Environmental Research Communications

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OPEN ACCESS

RECEIVED
21 October 2025

REVISED
13 March 2026

ACCEPTED FOR PUBLICATION
24 March 2026

PUBLISHED
13 April 2026

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PAPER

# Spatial variability of soil greenhouse gas emissions in oil palm plantation under different management zones

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**Keywords:** greenhouse gas, soil emission, soil organic carbon, plant residue, oil palm

## Abstract

As global demand for palm oil continues to rise, improving the accuracy of greenhouse gas (GHG) accounting in oil palm plantations is essential for evaluating their environmental sustainability. Spatial heterogeneity created by routine plantation management can strongly influence soil properties and GHG emissions. In this study, we assessed soil $CO_2$, $N_2O$, and $CH_4$ emissions across three principal management zones in a mature oil palm (nine-year-old) plantation cultivated in mineral soils- frond heap (FH), palm circle (PC), and harvesting path (HP) under standard operational practices. Soil GHG fluxes were measured using static chambers coupled with a Fourier-transform infrared (FTIR) gas analyser, alongside surface soil (0–5 cm) sampling to characterise soil organic carbon, total nitrogen, moisture content, bulk density, porosity, and pH. In total, 90 measurement points were evaluated to capture within-plantation spatial variability. The FH zone exhibited significantly higher soil organic carbon, total nitrogen, porosity, and moisture content, and lower bulk density than the PC and HP zones. These properties translated into significant higher mean GHG fluxes in FH soils, with $CO_2$, $N_2O$, and $CH_4$ emissions of 165.7 mg $m^{-2}$ $h^{-1}$, 0.25 mg mg $m^{-2}$ $h^{-1}$, and 0.25 mg $m^{-2}$ $h^{-1}$, respectively. In contrast, HP soils were more compacted, carbon-poor, and exhibited the lowest GHG emissions. Spearman's rank correlation analyses indicated that $CO_2$ emissions were primarily driven by increased soil porosity, while elevated soil moisture and organic matter inputs in FH zones promoted conditions conducive to $N_2O$ production and anaerobic microsite formation supporting $CH_4$ emissions. When expressed as $CO_2$-equivalents, the FH zone acted as biogeochemical hotspot, contributed disproportionately to plantation-scale GHG emissions despite occupying only one-third of the total area. These findings highlight the importance of incorporating fine-scale spatial variability when developing GHG inventories, emission factor development, and targeted, zone-specific mitigation strategies.

## 1. Introduction

Agriculture is one of the major contributors to climate change, primarily through the emissions of greenhouse gases (GHGs) such as carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and methane ($CH_4$). The agricultural sector accounts for approximately 10 to 20% of the total global anthropogenic GHG emissions (Ntinyari and Gweyi-Onyango 2021). These gases are released from various sources, including food system-driven land-use change, livestock, agricultural soils, and chemical inputs (Chataut *et al* 2023). As global agriculture shifts towards more sustainable practices to mitigate climate change, understanding the environmental impacts of different crop

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cultivation systems has become crucial. Among these systems, oil palm (*Elaeis guineensis*) plays a major role in supporting global food and energy demands while also influencing carbon and GHG dynamics.

Oil palm is one of the most efficient and cost-effective oil crops, widely cultivated for its high yield in which the average oil yield for oil palm is 4 ton $ha^{-1}$, surpassing annual oilseed crops characterised by yields ranging from 0.3 to 1.2 ton $ha^{-1}$ (Murphy 2014). Palm oil as a derivative of oil palm cultivation is a versatile commodity used in numerous food and non-food products such as biofuels, personal care, and cosmetic products (Yeong *et al* 2012, Kaniapan *et al* 2021). With the increased demand for palm oil, the global cultivated area of oil palm covers over 29 million hectares in 2022, with the main producing countries involving Indonesia and Malaysia (Voora *et al* 2023). Given the extensive scale of its cultivation, any alterations to soil management within oil palm plantations could significantly influence the carbon cycle and GHG emissions. Consequently, improving our understanding of soil-GHG exchanges in oil palm systems is essential for balancing productivity goals with climate change mitigation and sustainable land management.

The release of GHGs from soils in agricultural systems is closely linked to diverse management practices. Soil management interventions such as tillage, fertilisation, and organic matter management play a role in either accelerating or mitigating the release of GHG gases (Komatsuzaki and Ohta 2007, Bhattacharyya *et al* 2022). In oil palm plantations, soil management is often organised into three distinct zones: (1) the palm circle (PC), which is kept free of ground cover and weeds around the trunk; (2) frond heaps (FH), where pruned fronds are systematically stacked; and (3) harvesting paths (HP), designated for the collection and transportation of fresh fruit bunches (Rahman *et al* 2021). These spatially distinct management zones create pronounced heterogeneity in soil physical structure, organic carbon inputs, nutrient availability, and microbial activity, all of which are fundamental regulators of soil GHG production and consumption (Smith *et al* 2018, Basheer *et al* 2024, Valujeva *et al* 2024). As a result, oil palm plantations function as mosaics of biogeochemical 'hotspots' and 'coldspots', where ecosystem processes such as carbon sequestration, nitrogen cycling, and gas diffusion operate at different intensities within the same plantation. In this context, GHG 'hotspots' refer to spatially discrete areas that contribute disproportionately high greenhouse gas emissions relative to their spatial extent, while 'coldspots' represent areas with comparatively low emission rates resulting from limiting conditions (Hagedorn and Bellamy 2011, Gachibu Wangari *et al* 2023). Understanding this fine-scale spatial variability is therefore essential for accurately quantifying ecosystem-level GHG balances and identifying management practices that can enhance soil carbon storage while minimising emissions.

