Nutrient response efficiency, soil greenhouse gas fluxes, and nutrient leaching losses from a large-scale oil palm plantation under conventional and reduced management practices

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SUMMARY

The area of oil palm plantations has expanded rapidly in the tropics over the past few decades due to the high demand for palm oil and the considerable economic benefits. Oil palm is playing a vital role in the global vegetable oil supply and regional economic development. However, the conventional management with high fertilization rates and herbicide application from oil palm plantations brings various environmental concerns. Reduced fertilization with mechanical weeding is one of the proposed practical alternatives to conventional management, which has the potential to improve multiple ecosystem functions without sacrificing production and profit. A field full factorial oil palm management experiment (OPMX) with two fertilization rates (conventional and reduced fertilization, equal to nutrients exported via fruit harvest) and two weeding methods (herbicide and mechanical) was conducted since 2016 in a 15-year-old, large-scale oil palm plantation in Jambi, Indonesia. This thesis consists of three studies that were conducted during 3-4 years of the OPMX experiment. The main objectives were to assess differences in yield and nutrient response efficiency (study 1), soil greenhouse gas (GHG) fluxes (study 2), and nutrient leaching losses (study 3) between conventional management (conventional fertilization with herbicide weeding) and reduced management (reduced fertilization with mechanical weeding) in this mature large-scale oil palm plantation.

In the first study, the oil palm fruit yield, soil net N cycling rates, and soil mineral N stocks were measured. Nitrogen response efficiency (NRE), partial factor productivity of applied P (PFP_P) and K (PFP_K) fertilizer, and profit were calculated. The results showed that yield and soil net N cycling rates were comparable between conventional and reduced management. Reduced fertilization decreased soil mineral N stocks in 50-150 cm depth interval. Compared to conventional management, reduced fertilization with mechanical weeding increased NRE by 68%, PFP_P by 200%, PFP_K by 22%, and profit by 15%.

In the second study, soil CO_2, N_2O, and CH_4 fluxes were measured monthly for one year from three management zones, and global warming potential was calculated in this oil palm plantation. We found that soil GHG fluxes did not differ between conventional and reduced management practices. Annual soil GHG fluxes were 5.5 ± 0.2 Mg CO_2-C ha^{-1} yr^{-1}, 3.6 ± 0.7 kg N_2O-N ha^{-1} yr^{-1}, and -1.5 ± 0.1 kg CH_4-C ha^{-1} yr^{-1} across treatments. The palm circle, where fertilizers are commonly applied, covered 18% of the plantation area but accounted 79% of soil N_2O emission. The global warming potential of this planation was 3010 ± 750 kg CO_2-eq ha^{-1} yr^{-1} of which 55% was contributed by soil N_2O emission.

In the third study, soil element leaching losses at 1.5 m soil depth were measured from three management zones during 2019-2020. In conventional management, the annual element leaching was 46 kg N ha^{-1} yr^{-1}, 22 kg Al ha^{-1} yr^{-1}, 23 kg Ca ha^{-1} yr^{-1}, 9 kg K ha^{-1} yr^{-1}, 9 kg Mg ha^{-1} yr^{-1}, and 9 kg Na ha^{-1} yr^{-1}. Compared to the conventional fertilization, reduced fertilization decreased dissolved N leaching by 74%, Al leaching by 60%, and K leaching by 73%. Among the management zones, the fertilized palm circle had higher dissolved N, Al, Ca, K, Mg, and Na leaching losses than the inter-row and frond-stacked area.

Our results highlight the following findings during the first four years of the OPMX experiment. (1) Reduced fertilization with mechanical weeding maintained N availability in the topsoil ensuring a high yield, and thus improving both the nutrient response efficiency and profit. (2) Reduced fertilization with mechanical weeding cannot quickly decrease soil GHG emissions due to the strong legacy effect of over a decade of high fertilization. Reducing soil N_2O emissions is the key to reducing GHG footprint. (3) Reduced fertilization with mechanical weeding decreased N, Al, and K leaching losses compared to conventional management. Overall, our results show that reduced fertilization combined with mechanical weeding is a more sustainable management option for large-scale oil palm plantations.

ZUSAMMENFASSUNG

Die Anbaufläche von Ölpalmplantagen in den Tropen hat sich in den letzten Jahrzehnten aufgrund der hohen Nachfrage nach Palmöl und der beträchtlichen wirtschaftlichen Vorteile stark ausgeweitet. Die Ölpalme spielt eine wichtige Rolle für die weltweite Versorgung mit Pflanzenöl und die regionale wirtschaftliche Entwicklung. Die konventionelle Bewirtschaftung mit hohem Dünger- und Herbizideinsatz auf Ölpalmenplantagen ist jedoch mit verschiedenen Umweltproblemen verbunden. Eine reduzierte Düngung mit mechanischer Unkrautbekämpfung ist eine der vorgeschlagenen praktischen Alternativen zur konventionellen Bewirtschaftung, die das Potenzial hat, mehrere Ökosystemfunktionen zu verbessern, ohne die Produktion und den Gewinn zu beeinträchtigen. Ein vollfaktorielles Feldversuchsexperiment zur Ölpalmenbewirtschaftung (OPMX) mit zwei Düngungsraten (konventionelle und reduzierte Düngung, die den über die Fruchternte exportierten Nährstoffen entspricht) und zwei Unkrautbekämpfungsmethoden (Herbizid und mechanische Unkrautbekämpfung) wurde seit 2016 in einer 15 Jahre alten großflächigen Ölpalmenplantage in der Provinz Jambi, Indonesien, durchgeführt. Diese Arbeit besteht aus drei Studien, die während der 3-4 Jahre des OPMX-Versuchs durchgeführt wurden. Die Hauptziele waren die Bewertung von Unterschieden in der Ertrags- und Nährstoffreaktionsfähigkeit (Studie 1), den Treibhausgas (THG) -flüssen im Boden (Studie 2) und den Nährstoffauswaschungsverlusten (Studie 3) zwischen der konventionellen Bewirtschaftung (konventionelle Düngung mit Herbizideinsatz) und der reduzierten Bewirtschaftung (reduzierte Düngung mit mechanischem Jäten) in dieser großflächigen Ölpalmenplantage.

In der ersten Studie wurden der Ölpalmfruchtertrag, die Netto-N-Kreislaufraten des Bodens und die mineralischen N-Vorräte im Boden gemessen. Die Stickstoff-Nutzungseffizienz (NRE), die partielle Faktorproduktivität des ausgebrachten P- (PFP_P) und K-Düngers (PFP_K) und der Gewinn wurden berechnet. Die Ergebnisse zeigten, dass die Erträge und die Netto-N-Kreislaufraten des Bodens zwischen konventioneller und reduzierter Bewirtschaftung vergleichbar waren. Die reduzierte Düngung verringerte die mineralischen N-Vorräte im Boden im Tiefenintervall von 50-150 cm. Im Vergleich zur konventionellen Bewirtschaftung erhöhte die reduzierte Düngung mit mechanischer Unkrautbekämpfung die NRE um 68%, den PFP_P um 200%, den PFP_K um 22% und den Ertrag um 15%.

In der zweiten Studie wurden die CO_2-, N_2O- und CH_4-Flüsse im Boden dreier Bewirtschaftungszonen ein Jahr lang monatlich gemessen und das globale

Erwärmungspotenzial in dieser Ölpalmenplantage berechnet. Die Ergebnisse zeigten, dass sich die Treibhausgasflüsse im Boden zwischen konventioneller und reduzierter Bewirtschaftung nicht unterschieden. Die jährlichen THG-Flüsse im Boden betrugen 5,5 ± 0,2 Mg CO_2-C ha^{-1} yr^{-1}, 3,6 ± 0,7 kg N_2O-N ha^{-1} yr^{-1} und $-1{,}5 \pm 0{,}1$ kg CH_4-C ha^{-1} yr^{-1}. Der Palmenkreis, in dem üblicherweise Düngemittel ausgebracht werden, nahm 18% der Plantagenfläche ein, war aber für 79% der N_2O-Emissionen aus dem Boden verantwortlich. Das globale Erwärmungspotenzial dieser Plantage betrug 3010 ± 750 kg CO_2-eq ha^{-1} yr^{-1}, wovon 55% auf die N_2O-Emissionen des Bodens entfielen.

In der dritten Studie wurden die Auswaschungsverluste von Bodenelementen in 1,5 m Bodentiefe in den Jahren 2019-2020 in drei Bewirtschaftungszonen gemessen. Bei konventioneller Bewirtschaftung betrug die jährliche Elementauswaschung 46 kg N ha^{-1} yr^{-1}, 22 kg Al ha^{-1} yr^{-1}, 9 kg K ha^{-1} yr^{-1}, 9 kg K ha^{-1} yr^{-1}, 9 kg Mg ha^{-1} yr^{-1}, und 9 kg Na ha^{-1} yr^{-1}. Im Vergleich zur konventionellen Düngung verringerte die reduzierte Düngung die Auswaschung von gelöstem N um 74%, die Auswaschung von Al um 60% und die Auswaschung von K um 73%. Von den Bewirtschaftungszonen wies der gedüngte Palmenkreis höhere Verluste an gelöstem N, Al, Ca, K, Mg und Na auf als der Astverschnitt-Lagerungsbereich und der Bereich zwischen den Baumreihen.

Unsere Ergebnisse unterstreichen die folgenden Erkenntnisse aus den ersten vier Jahren des OPMX-Versuchs. (1) Durch die reduzierte Düngung mit mechanischer Unkrautbekämpfung blieb die N-Verfügbarkeit im Oberboden erhalten, was einen hohen Ertrag sicherte und somit sowohl die Nährstoffeffizienz als auch den Profit verbesserte. (2) Eine verringerte Düngung mit mechanischer Unkrautbekämpfung kann die THG-Emissionen im Boden nicht so schnell verringern, da die hohe Düngung über ein Jahrzehnt hinweg eine starke Altlast darstellt. Die Verringerung der N_2O-Emissionen aus dem Boden ist der Schlüssel zur Verringerung der THG-Bilanz. (3) Eine reduzierte Düngung mit mechanischer Unkrautbekämpfung verringerte die N-, Al- und K-Auswaschungsverluste im Vergleich zur konventionellen Bewirtschaftung. Insgesamt zeigen unsere Ergebnisse, dass eine reduzierte Düngung in Kombination mit mechanischer Unkrautbekämpfung eine nachhaltigere Bewirtschaftungsoption für großflächige Ölpalmenplantagen darstellt.

