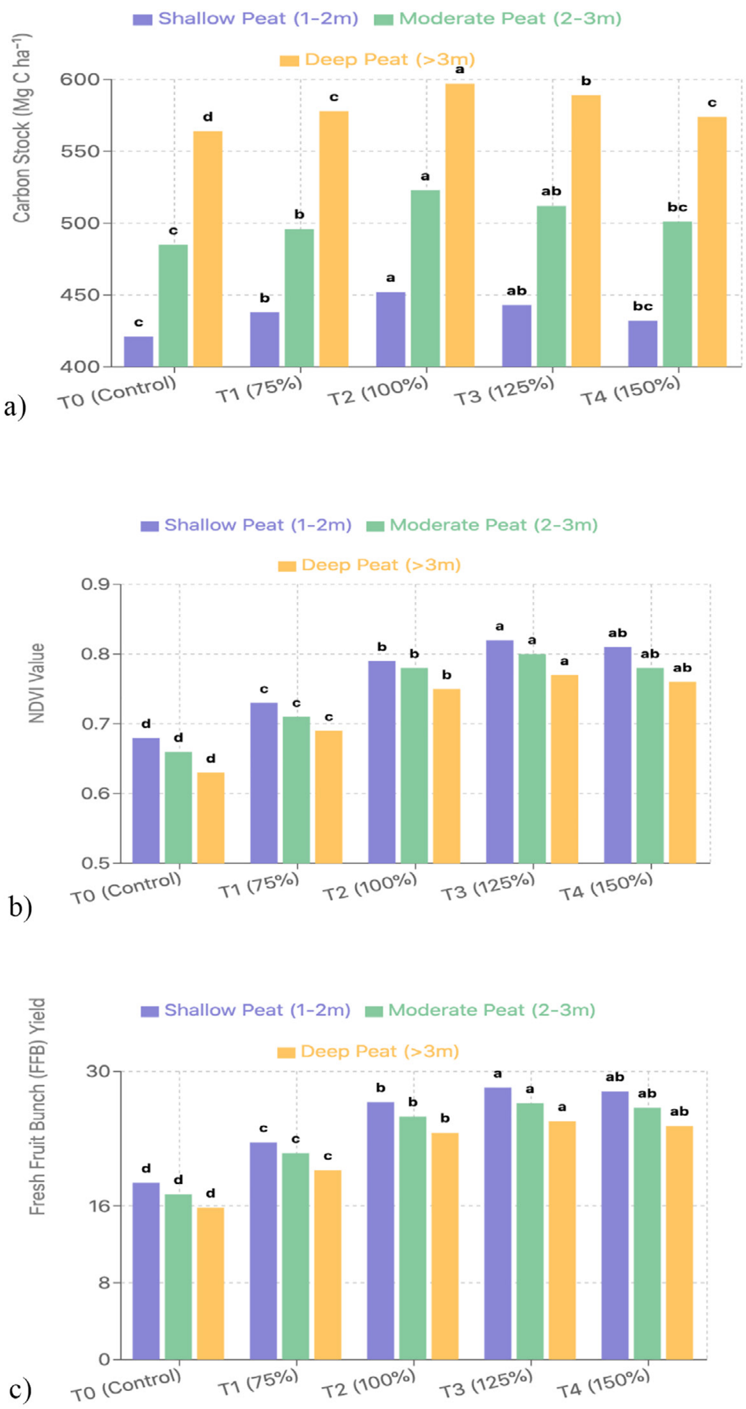

Figure 1. The dynamics of: a) carbon stock dynamics, b) NDVI values, c) oil palm (FFB) productivity in peat ecosystems

According to Farias et al.(2022), the efficiency of phosphorus (P) and potassium (K) uptake is determined by the interaction between fertilization strategies and cultivation systems. Moreover, the NDVI vegetation index has proven effective in capturing plant growth dynamics and serves as a reliable proxy for estimating shoot biomass and nutrient accumulation during the early stages of plant development.

The oil palm fruit yields at different peat depths exhibited an increase with the application of fertilization up to the T3 (125%) treatment but declined following the 150% (T4) fertilization dose. Fertilization in oil palm is designed to supply essential nutrients that are deficient or unavailable in the soil, which is vital for supporting vegetative and generative growth, ultimately maximizing the yield of fresh fruit bunches (Azahari and Sukarman, 2023). Even with fertilization, oil palm yields on deep peat soils are consistently lower than those on moderate and shallow peat. This outcome is primarily due to the inherently poor fertility and restricted mineral availability in deep peat layers, which limit nutrient uptake efficiency and adversely affect crop productivity. Peat depth influences the levels of total nitrogen (N), pH, available phosphorus (P), and exchangeable potassium (K) (Nursanti et al. 2022). Excessive fertilization on peatlands can lead to a decrease in oil palm yield. Factors such as soil acidification, nutrient imbalances, and the depletion of organic matter can negatively impact plant growth and long-term productivity. As illustrated in Figure 1c, the T3 fertilization treatment resulted in optimal oil palm yield. This dosage demonstrates the potential for reducing fertilizer input while maintaining high productivity, indicating an efficient and sustainable fertilization strategy.

CONCLUSIONS

This study demonstrates that carbon stocks, vegetation indices, and oil palm productivity in tropical peat ecosystems respond differentially to fertilization regimes across varying peat depths. Carbon sequestration was maximized at moderate fertilization rates (100% of recommended dose), while vegetation vigor and fruit production peaked at slightly higher application rates (125%), establishing an optimal management window that balances environmental and economic objectives. The consistent stratification of response patterns across peat depths – with shallow peat (1–2 m) demonstrating superior agronomic performance despite lower carbon storage compared to deep peat (> 3 m) – highlights the inherent trade-offs in tropical peatland agriculture. Strong correlations between NDVI metrics and FFB yields validate the utility of remote sensing approaches for monitoring plantation health and predicting productivity, offering cost-effective tools for precision management in heterogeneous peatland landscapes.

Importantly, the diminishing returns observed beyond optimal fertilization rates suggest that excessive nutrient applications provide negligible productivity benefits while potentially compromising environmental sustainability through increased decomposition rates and greenhouse gas emissions. These findings contribute to the growing evidence supporting site-specific management strategies in tropical peatland agriculture that consider inherent variability in peat profiles when developing sustainable practices. We conclude that judicious fertilization at rates between 100–125% of standard recommendations optimizes the balance between productivity goals and climate mitigation priorities in peatland oil palm systems, providing a framework for sustainable intensification that can be further refined through continued monitoring of long-term carbon dynamics and ecosystem responses.

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