While there is substantial research examining soil properties in oil palm plantations, studies focusing on GHG fluxes, particularly those extending beyond $CO_2$ in mineral soils remain limited, with much of the research centred predominantly on peat soils. For instance, the impact of converting peatland to oil palm plantations on $CO_2$ emissions has been explored by Cooper *et al* (2020) and McCalmont *et al* (2021), while comparisons of soil $CO_2$ emissions between oil palm plantations and forest ecosystems have been studied by Azizan *et al* (2021) and Melling *et al* (2005). However, the existing literature frequently overlooks the variations that occur across different management zones in the oil palm cultivation system (Uning *et al* 2020).

Recent studies have begun to explore spatial variability within plantations, often examining the effects of fertilisation, residue addition, or weed management on soil GHG fluxes (Rahman *et al* 2019, Rahman *et al* 2021, Chen *et al* 2024). While these treatment-based experiments provide valuable mechanistic insights, spatial management zones are typically incorporated as secondary or nested factors. As a result, observed differences among PC, FH, and HP zones are frequently interpreted as short-term responses to imposed treatments rather than as emergent properties of long-term, routine plantation management. This approach may limit our understanding of baseline, zone-specific GHG emission patterns that are essential for upscaling, emission factor development, and process-based modelling. Failing to account for zone-specific GHG dynamics may lead to biased plantation-scale emission estimates and ineffective mitigation strategies. A spatial understanding of soil GHG emissions can therefore inform targeted, zone-specific management interventions, supporting the development of more sustainable oil palm production systems. In this study, we addressed these gaps through a spatially explicit assessment to quantify soil properties and GHG emissions across the principal management zones of oil palm plantations under standard operational practices. The objectives of this study were therefore to: (1) characterise soil physicochemical properties across three operational management zones in oil palm plantations, and (2) quantify and compare $CO_2$, $N_2O$, and $CH_4$ emissions associated with each zone.

## 2. Methodology

### 2.1. Study area and experimental design

The study was conducted in an oil palm estate in Carey Island, Malaysia (2°51'58.2″N 101°24'55.9″E), (figure 1(A)) focusing on nine-year-old oil palms cultivated in Jawa soil series (Sulfic Endoaquepts). The study site has a mean annual air temperature of 28.9 °C, and average annual rainfall of 2,301 mm. The oil palms in the experimental site

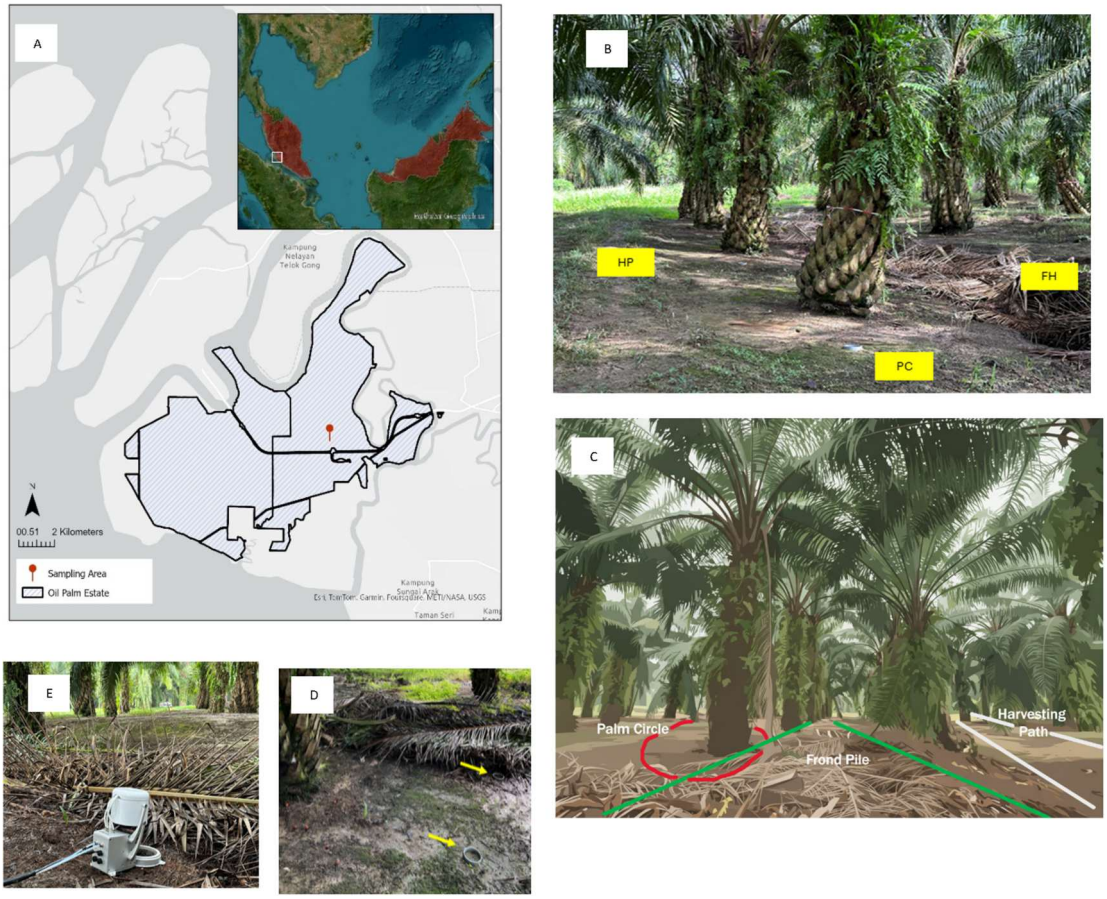


**Figure 1.** Study area and experimental design. (A) Study site; (B) & (C) Three management zones in oil palm plantation; (D) Soil collar inserted at FH and PC zones; (E) Eosense automatic soil flux chamber.

received two applications of ammonium-based NK compound fertiliser (14% N and 20% $K_2O$), applied at rates of 4.25 kg palm$^{-1}$ in March 2024 and 4.0 kg palm$^{-1}$ in September 2024. In addition, a single application of rock phosphate fertiliser (28% $P_2O_5$) was applied at a rate of 1.75 kg palm$^{-1}$ in May 2024. All fertilisers were broadcast mechanically using a fertiliser-spreading machine, targeting the area adjacent to the FH zone.