Chapter 1

General Introduction

1.1. Expansion of oil palm plantations

The oil palm (*Elaeis guineensis*), a woody oil plant native to Africa (Corley and Tinker 2015), produces fruit-derived palm oil which is widely used in food, industrial, and biofuels (Noleppa and Matt 2016). In the past several decades, oil palm plantations have expanded rapidly across the equatorial tropics (Comte et al. 2012) and globally, the area of oil palm plantations has increased from 4 million ha in 1980 to 28 million ha in 2019 (FAO 2021). Indonesia and Malaysia are the most significant contributors to this growth and are now the world's leading producers of palm oil (Sheil et al. 2009). The expansion of oil palm plantations is expected to continue to meet the increasing demand of a growing world population (OECD 2022). Oil palm is the most productive oil crops, yielding four to ten times more than soy, rapeseed, or sunflower under a unit area (Thomas et al. 2015) and it meets about 35% of global vegetable oil consumption using less than 10% of the oil crops' land (Meijaard et al. 2018). Due to its high yield and relatively low cost, oil palm plantations generate substantial revenues for farmers (Sheil et al. 2009). Additionally, the development of the palm oil industry has provided income and employment opportunities for millions of rural people, many of whom have been rescued from poverty (Sheil et al. 2009; Qaim et al. 2020). Therefore, oil palm plays a vital role in meeting the increasing demand for vegetable oil and promoting regional economic prosperity.

Oil palm expansion, however, drives deforestation and results in a series of negative environmental effects (Vijay et al. 2016). Between 1990 and 2005, over 50% of established oil palm plantations in Malaysia and Indonesia were converted from forests (Koh and Wilcove 2008). Tropical forests play a crucial role in regulating climate, storing carbon, providing habitat for wildlife, and supplying food and medicine (Lamb et al. 2005; Artaxo et al. 2022; Smith et al. 2023). Conversion of forests to oil palm plantations is accompanied by serious reductions in multiple ecosystem functions, including decreases in C storage (Kotowska et al. 2015; van Straaten et al. 2015), nutrient cycling and retention (Allen et al. 2015; Kurniawan et al. 2018), soil and water conservation (Sheil et al. 2009), and biodiversity losses (Clough et al. 2016). Oil palm-driven deforestation also negatively impacts forest-dependent communities who gather a variety of materials from forests (Sheil et al. 2006). Fortunately, the Roundtable on Sustainable Palm oil (RSPO), the major oil palm sustainability certification system, has incorporated protection for high conservation values forests and high carbon stock forests into its principles and criteria (RSPO 2018) that will help to halt deforestation resulting from oil palm plantation expansion.

1.2. Oil palm plantations and management practices

Oil palms are typically planted with a staggered triangle pattern, 7.5-9 m apart, and a density of 110-150 palms per hectare (Sheil et al. 2009). Although the lifespan of oil palm can exceed 120 years, they are usually replanted every 25-30 years because their fruit bunches are too high to harvest economically (Wahid et al. 2005). Oil palm plantations can be classified into smallholder plantations (< 50 ha per household, most around 2 ha and owned by individuals) and large-scale oil palm plantations (> 50 ha, can be up to 20000 ha and owned by corporations) (Lee et al. 2014; Dislich et al. 2017). Globally, large-scale oil palm plantations account for approximately 70% of the area of oil palm plantations (Descals et al. 2021) and are subject to intensive management aimed at achieving high productivity and profitability. In well managed mature oil palm plantations, 15-30 tons of fresh fruit bunches are harvested per hectare per year (Sheil et al. 2009). Fertilizer application is necessary to compensate for the massive nutrients exported via fruit harvest. Fertilizer is generally applied within 1-2 m from the trunk where have high fine root biomass (Schroth et al. 2000), and this area is called the palm circle (Fig 1.1). The senesced frond leaves are regularly pruned to facilitate harvesting and prevent the continued consumption of nutrients by senesced leaves. Those pruned frond leaves are usually stacked in every second row and this area is called as the frond-stacked area (Fig 1.1). Herbicides are applied in the oil palm plantation, except in the frond-stacked area, to control the underground weeds. Understory weed control prevents nutrient competition between weeds and oil palm and facilitates the fruit harvesting and transfer of oil palm fruits out of the plantation. The unfertilized but weeded area is called the inter-row (Fig 1.1). Therefore, conventional management practices result in three distinct management zones in large-scale oil palm plantations: the palm circle, inter-row, and frond-stacked area.

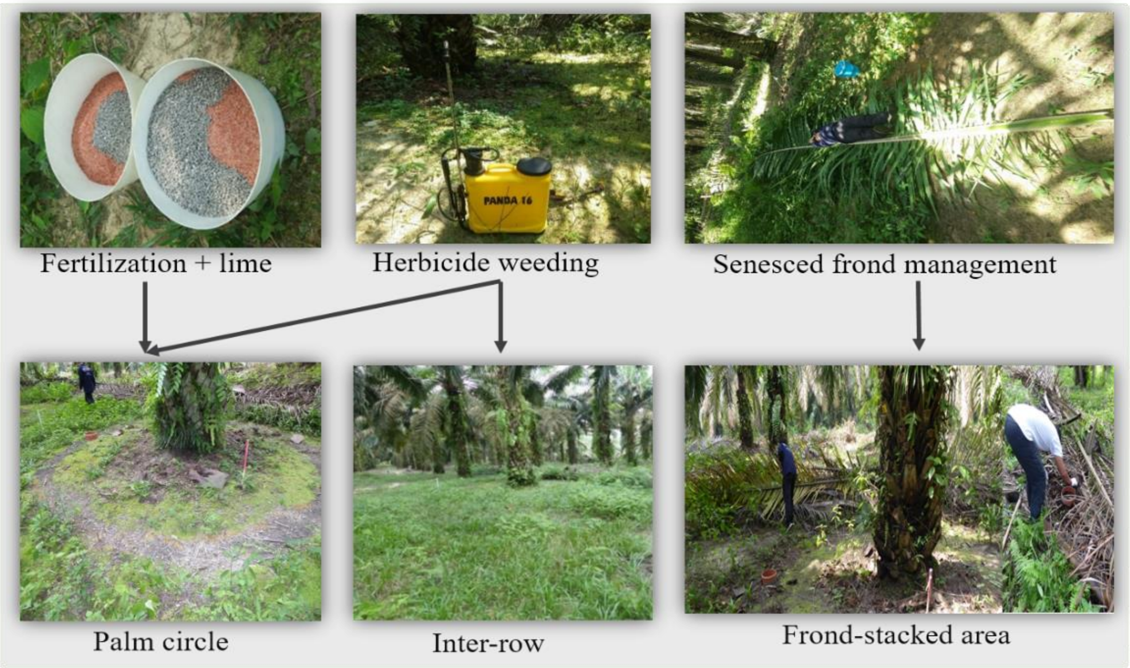

Fig. 1.1 Fertilization, herbicide application, and senesced frond management forms three distinct management zones in oil palm plantations under conventional management

Since oil palm plantations are established, they will be intensively managed for decades. Under long-term management, the three management zones have significantly different soil properties, which in turn affect various ecological processes. For soil physical properties, frequent management activities (weeding, pruning and harvesting) in the palm circle and inter-row, result in soil compaction by foot traffic. The palm circle and inter-row have higher soil bulk density than the frond-stacked area (Formaglio et al. 2021). For soil biochemical properties, the palm circle and inter-row with low organic matter input exhibit low soil organic C, microbial biomass, and nutrient cycling rates (Formaglio et al. 2021). But the fertilizer application improves the nutrient availability in the palm circle. The frond-stacked area, litter decomposition offers much organic matter to the soil and results in high soil organic C, microbial biomass, and nutrient cycling rates (Moradi et al. 2014; Rüegg et al. 2019; Formaglio et al. 2020; Dassou et al. 2021). Additionally, the palm circle and frond-stacked area had higher root biomass than the inter-row (Schroth et al. 2000).

1.3. Oil palm management experiment

Reconciling yield, profit, and ecosystem multifunctionality in oil palm plantations is key to achieving sustainable palm oil (RSPO 2018). Through improve management practices, oil palm plantations have potential to support relatively high levels of biodiversity and ecosystem functions (Popkin et al. 2022). Reducing fertilizer application and employing mechanical weeding to replace herbicide weeding is one of the proposing solutions to improve the ecosystem multifunctionality without sacrificing yield and profit. Verifying this requires data from long-term interdisciplinary collaborative field research.

A full factorial oil palm management experiment (OPMX) with two fertilization rates (260 N, 50 P, 220 K kg ha^{-1} yr^{-1} as conventional practice, and 136 N, 17 P, 187 K kg ha^{-1} yr^{-1}, equal to harvest export, as reduced management) and two weeding methods (conventional herbicide application, and mechanical weeding as reduced management) was established in November 2016 at a mature large-scale oil palm plantation on a sandy clay loam Acrisol soil in Jambi, Indonesia (Darras et al. 2019; Iddris et al. 2023). The OPMX experiment is in the framework of the interdisciplinary research project of EFForTS (Ecological and Socioeconomic Functions of Tropical Lowland Rainforest Transformation Systems). In the OPMX experiment, the research groups from multiple disciplines study yield and profit, biodiversity, and ecosystem multifunctionality including soil fertility, greenhouse gas regulation, water filtration, erosion prevention, pollination, plant refugium, biological control, litter decomposition (Darras et al. 2019; Iddris et al. 2023). The central hypothesis of OPMX is that reduced fertilization rate with mechanical weeding, compared to conventional high fertilization rate with herbicide treatment, will enhance ecosystem functions and biodiversity while maintaining high productivity and increased profit (Iddris et al. 2023).

1.4. Nutrient response efficiency, soil greenhouse gas fluxes, and nutrient leaching

Oil palm yield is linked to the ecosystem’s food provision function (Garland et al. 2021). Palm oil supply is related to global food security because the population and per capita vegetable oil consumption will continue to grow in the next decade (OECD 2022). Nitrogen response efficiency (NRE) is the amount of yield produced per unit of plant-available N, indicating the efficiency of plants in utilizing soil N resources for biomass production (Pastor and Bridgham 1999). Specific management practices including fertilization rates and underground weed control can change soil nutrients availability and root nutrient acquisition to affect yield and NRE in oil palm plantations (Pauli et al. 2014; Tao et al. 2016; Bessou et al. 2017). Enhancing NRE in oil palm plantations has both environmental and economic benefit which means reducing the negative impact of nutrient losses on the surrounding environment and cutting the costs of excessive fertilizer (Congreves et al. 2021).

Soil greenhouse gas (GHG) fluxes, including CO_2, N_2O, and CH_4, are linked to ecosystem’s GHG regulation function (Garland et al. 2021). Soil is a critical environmental compartment and act as both sources and sinks for GHG (Oertel et al. 2016). Land use change and land management practices affect the net soil GHG flux between soil and atmosphere therefore become key factors driving global climate change (Veldkamp et al. 2008; Nayak et al. 2015; Tchiofo Lontsi et al. 2020; Feng et al. 2022). Oil palm cultivation, as a significant driver of land use change in tropical area, its impact on soil GHG fluxes get much attention. Field observation has shown that compared to forests, the reduced soil organic matter, microbial biomass, and increased soil bulk density in oil palm plantations significantly decrease the soil GHG abatement capability (Aini et al. 2015; Hassler et al. 2015; Clough et al. 2016; Drewer et al. 2021). The intensity of management in oil palm plantations further affects soil GHG emissions by regulating environmental variables such as soil moisture, nutrient availability, root and microbial biomass, and soil texture. There is potential to improve the GHG regulation function through optimized management in oil palm plantations. Whereas, long-term quantitative field observations on the impact of management practices including different fertilization and weeding management on soil GHG emissions are scarce (Comte et al. 2012).