A total of 90 measurement points were selected, with 30 sampling points allocated to each of the three key management zones (PC, FH, and HP). Each measurement point was located adjacent to individual palm trees. The soil and gas sampling were conducted between January and February 2024. The was no fertiliser input to the study site in the month preceding the sampling period or during the sampling itself.

### 2.2. Gas sampling and calculation of fluxes

Soil collars were inserted into the soil at a depth of 3 cm one day before gas sampling and removed immediately after sampling. Gas concentrations of $CO_2$, $N_2O$, and $CH_4$ were quantified using a FTIR GT5000 Terra gas analyser (Gasmet, Finland) coupled with an eosAC automated flux chamber (Eosense, Canada) (Hashemi *et al* 2024, Park *et al* 2024). The gas analyser was calibrated with nitrogen gas each time before the field gas sampling. At each measurement point, the chamber was deployed for a total duration of 16 min, during which gas concentrations were recorded at 4 min intervals, yielding four concentration measurements per deployment. The gas sampling was conducted between 9:00 am to 11:00 am. Atmospheric pressure during the sampling period was stable (1012–1013 mbar), therefore, pressure-related variation in molar volume was considered negligible, and flux calculations was calculated using equation (1) (Gasmet Technologies Oy 2020):

$$Soil\ gas\ flux(\mu mol\ m^{-2}s^{-1}) = \frac{\Delta C}{\Delta t} \times \frac{v}{v_a \times \frac{T_2}{T_1}} \times \frac{1}{A} \quad (1)$$

where $\frac{\Delta C}{\Delta t}$ is the rate of change of concentration of gas (ppm), $v$ is the volume of the vessel including cell and sample lines, $v_a$ is the molar volume for ideal gas at 273 K ($22.4 \times 10^{-3}$ m$^3$ mol$^{-1}$), $T_2$ is the air temperature (K), $T_1$ is the standard temperature (K), and $A$ is the footprint area of the chamber (m$^2$).

The rate of change of the gas concentration was derived by calculating the slope of the linear change in gas concentration over time within the chamber. Only regression models with an $R^2$ value of 0.8 or greater were included in the analysis.

The mass fluxes (mg $m^{-2}$ $h^{-1}$) was then obtained by multiplying the soil gas flux ($\mu mol\ m^{-2}s^{-1}$) with its molar weight ($CO_2 = 44.009$ g $mol^{-1}$; $N_2O = 44.013$ g $mol^{-1}$; $CH_4 = 16.04$ g $mol^{-1}$) (National Library of Medicine (PubChem) 2025).

### 2.3. Soil sampling and analysis

Following gas sampling, soil samples were collected at the top 5 cm of each point using a 5 cm × 5 cm soil core ring. The fresh weight of each sample was recorded before drying at 50 °C until a constant weight was achieved to determine the dry weight. Subsequently, soil gravimetric water content (2) (adapted from FAO 2023a), bulk density (3) and total soil porosity (4) (FAO 2023b) were calculated.

$$Soil\ Gravimetric\ Water\ Content\,(gg^{-1}) = \frac{Weight\ of\ wet\ soil - Weight\ of\ dry\ soil}{Weight\ of\ dry\ soil} \tag{2}$$

$$Soil\ Bulk\ Density\,(g\ cm^{-3}) = \frac{Weight\ of\ dry\ soil}{Volume\ of\ soil} \tag{3}$$

$$Total\ soil\ porosity = 1 - \left(\frac{Bulk\ density\ of\ soil\ sample}{Particle\ density\ of\ soil}\right) \times 100 \tag{4}$$

The air-dried soil samples were then sieved (with a 2 mm sieve) and analysed for soil organic carbon (SOC), total nitrogen, and pH. The SOC was determined via dry combustion method, using an Elementar Vario Max (Elementar, Germany) (Department of Standards Malaysia 2016). Soil total nitrogen was measured through Kjeldahl method (Kjeldahl 1883). Soil pH was measured in a 1:2.5 soil:deionised water suspension and analysed with a pH probe (adapted from ISO 10390:2005 procedure) (International Organization for Standardization 2005).

### 2.4. Calculation of soil GHG emissions per hectare and $CO_2$-equivalent emissions in oil palm cultivation systems

For each zone, the mean $CO_2$, $N_2O$, and $CH_4$ fluxes calculated from 30 measurements were then upscaled to a per-hectare basis by multiplying them by the proportional area coverage of each management zone within one hectare of oil palm plantation. The spatial coverage per hectare was categorised as follows: PC covering 1,800 $m^2$, FH covering 2,800 $m^2$, and HP covering 3,600 $m^2$.

The $CO_2$-equivalent emissions for each management zone were calculated using the Global Warming Potential (GWP) values provided in the IPCC Sixth Assessment Report (Forster *et al* 2021). The GWPs used for a 100-year time horizon were 273 for $N_2O$, and 27 for $CH_4$.

The $CO_2$ equivalent emissions for each gas per hectare were calculated in (5):

$$CO_2 equivalent\ emissions\,(kg\ hr^{-1}) = GHG\ flux\,(kg\ hr^{-1}) \times GWP \tag{5}$$

## 3. Statistical analysis

The data sets were first tested for normality using Shapiro-Wilk's test. For variables that did not conform to a normal distribution, log-transformation was applied. Subsequent analysis was performed using one-way Analysis of Variance (ANOVA) to compare group differences, followed by Tukey's Honest Significant Difference (HSD) post-hoc test with a significance threshold set at $p < 0.05$. For data that remained non-normally distributed despite transformation, the Kruskal–Wallis test was applied. Significant group differences were further examined using Dunn's test for post-hoc comparisons at $p < 0.05$. The relationship between soil GHG fluxes and soil physicochemical parameters was assessed using Spearman's rank correlation test with a total measurement of 90 ($n = 90$), and correlations were considered statistically significant at $p < 0.05$. All analyses were conducted using R version 4.3.2.

## 4. Results

### 4.1. Soil physiochemical properties on different management zones

The soil characteristics measured across FH, HP, and PC are summarised in table 1. The highest median total nitrogen (0.34 g $kg^{-1}$) was recorded for FH, followed by PC (0.22 g $kg^{-1}$), and HP (0.15 g $kg^{-1}$). Organic carbon content varied among the locations. FH exhibited the highest organic carbon content with a median value of

**Table 1.** Soil characteristics across frond heap (FH), harvesting path (HP), and palm circle (PC) zones.

| Management Zone | Total N ($g\,kg^{-1}$) | Organic C ($g\,kg^{-1}$) | pH | Bulk density ($g\,cm^{-3}$) | Soil porosity (%) | Soil gravimetric water content ($g\,g^{-1}$) |
|---|---|---|---|---|---|---|
| FH | $3.4^{b}$ | $38.6^{b}$ | $4.00^{a}$ | $0.87^{c}$ | $66.38^{c}$ | $0.65^{c}$ |
| HP | $1.5^{a}$ | $17.6^{a}$ | $3.70^{b}$ | $1.39^{b}$ | $46.58^{b}$ | $0.29^{b}$ |
| PC | $2.2^{a}$ | $22.1^{a}$ | $4.00^{a}$ | $1.21^{a}$ | $53.46^{a}$ | $0.37^{a}$ |

*Different alphabets (a, b, c) indicate significant differences among management zones for each parameter at $p < 0.05$.

3.86 $g\,kg^{-1}$. HP and PC were shown to have lower values, with medians of 1.76 $g\,kg^{-1}$ and 2.21 $g\,kg^{-1}$ respectively. Soil pH measurements demonstrated that all locations had acidic soil. FH and PC both had a median pH of 4.0, while HP was slightly more acidic with a median pH of 3.7. Bulk density was found to be the lowest at FH, with a median value of 0.87 $g\,cm^{-3}$. In contrast, HP had the highest bulk density at 1.39 $gcm^{-3}$, while PC had an intermediate value of 1.21 $g\,cm^{-3}$. Soil porosity was highest at FH with a median value of 66%. HP had the lowest porosity at 46%, indicative of more compact soil, while PC had an intermediate porosity of 53%. Soil gravimetric water content followed a similar pattern, with FH having the highest moisture content at a median of 0.65 $g\,g^{-1}$. HP had the lowest water content at 0.29 $g\,g^{-1}$, and PC had a median value of 0.37 $g\,g^{-1}$, suggesting drier soil conditions.

### 4.2. GHG emission

The log-transformed mean $CO_2$ fluxes from the soil in three distinct management zones were significantly different (figure 2(A)). The FH zone exhibited the highest mean $CO_2$ flux, at 165.66 $mg\,m^{-2}\,h^{-1}$, followed by PC zone, with 129.75m $g\,m^{-2}\,h^{-1}$, and HP zone with 82.35 $mg\,m^{-2}\,h^{-1}$. The nitrous oxide ($N_2O$) flux was shown in figure 2(B). The FH zone showed a median value of 0.25 $mg\,m^{-2}\,h^{-1}$, significantly different compared to HP and PC zones that recorded an $N_2O$ flux near to zero $mg\,m^{-2}\,h^{-1}$ for both zones. The methane ($CH_4$) flux measurements were summarised in figure 2(C). The FH zone showed a median value of 0.25 $mg\,m^{-2}\,h^{-1}$. In contrast, the HP and PC zones recorded an $CH_4$ flux at 0.01 and 0.02 $mg\,m^{-2}\,h^{-1}$ for respectively.

The Spearman correlation showed several key relationships between soil properties and GHG emissions (figure 3). A significant moderate positive correlation was noted between soil porosity and $CO_2$ flux ($r = 0.56$), as well as SOC and $CO_2$ flux ($r = 0.49$). A weak positive correlation ($r = 0.23$) was observed between gravimetric soil water content and $N_2O$ emissions. Additionally, a moderate positive correlation was noted between gravimetric soil water content and $CH_4$ emissions ($r = 0.49$).

Table 2 summarises the soil GHG ($CO_2$, $N_2O$, and $CH_4$) emissions per-hectare basis and the $CO_2$-equivalent emissions in oil palm cultivation systems. Among the zones, the FH exhibited the highest combined emissions, with $CO_2$ emissions of 0.46 $kg\,ha^{-1}$, alongside the highest $N_2O$ (0.0009 $kg\,ha^{-1}\,hr^{-1}$) and $CH_4$ (0.00045 $kg\,ha^{-1}\,hr^{-1}$) emissions. These contributions resulted in the highest $CO_2$-equivalent emission of 0.72 $kg\,ha^{-1}\,hr^{-1}$. The PC zone showed comparatively lower emissions across all gases, with a $CO_2$-equivalent emission of 0.37 $kg\,ha^{-1}\,h^{-1}$. In contrast, the HP zone recorded the lowest $CO_2$-equivalent emission (0.23 $kg\,ha^{-1}\,hr^{-1}$) among the zones with negligible $N_2O$ emissions and minimal $CH_4$ emissions (0.00002 $kg\,ha^{-1}\,hr^{-1}$).