Nutrient leaching represent a significant pathway of nutrient losses from ecosystem especially for N, and is connected to ecosystem’s water purification function (Garland et al. 2021). High nutrient leaching represents losses of soil nutrients and can cause eutrophication of water system and threats to drinking water health (Schindler 2006; Wang et al. 2019). Agricultural managment practices including fertilization rate, weed control, catch crop, tillage practices can through affect both soil drainage fluxes and nutrient concentration in soil-pore water to regulate nutrient leaching fluxes (Kirchmann et al. 2002). In oil palm plantaions, high chemical fertilizer application rate can signficantly increase nutrient concentration in soil-pore water and frequantly footraffic influence water infltration, thus affecting nutrient leaching losses (Comte et al. 2012; Kurniawan et al. 2018). However, few studies have been conducted to quantify nutrient leaching in oil palm plantations, especially under different managment practices.

1.5. Objectives and hypotheses

This thesis consists of three studies that were conducted during 3-4 years of the OPMX experiment. The main objectives were to assess differences in yield and nutrient response efficiency (study 1), soil GHG fluxes (study 2), and nutrient leaching losses (study 3) between conventional management (conventional fertilization with herbicide weeding) and reduced management (reduced fertilization with mechanical weeding) taking into consideration of different management zones (the palm circle, inter-row, and frond-stacked areas) in this mature large-scale oil palm plantation.

The hypothesis of study 1 were (1) reduced management will maintain soil net N cycling rates and fruit yield compared to conventional management; (2) reduced management will maintain soil extractable mineral N stocks in the topsoil while decreasing soil mineral N stocks in the subsoil; (3) reduced management will improve nutrient response efficiency in this oil palm plantation.

The hypothesis of study 2 were (1) reduced fertilization with mechanical weeding will have similar soil CO_2 and CH_4 fluxes but lower soil N_2O emissions than the conventional fertilization with herbicide weeding; (2) the fertilized palm circle will have large soil CO_2 and N_2O emissions but small soil CH_4 uptake. The unfertilized inter-row will have small soil CO_2, N_2O emissions and CH_4 uptake. The frond-stacked area will have large soil CO_2 emissions and CH_4 uptake but small soil N_2O emissions.

The hypothesis of study 3 were (1) reduced management, with relatively low N fertilization rate, will have lower soil N and cation elements leaching losses than the conventional fertilization and have comparable soil DOC leaching with the conventional management; (2) the fertilized palm circle will have higher soil N and cation elements leaching losses than the inter-row and frond-stacked area and three management zones will have comparable soil DOC leaching.

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Chapter 2

Reduced fertilization with mechanical weeding increases nutrient response efficiency and profit in a large-scale oil palm plantation

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2.1. Abstract

Conventional management with high fertilization rate and herbicide application results in high yield in oil palm plantations, but corresponding low fertilizer use efficiency causes various environmental problems. This study aimed to assess a practical alternative to conventional management, reduced fertilization with mechanical weeding, to improve nutrient response efficiency without sacrificing production and profit. Since 2016 we conducted a full factorial experiment with two fertilization rates (conventional and reduced fertilization, equal to nutrients exported via fruit harvest) and two weeding methods (herbicide and mechanical) in a ≥ 15-year-old, mature large-scale oil palm plantation in Indonesia. Between 2017–2020 we measured soil net N cycling rates in the top 5 cm (22 monthly measurements) and fresh fruit yield. Furthermore, soil extractable mineral N stocks from 0-50 cm, 50-100 cm, and 100-150 cm depth intervals were measured after 5 years of treatments. Nitrogen response efficiency (NRE), partial factor productivity of applied P (PFP_P) and K (PFP_K) fertilizer were calculated. Fresh fruit yield (30 ± 1 Mg ha^{-1} yr^{-1}) and soil net N cycling rates did not differ among treatments. Compared to conventional fertilization, soil extractable mineral N stocks from reduced fertilization were comparable at 0-50 cm depth interval but lower at 50-150 cm depth interval. Reduced fertilization with mechanical weeding increased NRE by 68%, PFP_P by 200%, PFP_K by 22%, and profit by 15% compared to conventional management. During the first four years of treatment, reduced fertilization with mechanical weeding maintained N availability in the top 50 cm soil ensuring a high yield, and thus improving both the nutrient response efficiency and profit. Our results show that reduced fertilization combined with mechanical weeding is a more sustainable management option for large-scale oil palm plantations, which can even increase profit.

Keywords: Fertilization management; Indonesia; Tree cash crop plantation; Weeding practices; Nutrient response efficiency

2.2. Introduction

Palm oil, derived from oil palm fruits, is widely used in food, cosmetics, and biofuels (Thomas et al. 2015) and represents approximately 35% of global vegetable oil consumption (Meijaard et al. 2018). Oil palm is a productive crop, yielding four to ten times more than soy, rapeseed, or sunflower on a per-unit area basis (Thomas et al. 2015; Meijaard et al. 2018). Oil palm is also a profitable tropical cash crop that can increase income for farm and non-farm households, and improve their livelihoods (Sheil et al. 2009; Bou Dib et al. 2018).

Due to the high demand for palm oil and the considerable economic benefits, the area of oil palm plantations has rapidly increased in the past decades, especially in Southeast Asia (Sheil et al. 2009; Danylo et al. 2021). For example, Indonesia and Malaysia increased their oil palm-planted area from 1 million ha in 1980 to 20 million ha in 2019 (FAO 2021) which made them the world's leading palm oil producers. However, this expansion of oil palm plantations also resulted in wide-spread deforestation (Vijay et al. 2016; Pendrill et al. 2022), resulting in biodiversity losses (Koh and Wilcove 2008; Clough et al. 2016; Meijaard et al. 2018) and degradation of ecosystem multifunctionality (Dislich et al. 2017; Iddris et al. 2023), such as soil nutrient retention (Allen et al. 2015; Kurniawan et al. 2018), carbon storage (Kotowska et al. 2015; van Straaten et al. 2015), and greenhouse gas abatement (Hassler et al. 2017; Drewer et al. 2021). There is general agreement that a more sustainable oil palm management with less environmental impact while reconciling the high yield and economic benefits would be a substantial contribution to improve this situation (RSPO 2018).

The maximum attainable oil palm yield is currently realized in large-scale oil palm plantations (> 50 ha planted area and owned by corporations) through intensive management practices, including high rates of fertilizer and herbicide application over a rotation cycle of 25-30 years. Indeed, fertilizer consumption for oil palm cultivation has increased from 2.6 Mt of nutrients in 2006 to 5.0 Mt of nutrients in 2014 (Heffer 2009, 2017). In Malaysia, oil palm plantations account for 89% of the country's fertilizer consumption and in Indonesia this is 57% (Ludemann et al. 2022). Whereas high fertilization rates guarantee the nutrient requirements of oil palm, fertilization rates beyond an optimal rate do not further increase yield. Woittiez et al. (2017) summarized three studies on the yield response in different fertilization rates in oil palm plantations and found that, fertilizer application can improve oil palm yield compared with unfertilized plantation. However, the yield does not increase continuously with the increase of applied fertilization rates. Instead, high fertilization rates, beyond optimal rates, can cause serious environmental concerns in oil palm plantations, such as high emissions of soil N_2O, a potent greenhouse gas and an agent of ozone depletion (Davidson et al. 2000; Aini et al. 2015; Hassler et al. 2017; Rahman et al. 2019), and substantial N leaching losses (Formaglio et al. 2020) that lead to eutrophication and threaten drinking water safety (Wang et al. 2013). Furthermore, fertilizer costs represent a major component of material expenditure in oil palm plantations (Pauli et al. 2014; Pardon et al. 2016). Controlling understory weeds is another essential management practice in oil palm plantations to avoid competition for nutrients and facilitate the high frequency fruit harvests (about every 10 days) (Meijaard et al. 2018; Tohiran et al. 2019). Herbicides are widely used in oil palm plantations that can conveniently and quickly kill understory plants (Tohiran et al. 2017). However, herbicide weeding poses potential health risk, reduces understory vegetable diversity, soil fauna biodiversity, and litter decomposition rate in oil palm plantations (Ashton-Butt et al. 2018). Moreover, a typical oil palm plantation uses up to 90% of its pesticide budget on herbicides, which represents a significant material cost (Ashton-Butt et al. 2018). Implementation of reduced fertilization in combination with mechanical weeding has the potential to improve nutrient response efficiency and ecosystem multifunctionality without sacrificing yield and profit in oil palm plantations. However, the effect of different fertilization rates and weeding methods on yield, soil N cycling, and nutrient response efficiency in oil palm plantations remain unknown.

Nitrogen response efficiency (NRE) is an index reflecting the efficiency of plants in using soil N resources to produce biomass (Pastor and Bridgham 1999); for crops, NRE is calculated as the yield produced per unit of plant-available N (Schmidt et al. 2021). Plant-available N is quantified as the sum of annual soil net N mineralization rate, N fertilization, and N deposition through rainfall (Schmidt et al. 2021). Compared with partial factor productivity (PFP) from applied N fertilizer, which measures the amount of biomass produced per unit of applied N fertilizer (Cassman et al. 2002), NRE takes into account the mineral N supply capacity through inherent soil mineralization. NRE is more suitable for assessing N efficiency in oil palm plantations because the years of intensive fertilization will have a strong legacy effect on soil N cycling (Formaglio et al. 2021). According to nutrient response curve theory, if higher N fertilization leads to substantially higher biomass production and/or crop yield, NRE will increase or at an optimum. However, if the increase in N fertilization has limited or no yield improvement, NRE will consequently decrease (Pastor and Bridgham 1999). In the field, measurements of soil net N mineralization rates are frequently conducted in the top 5-10 cm soil, which only covers a portion of oil palm's root vertical distribution (Nodichao et al. 2011). However, deeper soil mineral N stocks can also contribute to soil N availability in oil palm plantations. This is especially the case in deeply weathered soils in tropical regions, where highly weathered acidic soils with low activity clays often have a substantial anion exchange capacity (Veldkamp et al. 2020). Under intensive management agriculture, excessive N fertilizer application will be leached and increase soil NO_3^- stocks in the subsoil (Rasiah et al. 2003; Neill et al. 2013; Tully et al. 2016; Huddell et al. 2022). Thus, over-fertilization tends to increase soil mineral N stocks below the root zone in highly weathered acidic tropical soils.

In oil palm plantations, management practices, including fertilization, herbicides application, and mulching with pruned and senesced fronds are conducted in different spatial areas, forming three distinct management zones: the palm circle (weeded and fertilized) around the palm trees, the frond-stacked area (where pruned fronds are piled) and the inter-row (basically the remainder of the plantation which is weeded but not fertilized) (Nelson et al. 2014; Carron et al. 2015; Ashton-Butt et al. 2018). Fertilizer application in the palm circle offers nutrients where root uptake is the highest, however it also leads to high N leaching losses because of the high nutrient concentrations, following fertilization, which often surpass the immediate uptake (Kurniawan et al. 2018). Frond litter decomposition contributes significant amounts of organic matter and nutrients to the soil from the frond-stacked area, resulting in higher soil organic C, microbial biomass, and gross N cycling rates than other zones (Formaglio et al. 2021). It is thus essential to consider the spatial distribution among the management zones, when assessing plant-available N and soil mineral N stocks in oil palm plantations.