## 5. Discussion

### 5.1. Soil Properties of different management zones in oil palm plantation

The FH area exhibits the lowest bulk density and highest SOC among the management zones, which could be primarily attributed to the large input of organic matter. Following each harvesting cycle, which occurs fortnightly, old fronds are systematically cut and deposited in FHs, with approximately 24 fronds are stacked at this area annually (Corley and Tinker 2015). As these fronds decompose, they contribute substantial amounts of organic matter to the soil (Formaglio *et al* 2021). This organic matter serves as a binding agent for soil particles, fostering the formation of stable soil aggregates (Moradi *et al* 2015). Such positive effects of organic matter inputs on soil aggregate stability are well documented in tropical soils, which soil structures are often weak under intensive land cultivation systems (Yulnafatmawita and Anggriani 2013, Tao *et al* 2018, Kunmala *et al* 2023). Consistent with the findings of the present study, positive correlations between soil carbon content and total porosity ($r = 0.64$) as well as the soil structural index ($r = 0.96$) have been reported in a 13-year-old oil palm agroforestry system in eastern Amazon, Brazil, where frond pile area exhibited the highest total porosity (53%) in the top 5 cm compared to PC and HP (De Oliveira *et al* 2022). The enrichment of organic carbon in FH areas enhances soil structure by increasing inter-aggregate pore space, thereby improving total porosity and

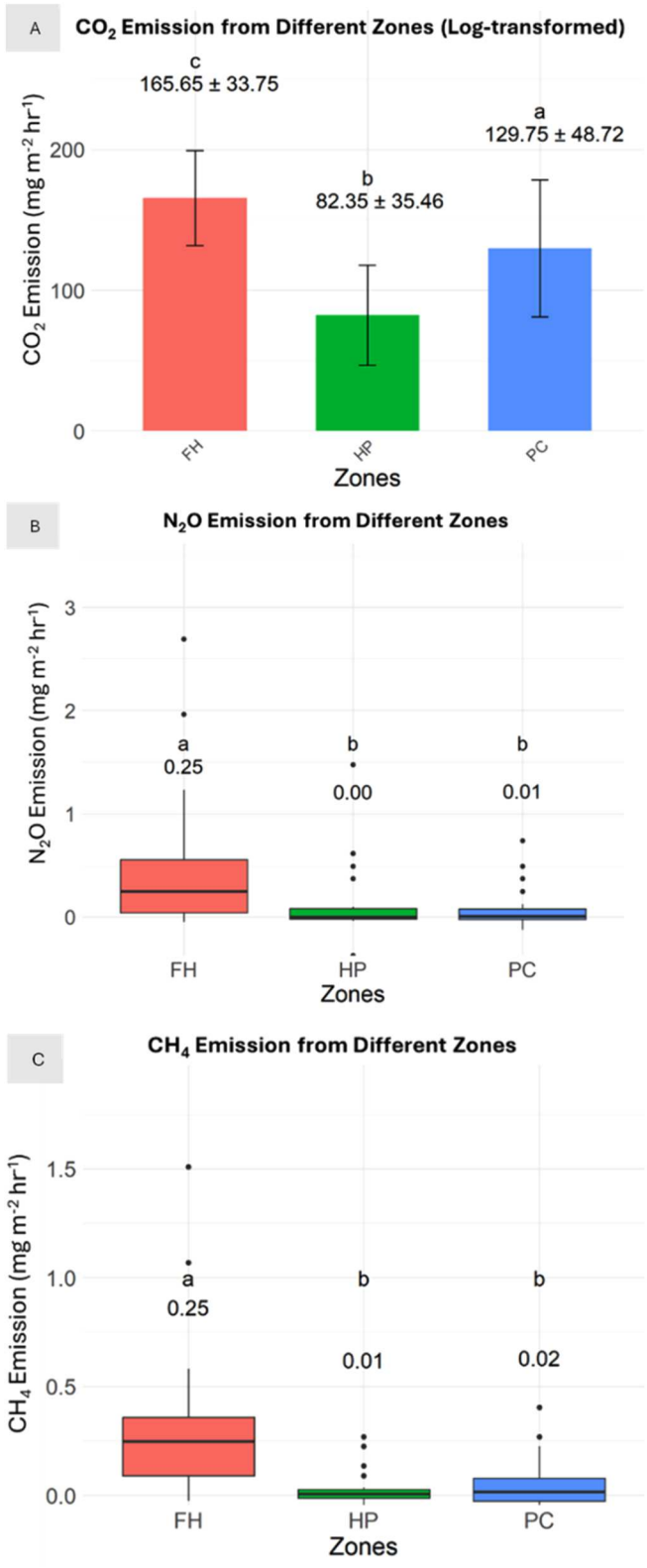


**Figure 2.** $CO_2$, $N_2O$, and $CH_4$ flux from different management zones.

water-holding capacity. Strong negative correlation between SOC and bulk density ($r = -0.81$) demonstrated in the present study further supports this mechanism.