In this study, we evaluated soil net N cycling (0-5 cm depth), soil mineral N stocks (0-150 cm depth), palm yield, NRE, partial factor productivity from applied P (PFP_P) and K fertilizer (PFP_K) under conventional management (conventional fertilization with herbicide weeding) and reduced management (reduced fertilization which compensates for the nutrients exported via fruit harvest together with mechanical weeding) by taking into consideration the different management zones in a mature large-scale oil palm plantation. Additionally, we assessed the relationship between nutrient response efficiency and profit among different management systems. Our hypothesis were that (1) reduced management will maintain soil net N cycling rates and palm yield compared to conventional management; (2) reduced management will maintain soil extractable mineral N stocks in the topsoil while decreasing soil mineral N stocks in subsoil; (3) reduced management will improve NRE, PFP_P and PFP_K in this oil palm plantation.

2.3. Materials and methods

2.3.1. Site description and experimental design

This study was conducted in a large-scale oil palm plantation (1°43′8″ S, 103°23′53″ E, 73 m above sea level) located in Jambi province, Indonesia. The plantation covers an area of 2025 ha and has a planting density of 142 palms ha^{-1}. Oil palms were planted between 1998 and 2002 in a triangular pattern with 8 m spacing between palms. The research area had a mean annual air temperature of 26.9 ± 0.2 °C and a mean annual precipitation of 2078 ± 155 mm from 2010 to 2020. The plantation follows conventional management practices which result in three distinct management zones (Fig. S2.1). Fertilizer and lime were applied only within a 2 m radius around each palm base where also herbicides were applied quarterly. This area is referred to as the palm circle, covering 18% of the total plantation area. Senesced fronds were piled in the middle of every second palm row where no fertilizer and herbicide were applied. This area is referred to as the frond-stacked area and covers 15% of the total area. The remaining area is referred to as the inter-row, covering 67% of the area, and was weeded every six months but without fertilizer application (Fig. S2.1). The soil is Acrisol soil with sandy clay loam texture. The general soil characteristics of three management zones are summarized in Table S2.1. Briefly, these three management zones had comparable soil texture but the frond-stacked area had higher soil organic C, total N and lower bulk density than the palm circle and inter-row. In the study area, oil palm roots are mainly distributed in the 0–1 m soil depth with > 80% of fine roots were located in the top 50 cm depth (Kurniawan et al. 2018).

In November 2016 we started a management experiment using a 2^2 factorial design with two fertilization rates and two weeding methods in this large-scale oil palm plantation. The experiment had four treatments: conventional fertilization – herbicide weeding (ch), conventional fertilization – mechanical weeding (cw), reduced fertilization – herbicide weeding (rh), and reduced fertilization – mechanical weeding (rw). There were four replicate blocks and each block had four 50 m × 50 m plots representing the four treatments (Fig. S2.1). Conventional fertilization (260 kg N – 50 kg P – 220 kg K ha^{-1} $year^{-1}$) and herbicide weeding (1.5 L glyphosate ha^{-1} $year^{-1}$ in the palm circle and 0.75 L glyphosate ha^{-1} $year^{-1}$ in the inter-row) followed the common practices in large-scale oil palm plantations in Jambi, Indonesia (Formaglio et al. 2020). Reduced fertilization had the same frequency as conventional fertilization but the rate (136 kg N – 17 kg P –187 kg K kg ha^{-1} $year^{-1}$) was equal to nutrients exported via fruits harvest (details calculation provided by Formaglio et al. 2021). Mechanical weeding was carried out using a brush cutter at the same frequency as the herbicide applications. Fertilizer was divided into two equal parts and typically applied in April and October. Herbicide was applied into quarterly applications in the palm circle and two applications in the inter-row. The fertilizer sources were urea, triple superphosphate, muriate of potash, or NPK-complete. All treatments received the same rates of lime (426 kg dolomite ha^{-1} $year^{-1}$) and micronutrients (142 kg micro-mag ha^{-1} $year^{-1}$ with 0.5% B_2O_3, 0.5% CuO, 0.25% Fe_2O_3, 0.15% ZnO, 0.1% MnO and 18% MgO) in the palm circle. To avoid edge effects, all measurements including soil analysis and fruit yield recording were carried out in the inner 30 m × 30 m area of each 50 m × 50 m plot.

2.3.2. Soil net N cycling rates and mineral N stocks

Soil net N mineralization and nitrification rates were measured monthly from March 2017 until February 2018 during 1.5 years of this management experiment and again monthly from July 2019 until June 2020 during 3.5 years of this experiment. The soil net N cycling rates were measured by buried bag method using in-situ incubations of intact soil cores (Hart et al. 1994). Measurements were conducted in the three management zones in all 16 plots, totaling to 96 measurements on each month (Fig. S2.1). On each monthly measurement, two soil cores (0–5 cm depth) were collected from each management zone; one soil core was extracted immediately (T_0) for mineral N and the other pair was placed in a plastic bag, buried back at the original position and incubated in the field for 7 days (T_7) before mineral N extraction. For mineral N extraction in the field, a soil sample was added to a prepared bottle containing 150 mL 0.5 M K_2SO_4. Upon arrival at the field laboratory, extraction proceeded by shaking the bottles for 1 hour and the extracts were filtered and frozen immediately in 20 mL vials until analysis. Soil gravimetric moisture content was measured by oven-drying at 105°C for 24 h and was used to calculate the dry mass of soil extracted for mineral N. We were unable to conduct soil net N cycling rate measurements in April and May 2020 due to restrictions from the COVID-19 pandemic.

All frozen extracts were transported to Goettingen University by air freight for analysis. The concentration of NH_4^+–N and NO_3^-–N were measured using continuous flow injection colorimetry (SEAL Analytical AA3, SEAL Analytical GmbH, Norderstedt, Germany). Soil extractable mineral N content was calculated as the sum of extractable NH_4^+–N and NO_3^-–N. Soil net N mineralization rates were calculated as (mineral N in T_7 – mineral N in T_0) / 7 days and soil net nitrification rates were calculated as (nitrate in T_7 – nitrate in T_0) / 7 days (Martinson et al. 2013). For plot-level estimate of soil net N mineralization or nitrification rate, area-weighted value was calculated using the areal coverages of the three management zones (see above). Annual soil net N mineralization rate in each plot was calculated as the average over the whole year of net N mineralization rates × 365 days.

As a supporting parameter, we measured in March 2021 the extractable mineral N stocks from the three management zones at three depths intervals: 0–50 cm, 50–100 cm, and 100–150 cm. Two sampling points were randomly selected in each management zone in each plot and soil samples were collected using a soil auger and pooled for each management zone and each soil depth interval. Soil mineral N was extracted using the same procedures described above. Soil extractable mineral N stocks were calculated based on the measured soil bulk density from each soil depth interval in each management zone (bulk density data from Formaglio et al. 2020).

2.3.3. Yield, nutrient response efficiency, and profit

The weight of harvested fresh fruit bunches was measured from each of the oil palms located within the inner 30 m × 30 m area of each replicate plot during 2017-2020. The annual palm yield was calculated as the average annual yield per palm in each plot × palm density (142 palms per ha). Mean annual palm yield was calculated in three time-ranges: 2017–2018, 2019–2020, and 2017–2020. Plant-available N was expressed in annual value, summing the annual soil net N mineralization rate over a year, N fertilization rate, and N deposition through rainfall, quantified previously in the same study area (12.9 kg N ha^{-1} $year^{-1}$, Kurniawan et al. 2018). Nitrogen response efficiency (NRE) was calculated as the fresh weight of annual palm yield (mean of 2017–2018 or 2019–2020) divided by the annual plant-available N of the corresponding periods when we measured the soil net N mineralization rates (March 2017 – February 2018 and July 2019 – June 2020) (Pastor and Bridgham 1999). Partial factor productivity from applied P (PFP_P) and K fertilizer (PFP_K) were calculated as the fresh weight of annual palm yield (mean of 2017–2020) divided by the annual P and K fertilization rates (Cassman et al. 2002).

Moreover, we assessed the relationships of NRE, PFP_P, and PFP_K with profit, using the data of annual profit (mean of 2017–2020) from this oil palm management experiment (Iddris et al. 2023). Shortly, profit was calculated as the revenues minus material costs minus labor costs. Revenues were calculated from the yield multiplied by the price of the fruit bunches. Material costs included fertilizers, herbicides, and gasoline for the brush cutter. Labor costs included harvesting, fertilizing, and weeding operations. Detailed material costs and labor hours were recorded in 2017 from each plot, and labor costs were calculated from the minimum wage in Jambi and the labor hours. To be consistent with cost data (materials and wages) recorded in 2017, we used fruit bunches’ price data of 2016-2017. Because our focus was management effects, profit was calculated using the same fruit prices and costs for all four years. Thus, we were able to assess the profit differences depending on management practices only and excluding exogenous factors such as e.g. price fluctuations, changes in wages, etc.

2.3.4. Statistical analysis

Each parameter was first tested for normal distribution using Shapiro-Wilk’s test and equality of variance using Levene’s test. Parameters with non-normal distributions or unequal variances were log-transformed. For net N mineralization and nitrification rates that were measured monthly, linear mixed-effects (LME) models with Tukey's HSD test were used to assess the differences among treatments or management zones. First, differences in soil net N cycling rates among treatments were analyzed for each management zone with fertilization, weeding, and their interaction as fixed effects and measurement dates and plots as random effects. Since there was no significant treatment effect (fertilization, weeding and their interaction had $p > 0.05$) in each management zone, we further tested the differences in soil net N cycling rates among management zones across treatments with management zone as fixed effect and measurement dates and plots as random effects. The LME models further included a variance function (to account for heteroscedasticity of the fixed-factor variances) and/or a first-order temporal autoregressive process (to account for decreasing autocorrelation between sampling days with increasing time interval), if this improved the model performance based on Akaike information criterion. For annual plant-available N, palm yield, NRE, PFP_P, and PFP_K, the effects of fertilization, weeding and their interaction were tested by factorial ANOVA with Tukey's HSD test. For soil mineral N stocks measured in 0-150 cm depth at three equal depth intervals, the treatment effects were analyzed for each management zone separately for each depth interval using factorial ANOVA with Tukey's HSD test. To assess whether treatment effects on mineral N stocks were expressed distinctly at depths, differences among three depth intervals was conducted for each treatment and management zone using one-way ANOVA with Tukey's HSD test. The statistical significance for all the tests was set at $p \leq 0.05$. All data analyses were performed using R version 4.0.5 (R core Team 2021).