The intermediate bulk density observed in the PC area might be due to a moderate soil compaction, attributed to regular maintenance and harvesting activities, where workers frequently traverse the area, resulting in some degree of soil compaction. However, the compaction is less pronounced compared to the HP, which serves as a thoroughfare for machineries such as mechanised fertiliser spreaders and chemical sprayers. The weight and travel frequency of machinery in the plantation has prominent effects on soil bulk density and

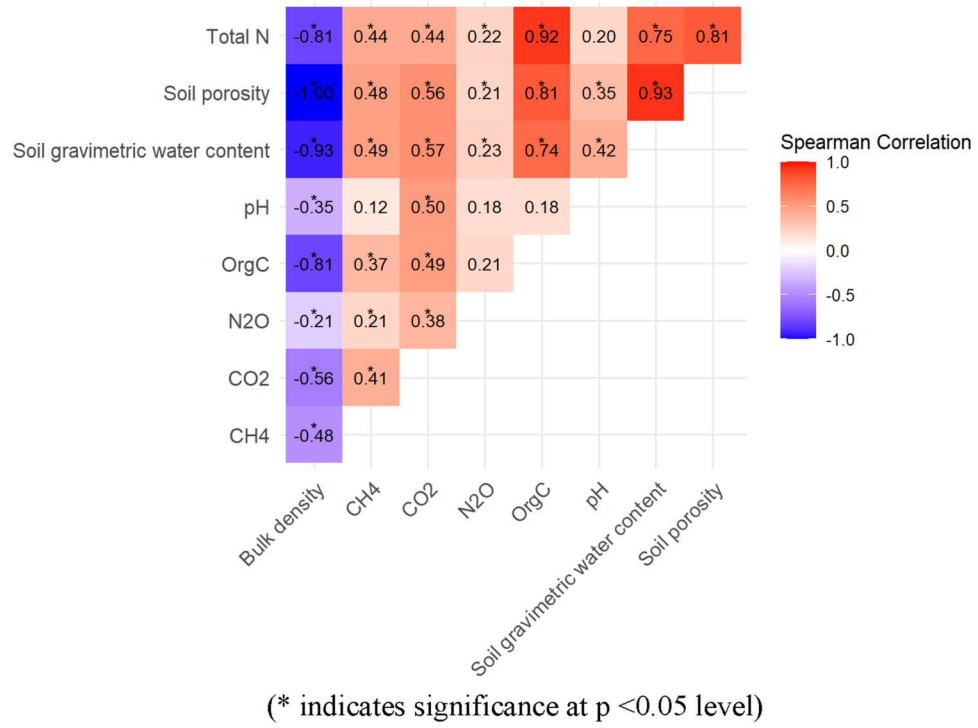


**Figure 3.** Spearman correlation between soil physiochemical parameters and soil GHG fluxes.

**Table 2.** Soil GHG emission rates per-hectare basis and $CO_2$-equivalent emission in oil palm cultivation system.

| Management zone | Emission (kg ha$^{-1}$ h$^{-1}$) | | | |
|---|---|---|---|---|
| | $CO_2$ | $N_2O$ | $CH_4$ | $CO_2$-equivalent |
| FH | 0.46$^{c}$ | 0.00090$^{a}$ | 0.00045$^{a}$ | 0.72$^{c}$ |
| HP | 0.23$^{b}$ | 0$^{b}$ | 0.00002$^{b}$ | 0.23$^{b}$ |
| PC | 0.36$^{a}$ | 0.00004$^{b}$ | 0.00004$^{b}$ | 0.37$^{a}$ |

*Different alphabets (a, b, c) indicate significant differences among management zones for each parameter at $p < 0.05$.

porosity. Zuraidah (2019) observed that bulk density was increased by 8%–12% and soil porosity was reduced by 4%–6% when heavier machines are travelling more frequently in the oil palm plantation. In addition to soil compaction, the HP and PC areas recorded significantly lower SOC compared to the FH. These zones receive minimal organic inputs, as they are not designated for organic residue deposition like the FH. Although small amounts of organic residues, such as dried weeds or fallen fruitlets, might accumulate in these areas, they are insufficient to elevate SOC levels effectively.

### 5.2. Soil greenhouse gas emissions across different management zones and their relations to soil properties

#### *5.2.1. $CO_2$ emissions*

The $CO_2$ flux is an indicator of soil biological activity and soil $CO_2$ emissions are rarely zero, even in undisturbed soils. Elevated $CO_2$ fluxes often signify active microbial decomposition of organic matter, a key process for nutrient cycling and maintaining soil health. In this study, the FH zone recorded the highest $CO_2$ emissions, and a moderate positive correlation ($r = 0.49$) between SOC and $CO_2$ emissions was observed. These findings are consistent with the results of Hassler *et al* (2015) and Goodrick *et al* (2016), who identified organic matter decomposition as the primary driver of soil $CO_2$ emissions, with the FH zone showing the highest emissions, followed by PC and HP zones. SOC is the primary energy source for soil microorganisms, and elevated SOC levels could promote microbial proliferation, enhance decomposition rates, and drive $CO_2$ emissions through microbial respiration (Gougoulias *et al* 2014, Anjum and Khan 2020). The incorporation of crop residues could significantly boost soil microbial abundance and activity, thereby amplifying $CO_2$ emissions (Govaerts *et al* 2007, Murphy *et al* 2016, Wang *et al* 2020). Although the PC is generally kept free of

surface vegetation, higher $CO_2$ emissions and SOC in this zone were observed compared to HP. PC is located in close to the palm trunk, where root density is the greatest, thereby resulting in significant contributions from root biomass, exudation, and turnover that promote SOC accumulation and stimulate soil respiration (Intara *et al* 2018). Soil respiration that is strongly influenced by root density, decreases with increasing distance from the oil palm trunk. Soil respiration rates of mature oil palms are reported to be the highest within 1 m of the palm trunk and gradually decrease, reaching a plateau at distances beyond 3 m from the trunk (Dariah *et al* 2014, Sabiham *et al* 2014, Matysek *et al* 2018).