2.4. Results

2.4.1. Soil net N cycling rates and mineral N stocks

During 2017–2018, soil net N mineralization and nitrification rates from the palm circle and frond-stacked area were higher than the inter-row ($p < 0.01$; Table 2.1). During 2019–2020, soil net N mineralization and nitrification rates followed the order: the palm circle > frond-stacked area > inter-row ($p < 0.01$; Table 2.1). Fertilization and weeding treatments did not affect area-weighted soil net N mineralization and nitrification rates in the two measurement periods (fertilization: p = 0.45–0.91, weeding: p = 0.56–0.91, their interaction: p = 0.63–0.73; Table 2.1).

Across treatments, the palm circle had higher soil extractable mineral N stocks than the inter-row and frond-stacked area in 0–150 cm soil depth ($p < 0.01$; Fig. 2.1). In the palm circle under conventional fertilization, 0–50 cm soil depth interval had lower extractable mineral N stocks than 50–100 cm and 100–150 cm soil depth interval ($p < 0.01$; Fig. 2.1). However, in the palm circle under reduced fertilization, three soil depth had comparable soil extractable mineral N stocks ($p = 0.20$; Fig. 2.1). In the inter-row, 0–50 cm, 50–100 cm and 100–150 cm soil depth intervals had comparable soil extractable mineral N stocks across treatments ($p = 0.96$; Fig. 2.1). In the frond-stacked area, mineral N stocks from 0–50 cm soil depth interval was larger than 50–100 cm and 100–150 cm soil depth intervals across treatments ($p < 0.01$; Fig. 2.1). Fertilization treatments did not affect soil mineral N stocks at 0–50 cm soil ($p > 0.10$; Fig. 2.1). Conventional fertilization from each management zone had higher soil NO_3^-–N stock than reduced fertilization at 50–100 cm and 100–150 cm soil depth interval ($p < 0.02$; Fig. 2.1). In the palm circle, conventional fertilization at 100–150 cm soil depth interval had a higher soil NH_4^+–N stock than reduced fertilization ($p = 0.03$; Fig. 2.1).

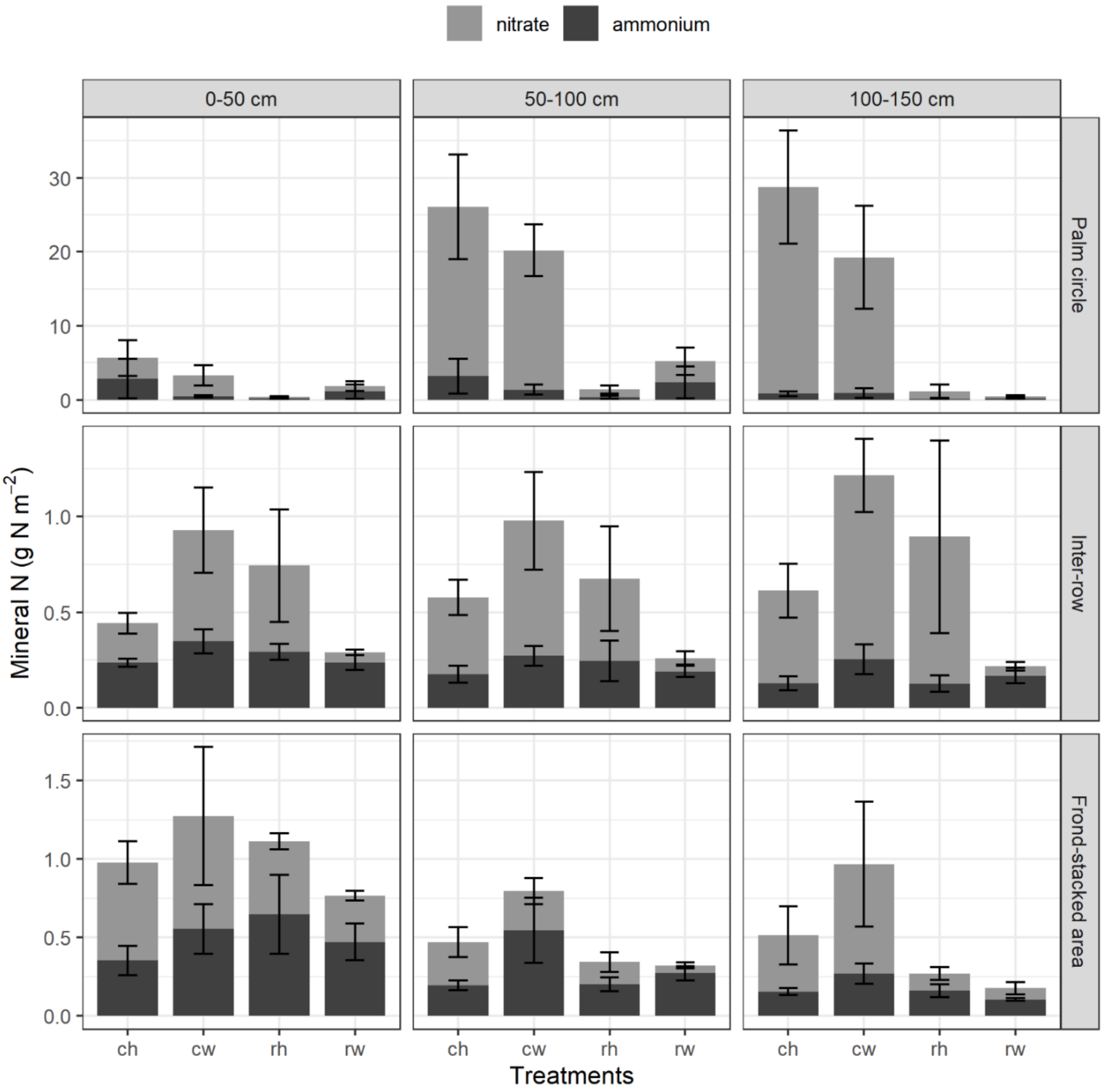


Fig. 2.1 Soil extractable mineral N contents (mean ± SE, *n* = 4 plots) within 0–50 cm, 50–100 cm, and 100–150 cm depths in different fertilization and weeding treatments of a large-scale oil palm plantation, Jambi, Indonesia, measured in March 2021. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

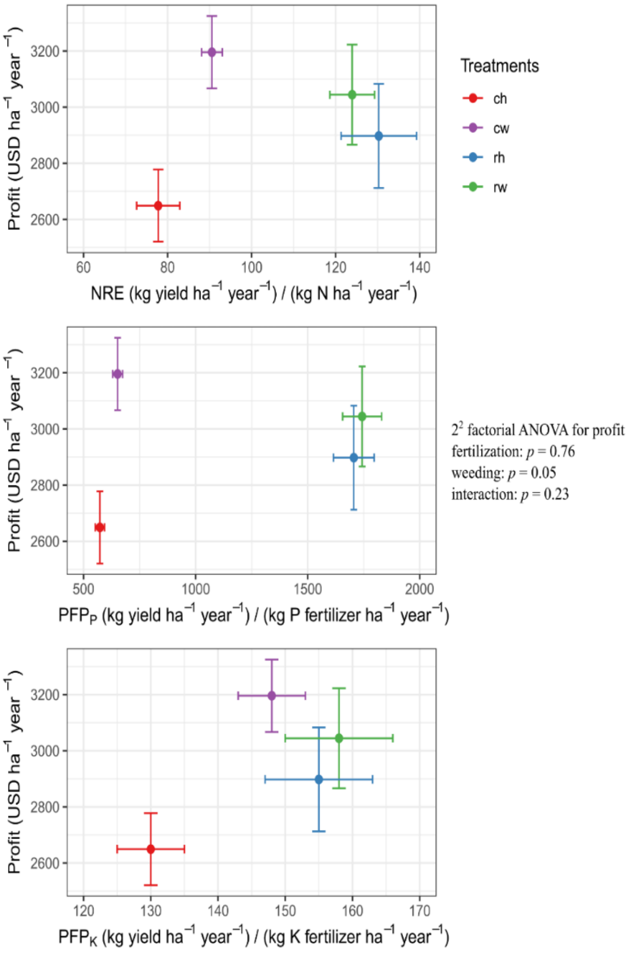
Table 2.1 Net nitrogen mineralization and nitrification rates (mean ± SE, *n* = 4 plots) in the top 5 cm soil from each management zone in different fertilization and weeding treatments of a large-scale oil palm plantation, measured monthly during March 2017– February 2018 and July 2019 – June 2020

Parameters	Measurement period	Management zones	Treatments				LME *p*-value numDF = 1, denDF = 12			Across treatments
			ch	cw	rh	rw	Fertilization	Weeding	Interaction	
Net N mineralization (mg N m^{-2} day^{-1})	2017–2018	Palm circle	35.4 ± 3.0	48.1 ± 17.5	27.9 ± 4.9	52.7 ± 34.3	0.20	0.55	0.81	41.0 ± 9.1 a
		Inter-row	12.3 ± 1.7	13.8 ± 2.7	16.7 ± 3.3	17.8 ± 1.5	0.19	0.88	0.98	15.1 ± 1.2 b
		Frond-stacked area	39.2 ± 3.5	33.8 ± 5.1	35.9 ± 6.3	34.9 ± 4.9	0.52	0.72	0.38	36.0 ± 2.3 a
		Area-weighted	20.5 ± 1.0	23.0 ± 1.4	21.6 ± 2.2	26.7 ± 7.2	0.89	0.86	0.73	22.9 ± 1.8
	2019–2020	Palm circle	128.2 ± 45.4	36.2 ± 10.4	24.1 ± 5.2	70.0 ± 31.3	0.21	0.51	0.31	64.6 ± 16.4 a
		Inter-row	10.7 ± 1.7	18.4 ± 4.4	12.4 ± 3.0	14.5 ± 3.8	0.73	0.14	0.40	14.0 ± 1.7 c
		Frond-stacked area	34.3 ± 3.3	42.0 ± 8.8	53.7 ± 16.9	24.4 ± 4.9	0.78	0.10	0.08	38.6 ± 5.3 b
		Area-weighted	34.2 ± 8.5	25.1 ± 5.0	20.2 ± 4.1	25.9 ± 8.6	0.45	0.91	0.71	26.4 ± 3.3
Net N nitrification (mg N m^{-2} day^{-1})	2017–2018	Palm circle	35.8 ± 3.8	42.3 ± 13.2	30.7 ± 5.9	44.2 ± 24.3	0.26	0.37	0.78	38.2 ± 6.5 a
		Inter-row	13.2 ± 2.0	15.0 ± 2.4	18.1 ± 3.9	20.0 ± 1.9	0.10	0.77	0.93	16.6 ± 1.4 b
		Frond-stacked area	40.8 ± 4.0	36.6 ± 5.6	38.1 ± 5.4	38.3 ± 4.6	0.57	0.88	0.37	38.5 ± 2.2 a
		Area-weighted	21.4 ± 0.8	23.1 ± 1.0	23.4 ± 2.6	27.1 ± 5.4	0.60	0.83	0.70	23.8 ± 1.5
	2019–2020	Palm circle	89.1 ± 31.0	35.8 ± 8.8	61.7 ± 25.2	101.9 ± 35.1	0.95	0.41	0.25	72.1 ± 13.7 a
		Inter-row	10.2 ± 1.4	15.9 ± 2.7	11.0 ± 2.2	12.1 ± 1.7	0.64	0.06	0.31	12.3 ± 1.1 c
		Frond-stacked area	34.8 ± 3.7	43.8 ± 9.1	53.8 ± 17.6	26.9 ± 5.1	0.94	0.24	0.09	39.8 ± 5.3 b
		Area-weighted	26.6 ± 6.0	23.7 ± 3.7	26.5 ± 4.9	30.5 ± 7.5	0.91	0.56	0.63	26.8 ± 2.6