In this study, bulk density exhibited a moderate negative correlation with $CO_2$ flux ($r = -0.51$). Management zones with higher bulk densities, such as the PC and HP, had lower $CO_2$ emissions compared to the FH, which featured lower bulk density and higher porosity. Soils with lower bulk density are more porous, enhancing oxygen diffusivity and air permeability, which in turn facilitates microbial activity (Ball 2013, Gui *et al* 2023). Greater porosity also supports increased root formation and growth, contributing to elevated respiration rates and higher $CO_2$ emissions (Buivydienė *et al* 2024). These findings suggest that soil structure plays a role in mediating $CO_2$ emissions, with looser and well-aerated soils at FH providing optimal conditions for microbial and root activity, thereby driving higher respiration rates.

Nevertheless, it is important to note that that the $CO_2$ emission rates observed in this study were at the lower end of the spectrum when compared to other research conducted in oil palm plantations in Malaysia, where $CO_2$ fluxes ranged from 0.52 to 0.97 g $m^2$ $hr^{-1}$ (Goodrick *et al* 2016). This may be attributed to several factors, including variations in soil type and structure, as well as specific environmental conditions of the study areas. Notably, the timing of this study during the rainy season, may have influenced microbial dynamics and organic matter decomposition rates, ultimately affecting the $CO_2$ emission measurements.

*5.2.2. $N_2O$ emissions*

Soil $N_2O$ production is primarily regulated by the balance between nitrification and denitrification, which in turn is controlled by soil moisture content, soil texture, oxygen availability, and nitrogen substrate supply (Del Prado *et al* 2006, Li *et al* 2022, Pan *et al* 2022). However, only a weak positive correlation ($r = 0.23$) between gravimetric soil water content and $N_2O$ emissions was observed in this study. Similar findings were reported in studies by Nishina *et al* (2009a, 2009b), which documented very low positive correlations ($r = 0.003$, $r = 0.18$) between water-filled pore space (WFPS) and $N_2O$ emissions. The weak relationship likely reflects the spatial heterogeneity in soil moisture across the study sites, where suboptimal or inconsistent moisture levels may not have uniformly supported the conditions required for peak $N_2O$ production. Study by Ciarlo *et al* (2006) demonstrated that $N_2O$ emissions are the highest when approximately 80% of soil pore spaces are water-filled. Similarly, Adviento-Borbe *et al* (2006) reported that $N_2O$ production can be 2 to 40 times higher when WFPS reaches 90%, compared to 60%. Although direct measurements of soil oxygen availability were not conducted, the clay-rich texture of the study site may have contributed to $N_2O$ emissions by limiting soil aeration. Previous studies have shown that increasing clay content can substantially reduce oxygen diffusion and soil respiration under comparable moisture conditions, promoting the formation of anaerobic microsites conducive to denitrification (Ball 2013, Moyano *et al* 2013).

Despite the weak soil moisture-$N_2O$ emission relationship at the broader scale, local interactions between soil moisture, organic residues, and nitrogen availability are important, particularly in the FH zone. A strong positive correlation ($r = 0.92$) between SOC and total nitrogen highlights the role of organic matter in supporting soil fertility and nitrogen cycling. These results align with Kasno and Subardja (2010), who observed similar dynamics in an oil palm plantation cultivated on Spodosols in West Kalimantan. In the FH zone, nitrogen is actively mineralised during organic matter decomposition, driven by elevated microbial activity. This observation corroborates the work of Formaglio *et al* (2021), who reported significantly higher gross nitrogen mineralisation, nitrification, microbial biomass carbon and nitrogen in the FH area compared to the PC and interrow zones. Plant residues accumulated in this zone can enhance soil water retention and influence soil moisture dynamics. When combined with concentrated fertiliser inputs, these conditions may intensify $N_2O$ production (Rahman *et al* 2019, Skiba *et al* 2020, Luo *et al* 2023).

Fertilisers are typically broadcasted at the FH area, particularly for matured oil palm where active feeder roots have extended beyond the PC (Pauli *et al* 2014). Common nitrogen fertilisers used in oil palm cultivation include urea and ammonium-based fertilisers such as ammonium chloride and ammonium sulphate, with the choice largely guided by cost and availability rather than environmental considerations (Pardon *et al* 2016). The sensitivity of $N_2O$ emissions to fertiliser management is illustrated by contrasting findings reported by Chen *et al* (2024), who observed higher $N_2O$ emissions in the PC rather than the FH. In their study, urea was applied directly within the PC at rates approximately 20% higher than those used in the present study, thereby shifting N availability and N transformation processes towards the PC zone. Beyond fertiliser placement, the form of nitrogen applied can further modulate $N_2O$ emission responses across different soil types. Previous work in oil palm plantations has demonstrated that $N_2O$ emissions vary substantially when different N fertilisers, such as

ammonium sulphate and coated N fertilisers, are applied to contrasting soil textures, including sandy, sandy loam, and peat soils (Sakata *et al* 2015). These findings highlights that interactions between fertiliser and soil types should be considered when developing mitigation strategies for $N_2O$ emissions in oil palm production systems.

*5.2.3. $CH_4$ emissions*

The moisture retention capabilities of the FH zone not only impact $N_2O$ emissions but also create conditions favourable for $CH_4$ production, particularly during the rainy season. When oxygen is depleted in the soil, methanogens utilise the available organic carbon to produce $CH_4$ as a metabolic byproduct (Lyu *et al* 2018). This explains the elevated $CH_4$ emissions observed in the FH zone. In contrast, the PC and HP zones, which have lower soil water content and reduced anaerobic conditions, exhibited near-zero $CH_4$ emissions. The relatively drier conditions in these zones limit the formation of anaerobic microenvironments required for methane production.