Different letters indicate significant differences among management zones for each measurement period (2^2 factorial ANOVA with linear mixed-effects models (LME) and Tukey HSD test at $p \leq 0.05$); numDF and denDF are numerator and denominator degrees of freedom, respectively. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

2.4.2. Yield, nutrient response efficiency, and profit

Regardless of treatments, there was no detectable inter-annual differences in palm yield, plant-available N, and NRE between the two measurement periods (2017–2018 and 2019–2020) ($p \geq 0.59$; Table 2.2). Fertilization and weeding treatments did not affect palm yield during 2017–2020 (fertilization: $p = 0.38$–0.53, weeding: $p = 0.12$–0.36, their interaction: $p = 0.12$–0.35; Table 2.2). Reduced fertilization had lower plant-available N and higher NRE than conventional fertilization (both $p < 0.01$; Table 2.2). Reduced fertilization also had higher $\mathrm{PFP_P}$, and $\mathrm{PFP_K}$ than the conventional fertilization ($p \leq 0.02$; Table 2.2). Reduced management had lower material cost than conventional management (fertilization: $p < 0.01$, weeding: $p < 0.01$; Table S2.2). Although mechanical weeding had higher labor cost than herbicide weeding (weeding: $p = 0.03$; Table S2.2), mechanical weeding resulted in higher profit than herbicide weeding (weeding: $p = 0.05$; Table S2.2). Compared with conventional fertilization with herbicide weeding, reduced fertilization with mechanical weeding improved the NRE, $\mathrm{PFP_P}$, $\mathrm{PFP_K}$ and profit in this large-scale oil palm plantation (Fig. 2.2).



2^2 factorial ANOVA for profit
fertilization: $p = 0.76$
weeding: $p = 0.05$
interaction: $p = 0.23$

Fig. 2.2 Relationships of profit with nitrogen response efficiency (NRE) and partial factor productivity from applied P ($\mathrm{PFP_P}$) and K fertilizers ($\mathrm{PFP_K}$) across different fertilization and weeding treatments in a large-scale oil palm plantation (mean ± SE of each treatment, based on 4 replicate plots during 2017–2020 measurement period). NRE = yield / plant-available N; $\mathrm{PFP_P}$ = yield / P fertilization rate; $\mathrm{PFP_K}$ = yield / K fertilization rate (see Table 2.2). ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

Table 2.2 Plant-available N, palm fruit yield, nitrogen response efficiency (NRE) (mean ± SE, *n* = 4 plots) and partial factor productivity from applied P (PFP_P) and K fertilizers (PFP_K) in different fertilization and weeding treatments of a large-scale oil palm plantation, measured during 2017–2020

Treatments	Plant-available N (kg N ha^{-1} year^{-1})		Yield (kg ha^{-1} year^{-1})		NRE (kg yield ha^{-1} year^{-1})/ (kg N ha^{-1} year^{-1})		PFP_P (kg yield ha^{-1} year^{-1})/ (kg P applied ha^{-1} year^{-1})	PFP_K (kg yield ha^{-1} year^{-1})/ (kg K applied ha^{-1} year^{-1})
	2017–2018	2019–2020	2017–2018	2019–2020	2017–2018	2019–2020	2017–2020	2017–2020
ch	348 ± 4 a	402 ± 32 a	28774 ± 1368 a	28527 ± 783 a	83 ± 4 b	73 ± 8 b	573 ± 21 b	130 ± 5 b
cw	357 ± 5 a	365 ± 18 a	33256 ± 784 a	31929 ± 2121 a	93 ± 3 b	88 ± 5 b	652 ± 22 b	148 ± 5 b
rh	228 ± 8 b	224 ± 17 b	28156 ± 2431 a	29848 ± 1147 a	125 ± 14 a	136 ± 12 a	1706 ± 91 a	155 ± 8 a
rw	246 ± 26 b	244 ± 32 b	30310 ± 2676 a	28942 ± 565 a	125 ± 11 a	123 ± 11 a	1743 ± 87 a	158 ± 8 a
Fertilization	< 0.01	< 0.01	0.38	0.53	< 0.01	< 0.01	< 0.01	0.02
Weeding	0.15	0.89	0.12	0.36	0.44	0.59	0.12	0.14
Interaction	0.72	0.36	0.35	0.12	0.49	0.13	0.26	0.30

Plant-available N = annual net N mineralization rate in the top 5 cm soil + N fertilization rate + N deposition rate. NRE = yield / plant-available N. PFP_P = yield / P fertilization rate. PFP_K = yield / K fertilization rate. Different letters within the column indicate significant differences among treatments (2^2 factorial ANOVA with Tukey HSD test at $p \leq 0.05$). ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

2.5. Discussion

2.5.1. Soil mineral N cycling and stocks under different management practices

The comparable soil net N mineralization rates in reduced and conventional fertilization (Table 2.1) indicate that despite substantial differences in N fertilizer applications, both treatments had similar soil N availability for oil palm through internal soil N cycling in the topsoil, which supports our first hypothesis. This finding was consistent with comparable gross N mineralization and gross N immobilization rates that were measured 1.5 years after the start of the experiment (Formaglio et al. 2021). We interpret this finding as an indication of substantial legacy effects, especially in the palm circle management zone, following decades of conventional high rates of N fertilizer application prior this experiment. Similar findings that net N mineralization was affected by prior soil N status were e.g. reported in N-saturated forest soils, where mineral N additions had almost no effect on soil N mineralization rates (Gilliam et al. 2001). Martinson et al. (2013) also found that N addition did not increase soil net nitrification rates in tropical forest soils with a large net mineralization rate. In our study, the palm circle represents only 18% of the plantation area, which means that even in reduced fertilization management, this area still receives high rates of N fertilizer application. The implication of our finding is that the reduced rate of fertilizer application is sufficient to maintain yield in the mature phase of the oil palm plantation without affecting yield, which is an important step toward optimizing its nutrient management.

Compared to conventional management, stocks of soil extractable mineral N in reduced fertilization treatment were comparable in 0-50 cm depth interval, but lower in 50-150 cm soil depth interval, especially in the fertilized palm circle (Fig. 2.1), supporting our second hypothesis. This result is in line with findings in Brazilian soybean-maize cropping systems, where 0-1 m soil extractable NO_3^- stocks decreased from 74 kg N ha^{-1} under fertilization with 200 kg N ha^{-1} year^{-1}, to 34 kg N ha^{-1} under fertilization with 80 kg N ha^{-1} year^{-1} (Jankowski et al. 2018). The decreased soil mineral N stocks indicated amelioration of N fertilizer overuse and supported earlier findings that reduced fertilization decreased soil NO_3^- leaching losses in this experiment (Formaglio et al. 2020). Although no significant reduction of soil N_2O emission during 3-4 years of treatments were observed (Iddris et al. 2023), we expect that lower soil N_2O emissions may occur in the future because the nitrate stocks have already reduced in the 50-150 cm soil depth interval after 5 years of treatments.

2.5.2. Soil mineral N cycling and stocks from three management zones

The observed differences in soil net N cycling rates (Table 2.1) and soil extractable mineral N stocks (Fig. 2.1) among management zones were probably the result of management practices. The palm circle and frond-stacked area exhibited higher soil net N cycling rates than the inter-row (Table 2.1), suggesting that both chemical N fertilizer application and frond litter input increased soil N cycling. These results were similar to studies where N fertilizer and/or leaf litter addition enhance soil N cycling in forests or plantations (Gurlevik et al. 2004; Nave et al. 2009; Xiao et al. 2020; Yan et al. 2022). Correspondingly, the inter-row area with minimal litter input and no fertilizer application displayed low net N cycling rates. The high soil extractable NO_3^- stocks in the fertilized palm circle (Fig. 2.1) are probably a reflection of the high anion exchange capacity in these highly weathered Acrisol soils with pH between 4.8–5.0 (Table S2.1). Similarly, considerable deep soil nitrate stocks were observed in fertilized agricultural systems on highly-weathered soils, under soybean-maize agriculture in Brazil (Huddell et al. 2022), sugarcane and banana plantations in North Queensland, Australia (Rasiah et al. 2003), and maize agriculture in Kenya (Tully et al. 2016). Soils dominated by low-activity clays can have substantial positive charge at low pH values and thus have a strong capacity to capture NO_3^- (Veldkamp et al. 2020). In the present study, the palm circle stored more extractable NO_3^- than the other management zones, especially in 50–150 cm soil depth interval (Fig. 2.2), although all management zones had similar clay content (Table S2.1), a result of long-term high N fertilizer applications in this management zone. The higher total N stocks (Table S2.1) and soil N cycling rates (Table 2.1) under the frond-stacked area were likely caused by long-term mulching with prune fronds which estimated at about 120 kg N ha^{-1} $year^{-1}$ (Comte et al. 2012; Moradi et al. 2014). Mulching also increased soil organic C and MBC (Table S2.1), promoting the storage of organic N and/or N-immobilization by microorganisms in the topsoil (Formaglio et al. 2021). Therefore, less soil NO_3^- was leached and accumulated in the subsoil, resulting in low soil extractable NO_3^- stocks in this zone (Fig. 2.1). This was further supported by earlier findings in smallholder oil palm plantations in the same research area where the frond-stacked area had lower N leaching losses than the palm circle (Kurniawan et al. 2018). The comparable low mineral stock in the inter-row, probably also resulted from the low N input.

How can N management be improved in the three management zones of oil palm plantations? Whereas in the palm circle, fertilization can improve soil mineral N availability, it also bears the risk of high N losses as indicated by mineral N accumulation in the subsoil (Fig. 2.1) and sizeable soil N_2O emissions (Chen et al. unpublished data). In contrast, in the frond-stacked area, mulching with fronds promoted soil N cycling and mineral N availability, however this was done with a reduced the risk of N leaching. An increase in the area occupied by frond-stacks and replacing part of chemical fertilizers by mulch, e.g. from empty fruits bunches, may further improve soil N cycling in oil palm plantations with lower risk of N losses. Under current conventional management, the frond-stacked area accounts for only 15% of plantation area whereas the palm circle receives nearly no litter return.

2.5.3. Yield, nutrient response efficiency, and profit

In line with our first hypothesis, four years of reduced fertilization combined with mechanical weeding did not decrease oil palm yield, suggesting that in mature oil palm plantations a reduced nutrient input, equal to nutrient export via fruit harvest, is sufficient to maintain yield. This was also supported by the comparable soil N cycling rates in the topsoil and mineral N stocks in 0-50 cm soil depth interval, given that 80% of oil palm's fine roots are located in the top 50 cm of the soil (Kurniawan et al. 2018). Furthermore, even in reduced fertilization, mineral N stocks in 50-150 cm soil depth interval were still comparable with 0-50 cm soil depth interval in the palm circle (Fig. 2.1), the zone that accounts for most palm roots. Annual yield in this oil palm plantation (30 t ha^{-1} on average; Table 2.2) was larger than the average actual yield (19.7 t ha^{-1}) from large-scale oil palm plantations in Indonesia and it was quite close to the "attainable yield" (31.6 t ha^{-1}) with maximize profit and return on input investments in mature large-scale oil palm plantations in Indonesia (Monzon et al. 2021). Maintaining high yields will help reduce the expansion of oil palm plantations under rising plant oil demand (Monzon et al. 2021), because projected vegetable oil consumption per capita in 2031 will further increase by 5% based on 2021 and palm oil is projected to contribute 36% of vegetable oil consumption in 2031 (OECD 2022).

Because the reduced fertilization treatment was able to maintain high yields with less fertilizer application, this treatment showed higher NRE, PFP_P, and PFP_K than the conventional fertilization in this mature oil palm plantation (Table 2.2), which supports our third hypothesis. Another study in a large-scale oil palm plantation in Kalimantan showed that 20% reduction of fertilizer input for four consecutive years did not decrease the yield and improved K fertilizer use efficiency (Tao et al. 2018). Improved nutrient response efficiency brings multiple positive environmental benefits. Reduced fertilizer consumption means the reduction of anthropogenic input of reactive N to ecosystems, thus avoiding a series of negative cascading effects, such as high N_2O emission, N deposition, and eutrophication (Galloway et al. 2003), and a reduction of potential social costs for dealing with N pollution (Keeler et al. 2016). Because of the increasing nutrient efficiency, the transition from conventional management to reduced management also improved the profit in this oil palm plantation (Fig. 2 and Table S2). The results were comparable to other agriculture systems which enhanced nutrient use efficiency and profit through optimizing nutrient management (Sapkota et al. 2014; Timsina et al. 2021). The higher profit indicates that avoiding excessive fertilization and using mechanical weeding instead of herbicides is a practical measure to improve the sustainability of oil palm plantations. The calculation of profit in our study avoided fluctuations in palm oil prices, labor costs, and materials prices, however, fluctuations in global palm oil prices are substantial (Cisneros et al. 2021) and affect the impact of management practices on profit. Independent of fluctuations in prices and costs, maintaining a high yield with less material input is certainly economically attractive. We emphasize that these results are from a ≥ 18-year-old large-scale oil palm plantation on mineral soil that previously was managed conventionally for more than a decade. Thus, our results cannot be extrapolated to smallholder oil palm plantations or oil palm plantations on peatland. Smallholder oil palm plantations usually have much lower fertilization rates and productivity than the large-scale oil palm plantations (Monzon et al. 2021). Applying the excess N fertilizer of large-scale oil palm plantations to smallholder plantations would probably help reducing the current yield gap between the actual yield and attainable yield and improve regional fertilizer use efficiency.

Weeding treatment did not affect soil N cycling and mineral N stocks (Table 2.1 and Fig. 2.1), fruit yield (Table 2.2), and nutrient efficiency (Table 2.2), indicating mechanical weeding was a viable alternative to herbicide weeding. Especially in area with low labor cost, mechanical weeding can even improve profit (Fig. 2.2 and Table S2.2). Furthermore, mechanical weeding has been shown positive effects on ecosystem multifunctionality in this large-scale oil palm plantation (Iddris et al. 2023).

2.6. Conclusions

Our study illustrated that more sustainable management in large-scale oil palm plantations is possible by reduced fertilization in combination with mechanical weeding. Because the lifespan of oil palm plantations can reach 25-30 years, long-term effects (beyond 5 years) of reduced management require further study, however, our results show that adjusting the management intensity with oil palm ages improves nutrient response efficiency and profit. Future investigations should evaluate whether reduced management will also improve abatement of greenhouse gasses such as N_2O, because that will be a critical contribution to further improve of the ecosystem functions of oil palm plantations

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2.8. Appendix

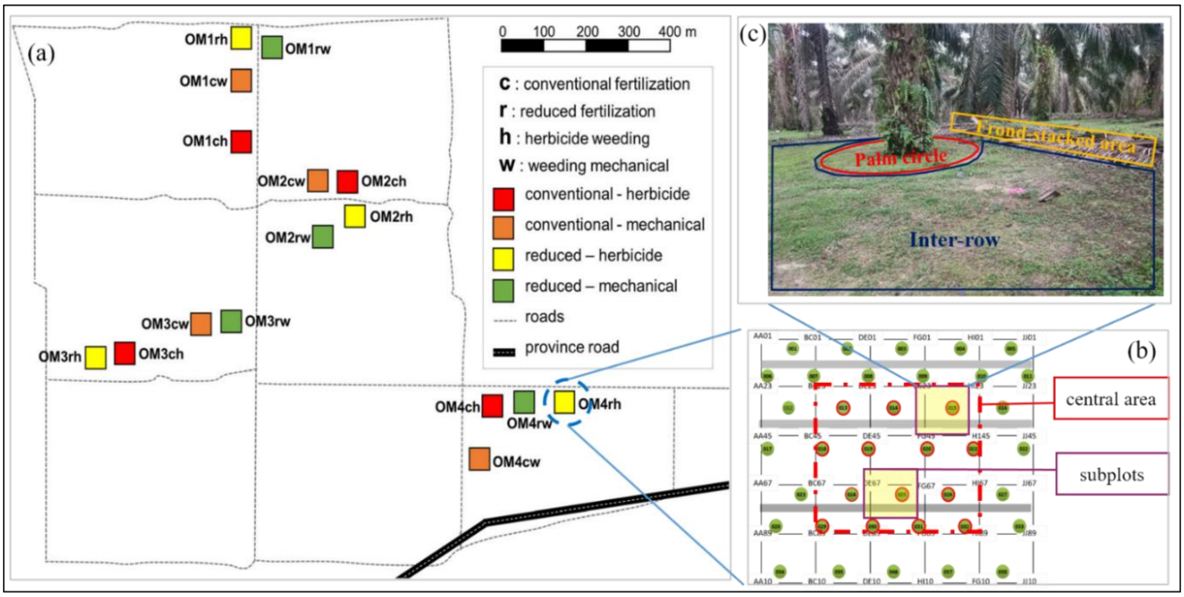

Fig. S2.1 Experimental set-up. 2^2 factorial experiment design with four blocks (OM1–4) within which are the four treatments (each plot was 50 m × 50 m; ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding) (a). Two subplots were selected in the central 30 m × 30 m area in each plot (b). Soil net N cycling rate was measured from three management zones (Palm circle, Inter-row, and Frond-stacked area) monthly during March 2017– February 2018 and July 2019 – June 2020 (c)

Table S2.1 Soil biochemical and physical characteristics (mean ± SE, *n* = 16 plots) in the top 50 cm depth determined in 2018 and soil texture in the 50–150 cm depth determined in 2021, reported for each management zone in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia

Characteristics	Palm circle	Inter-row	Frond-stacked area
Soil organic C (kg C m^{-2})	6.2 ± 0.6 b	6.4 ± 0.2 b	9.1 ± 0.8 a
Total N (g N m^{-2})	402 ± 31 b	426 ± 15 ab	571±39 a
ECEC ($mmol_{charge}$ kg^{-1})	35 ± 2 a	18 ± 1 b	28 ± 2 a
pH (1:4 soil-to-H_2O)	5.05 ± 0.08 a	4.81 ± 0.05 b	5.00 ± 0.08 ab
Bulk density (g cm^{-3})	1.37 ± 0.01 a	1.36 ± 0.01 a	0.89 ± 0.01 b
Clay (%)	23.30 ± 1.31 a	23.60 ± 1.00 a	25.47 ± 1.37 a
Silt (%)	7.80 ± 1.19 a	7.73 ± 1.23 a	6.47 ± 1.21 a
Sand (%)	68.90 ± 1.52 a	68.67 ± 1.35 a	68.07 ± 1.97 a

For each characteristic, different letters indicate significant differences among management zones (one-way ANOVA with Tukey HSD at $p \leq 0.05$). Except for soil texture, soil characteristics were reported by Formaglio et al. (2020)

Table S2.2 Annual material cost, labor cost, revenues and profit (mean ± SE, *n* = 16 plots) during 2017-2020 from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia

Treatments	Material cost USD ha^{-1} $year^{-1}$	Labor cost USD ha^{-1} $year^{-1}$	Revenues USD ha^{-1} $year^{-1}$	Profit USD ha^{-1} $year^{-1}$
conventional fertilization – herbicide weeding	703 ± 0	125 ± 4	3477 ± 129	2649 ± 129
conventional fertilization – mechanical weeding	620 ± 2	140 ± 8	3956 ± 129	3196 ± 135
reduced fertilization – herbicide weeding	495 ± 0	128 ± 3	3520 ± 185	2898 ± 188
reduced fertilization – mechanical weeding	413 ± 3	139 ± 5	3596 ± 178	3044 ± 180
Linear model - *p* value (numDF=1, denDF=12)				
fertilization	<0.01	0.89	0.34	0.76
weeding	<0.01	0.03	0.11	0.05
Fertilization × Weeding	0.75	0.71	0.23	0.23

Statistical *p*-values are results from 2 × 2 factorial ANOVA with linear models; numDF and denDF are numerator and denominator degrees of freedom, respectively. Those data were reported by Iddris et al. (2023)

Chapter 3

Large contribution of soil N_2O emission to the global warming potential of a large-scale oil palm plantation despite changing from conventional to reduced management practices

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3.1. Abstract

Conventional management of oil palm plantations, involving high fertilization rate and herbicide application, result in high yield but with large soil greenhouse gas (GHG) emissions. This study aimed to assess a practical alternative to conventional management, namely reduced fertilization with mechanical weeding, to decrease soil GHG emissions without sacrificing production. We established a full factorial experiment with two fertilization rates (conventional and reduced fertilization, equal to nutrients exported via fruit harvest) and two weeding methods (herbicide and mechanical), each with four replicate plots, since 2016 in an ≥ 15-year-old, large-scale oil palm plantation in Indonesia. Soil CO_2, N_2O, and CH_4 fluxes were measured during 2019 – 2020 and fruit yield was measured during 2017 – 2020. Fresh fruit yield (30 ± 1 Mg ha^{-1} yr^{-1}) and soil GHG fluxes did not differ among treatments ($p \geq 0.11$), implying legacy effects of over a decade of conventional management prior to the start of experiment. Annual soil GHG fluxes were 5.5 ± 0.2 Mg CO_2-C ha^{-1} yr^{-1}, 3.6 ± 0.7 kg N_2O-N ha^{-1} yr^{-1}, and −1.5 ± 0.1 kg CH_4-C ha^{-1} yr^{-1} across treatments. The palm circle, where fertilizers are commonly applied, covered 18% of the plantation area but accounted 79% of soil N_2O emission. The net primary production of this oil palm plantation was 17150 ± 260 kg C ha^{-1} yr^{-1} but 62% of this was removed by fruit harvest. The global warming potential of this planation was 3010 ± 750 kg CO_2-eq ha^{-1} yr^{-1} of which 55% was contributed by soil N_2O emission and only < 2% offset by soil CH_4 sink.