Methane emissions could also be influenced by the availability of substrates suitable for methanogenic microbes (Liu *et al* 2014). Methanogens rely predominantly on simple organic carbon compounds degraded from organic matter for anaerobic respiration (Conrad 2020). The FH with higher SOC provides an abundant supply of these substrates, thereby enhancing methanogenic activity and leading to elevated $CH_4$ emissions. In contrast, the PC and HP zones, characterised by lower SOC levels and drier soil conditions, limit substrate availability and microbial activity, resulting in negligible $CH_4$ emissions. Our findings contrast with those reported by Chen *et al* (2024), who observed net $CH_4$ uptake in oil palm plantations. This difference is likely attributable to differences in soil texture and microclimatic conditions between the studies. The higher clay content and substantially greater annual rainfall (approximately 220 mm higher) at our study site likely reduced soil gas diffusivity, limiting oxygen penetration and constraining methanotrophic activity. Consequently, the balance between $CH_4$ production and oxidation in our system appears to be shifted toward net emission rather than uptake.

### 5.3. $CO_2$-equivalent emissions in oil palm cultivation systems & management implications

The total GHG emissions across the three management zones, expressed as $CO_2$-equivalents highlight distinct emission patterns. The FH zone observed as a clear GHG emission hotspot, with the highest $CO_2$-equivalent emissions, primarily due to high $N_2O$ and $CH_4$ fluxes. The high global warming potential (GWP) of $N_2O$ and $CH_4$ made it a significant contributor to the overall GHG emissions. In contrast, HP zone with compacted soils and limited organic inputs, behaved as a relative emission coldspot within the plantation.

In oil palm plantations, fronds are systematically piled in the FH zone as part of a sustainable practice to recycle organic waste and enhance soil health. While this practice contributes to GHG emissions, particularly $N_2O$ and $CH_4$, the emissions are not at levels that significantly offset the benefits of carbon sequestration. The moderate GHG emissions observed represent a manageable trade-off, considering the substantial gains in SOM accumulation and overall soil fertility. Notably, $N_2O$ emissions from the FH zone are relatively lower compared to other cultivated systems. For instance, Acacia and eucalyptus plantations have been reported to emit up to 4 to 7.42 kg $ha^{-1}$ $h^{-1}$, while fertilised rubber plantations have shown $N_2O$ emissions up to 3.5 kg $ha^{-1}$ $h^{-1}$, underscoring the relatively moderate emissions from oil palm FHs (Ishizuka *et al* 2021, Yang *et al* 2024).

To mitigate $N_2O$ and $CH_4$ emissions in FH, practical modifications to the management of moisture conservation trenches should be considered. For instance, implementing mechanisms to open the trenches during heavy rainfall could promote drainage and reduce waterlogging, thereby minimising anaerobic conditions that favour denitrification and methane emissions in the FH zones. Additionally, optimising the timing and the selection of types of nitrogen fertilisers, such as splitting the dosage or incorporating slow-release formulations, could help limit the accumulation of nitrate and reduce the potential for $N_2O$ production.

## 6. Conclusion

The findings indicate that the FH zone, characterised by higher SOC and nitrogen levels, as well as improved soil structure significantly contributes to elevated $CO_2$, $N_2O$, and $CH_4$ emissions compared to the PC and HP zones. Nevertheless, the elevated GHG emissions were low which does not compromise the potential of strategic biomass management in oil palm plantations to enhance soil carbon sequestration. However, improper management such as prolonged water retention in moisture conservation trenches or excessive accumulation of frond residues without adequate drainage can increase soil moisture and restrict oxygen diffusion, promoting the formation of anaerobic microsites that enhance $N_2O$ and $CH_4$ emissions and create trade-offs in GHG mitigation efforts.

## Limitations and future studies

One limitation of this study is the lack of continuous, long-term measurements, which restricts insights into the temporal dynamics of GHG emissions. Seasonal variations and year-round monitoring would offer a more comprehensive understanding of the temporal patterns and variability in GHG fluxes. Nevertheless, this study can be used as a proof-of-concept that can be rolled over to multi-season and location monitoring exercise. Temporal changes in emissions are often influenced by the decomposition of organic inputs, which drive soil carbon dynamics and vary across different seasons (Moradi *et al* 2013, Wakhid and Hirano 2021). Future studies should prioritise addressing this gap by conducting continuous or periodic measurements across different (wet and dry) seasons to capture the full annual cycle.

In addition, this study did not include direct measurements of soil redox potential, which limits our ability to understand the biogeochemical controls on $N_2O$ production and consumption. Soil redox conditions strongly regulate the nitrification, denitrification, and $N_2O$ reduction pathways, particularly under fluctuating moisture regimes (Wang *et al* 2018). Incorporating direct redox monitoring in future research would enable a more robust assessment of how anaerobic conditions develop within specific management zones and how these conditions regulate $N_2O$ emissions.

Future research could also investigate the carbon dynamics of specific management zones, with particular emphasis on the role of crop residues like FHs in influencing soil carbon lability and long-term carbon storage. Comparative studies exploring various residue management strategies, such as differences in residue type and quantity, could provide critical insights into optimising carbon sequestration potential and reducing GHG emissions.

## Acknowledgments

The authors would like to express their sincere gratitude to SD Guthrie Research for providing the necessary resources and support to conduct this study. Special thanks are extended to the field and laboratory teams for their invaluable assistance with soil sampling, GHG measurements, and data analysis.

## Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.57996/cran.ceres-2830 (Data 2026).

## Funding details

This research was supported by SD Guthrie Research.

## Disclosure statement

Yu Yang Chang and Choon Cheak Sim are employed by SD Guthrie Research. The authors declare no other potential conflicts of interest.

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# Spatial variability of soil greenhouse gas emissions in oil palm plantation under different management zones

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**2026-04**
IOP Publishing
https://doi.org/10.1088/2515-7620/ae56d9
Chang YY, Sakrabani R, Golicz KK, et al., (2026) Spatial variability of soil greenhouse gas emissions in oil palm plantation under different management zones. Environmental Research Communications, Volume 8, Issue 4, April 2026, Article number 045025

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