Keywords: Fertilization management; Net ecosystem exchange; Net ecosystem productivity; Tree cash crop plantation; Weeding practice

3.2. Introduction

With increasing demand for vegetable oil, oil palm as a productive woody oil crop is widely planted in the tropics (Descals et al. 2021). Globally, the oil palm-planted area rapidly increased from 4 million ha in 1980 to 28 million ha in 2019 (FAO 2021) and oil palm plantations are expected to continue to expand to meet the increasing demand of a growing world population (OECD 2022). Oil palm expansion drives tropical deforestation (Vijay et al. 2016) and is accompanied by serious reductions in multiple ecosystem functions, e.g. decreases in C storage (Kotowska et al. 2015; van Straaten et al. 2015), nutrient cycling and retention (Allen et al. 2015; Kurniawan et al. 2018), and biodiversity losses (Clough et al. 2016). Despite these losses of ecosystem multifunctionality, profit gains increase under oil palm plantations (Grass et al. 2020), which increase farm and non-farm households' income and improve their livelihood (Bou Dib et al. 2018). Moreover, the high yield of oil palm plays an invaluable role in meeting human demand for vegetable oil (Thomas et al. 2015; Rochmyaningsih 2019). However, there is a need for a balance between economic gains and maintaining or avoiding further degradation of ecosystem functions (Bessou et al. 2017). Conventional management practices of large-scale oil palm plantations (> 50 ha, can be up to 20000 ha and owned by corporations), particularly high fertilization rates and herbicide application, are agents of these decreases in ecosystem functions (e.g. Tao et al. 2016; Ashton-Butt et al. 2018; Rahman et al. 2019). Thus, there is a need for practical solutions that can easily be implemented in order to reduce these negative impacts on ecosystem functions without sacrificing productivity and profit.

Soil greenhouse gas (GHG) emissions are a concern in oil palm plantations (Kaupper et al. 2020; Skiba et al. 2020). Compared to forests, the reductions in plant biomass production, soil organic carbon (SOC) and soil microbial biomass as well as C removal from the field via fruit harvest and increase in soil bulk density in oil palm plantations largely decrease the latter’s GHG abatement capability (Kotowska et al. 2015; van Straaten et al. 2015; Clough et al. 2016). This capability is influenced by agricultural management practices, especially fertilization rates (Sakata et al. 2015; Hassler et al. 2017; Rahman et al. 2019). N fertilization in oil palm plantations during the wet season can increase soil N_2O emissions (Aini et al. 2015; Hassler et al. 2017), a potent GHG and agent of ozone depletion (Davidson et al. 2000). Soil N_2O emissions from tropical agriculture is largely controlled by soil mineral N availability, which in turn is influenced by N fertilization rate, and soil moisture, as N_2O-production processes of denitrification and nitrification in the soil are favored under high soil mineral N and moisture levels (Khalil et al. 2002; Liyanage et al. 2020; Quiñones et al. 2022). In Indonesia, a large-scale oil palm plantation with commonly high N fertilization rate has higher soil N_2O emissions than smallholder oil palm plantations (< 5 ha of planted area per household) with low N fertilization rates (Hassler et al. 2017).

Soil CO_2 emissions originate from heterotrophic and root respiration (Bond-Lamberty et al. 2004). The temporal pattern of soil CO_2 emission follows the seasonal dynamics of soil moisture and/or soil temperature, exhibiting low soil CO_2 emissions at low soil moisture content, increases toward an optimum soil moisture, and decrease towards water saturation when oxygen availability and gas diffusion limit soil CO_2 emissions (Sotta et al. 2007; van Straaten et al. 2011). The spatial pattern of soil CO_2 emissions in tropical ecosystems is influenced by the spatial variation in soil organic matter, bulk density, root biomass and available N and P levels in the soil (Adachi et al. 2006; Hassler et al. 2015; Cusack et al. 2019; Tchiofo Lontsi et al. 2020). Another important GHG that is influenced by management practices in tropical plantations or croplands is CH_4 (e.g. Hassler et al. 2015; Quiñones et al. 2022). Soil surface CH_4 flux is the net effect of CH_4 production by methanogenic archaea and CH_4 oxidation by methanotrophic bacteria (Hanson and Hanson 1996). In well-drained tropical soils, CH_4 oxidation usually is more dominant than CH_4 production, resulting in a net soil CH_4 uptake or negative CH_4 flux (Veldkamp et al. 2013). Seasonal pattern of soil surface CH_4 flux in smallholder oil palm plantations in Indonesia reflects the seasonal variation of soil moisture, with lower CH_4 uptake during the wet season than the dry season (Hassler et al. 2015). In well-drained tropical soils with low N availability, soil CH_4 uptake or methanotrophic activity is enhanced with increase in soil mineral N content (e.g. Veldkamp et al. 2013; Hassler et al. 2015; Tchiofo Lontsi et al. 2020). However, in tropical agricultural soils with high soil mineral N levels (NH_4^+ and NO_3^-) from high N fertilization, competition of NH_4^+ against CH_4 for the active site of mono-oxygenase enzyme can reduce soil CH_4 uptake (Hanson and Hanson 1996). Veldkamp et al. (2001) observed a temporary inhibition of CH_4 uptake for approximately three weeks following NH_4^+-based fertilizer application in tropical pasture soils. In contrast, high soil NO_3^- level (e.g. resulting from nitrification of applied N fertilizer) can inhibit CH_4 production in the soil as NO_3^- is preferred over bicarbonate as an electron acceptor (Martinson et al. 2021; Quiñones et al. 2022). Nonetheless, across forests, smallholder rubber and oil palm plantations in Indonesia, the overriding pattern is the increase in soil CH_4 uptake with increase in soil mineral N, suggesting the prevailing control of N availability on methanotrophic activity in the soil (Hassler et al. 2015). The spatial patterns of soil surface CH_4 fluxes depict the spatial variations in soil properties that affects soil moisture content and gas diffusivity, such as soil texture (Veldkamp et al. 2013; Tchiofo Lontsi et al. 2020), soil bulk density and organic matter (e.g. at a plot or landscape scale; Tchiofo Lontsi et al. 2020).

In large-scale oil palm plantations, the typical management practices of fertilization, weeding, and pruning of senesced fronds result in three distinctive spatial management zones: palm circle (weeded and fertilizers are applied), inter-row (weeded but not fertilized) and frond-stacked area (where pruned fronds are piled) (Fig. 3.1; Formaglio et al. 2021). In the palm circle and inter-row, frequent management activities (weeding, pruning and harvesting) result in soil compaction by foot traffic (increased soil bulk density) and the low litter input in these zones exhibits low SOC and microbial biomass, and low soil N cycling rate (Formaglio et al. 2021). Additionally, root biomass is high in the palm circle (Dassou et al. 2021). In the frond-stacked area, decomposition of fronds results in large SOC (with decreased soil bulk density), large microbial and fine root biomass, and high soil N cycling rate (Moradi et al. 2014; Rüegg et al. 2019; Formaglio et al. 2020; Dassou et al. 2021). Overall, the differences in soil properties and root biomass among these spatially distinct management zones (Formaglio et al. 2021) potentially drive the spatial variation of soil GHG fluxes from oil palm plantations (Hassler et al. 2015, 2017; Aini et al. 2020). Thus, estimating soil GHG emissions from oil palm plantations should take into account the spatial variability among management zones within a site or plot.

This study aimed to (1) assess differences in soil GHG fluxes from conventional high fertilization rates with herbicide application compared to alternative management of reduced fertilization rates (equal to nutrient exported via fruit harvest) with mechanical weeding; and (2) determine the controlling factors of the soil GHG fluxes from a large-scale oil palm plantation. A 2 × 2 factorial field experiment with conventional and reduced fertilization rates as well as herbicide and mechanical weed control was established in an $\geq$ 15-year-old, large-scale oil palm plantation in Jambi, Indonesia starting in November 2016. The earlier studies during the first 1.5 years of this oil palm management experiment show comparable gross rates of soil N cycling, microbial biomass (Formaglio et al. 2021), and root biomass (Ryadin et al. 2022) among treatments. Thus, we hypothesized that during 2.5–3.5 years of this management experiment, the reduced fertilization with mechanical weeding will have comparable soil CO_2 and CH_4 fluxes but lower soil N_2O emissions than the conventional fertilization with herbicide weeding. Moreover, we hypothesized that the fertilized palm circle that has high soil bulk density and root biomass but low SOC, soil microbial biomass and N cycling rate (Dassou et al. 2021; Formaglio et al. 2021) will have large soil CO_2 and N_2O emissions but small soil CH_4 uptake. The unfertilized inter-row that has high soil bulk density but low SOC, microbial biomass and N cycling rate (Formaglio et al. 2021) will have small soil CO_2, N_2O emissions and CH_4 uptake. The frond-stacked area (i.e. unfertilized but piled with pruned fronds) that has large SOC, microbial biomass and N cycling rate but low soil bulk density (Formaglio et al. 2021) will have large soil CO_2 emissions and CH_4 uptake but small soil N_2O emissions. In this study, we assessed the soil GHG footprint and the global warming potential (GWP) of a typical large-scale oil palm plantation in order to evaluate reduced management (i.e. reduced fertilization rate with mechanical weeding) against the commonly employed conventional management (i.e. high fertilization rate with herbicide application).

3.3. Materials and methods

3.3.1. Site description and experimental design

This study was conducted in a large-scale oil palm plantation in Jambi, Indonesia (1°43′8″ S, 103°23′53″ E, 73 m above sea level). The plantation was 2025 ha and established between 1998 and 2002, and thus was ≥ 18 years old during our measurement from July 2019 to June 2020. The oil palms were planted in a triangular pattern with 8 m spacing between palms and the planting density was 142 palms ha^{-1}. Mean annual (2010–2020) air temperature is 26.9 ± 0.2 ℃ and mean annual precipitation is 2078 ± 155 mm. The soil is Acrisol with a sandy clay loam texture (Table S3.1). More than 18 years of management induced three distinct zones within this oil palm plantation: palm circle, inter-row, and frond-stacked area (Fig. 3.1) (Formaglio et al. 2020). The palm circle (a 2 m radius from the palm base) is the zone where fertilizers and lime are applied (in April and October of each year) and is weeded every three months; this represents 18% of the plantation area. The inter-row is unfertilized but weeded every six months; this represents 67% of the plantation area. The frond-stacked area is where senesced fronds are piled and is neither fertilized nor weeded; this represents 15% of the plantation area. As consequences of these management activities, SOC and total N stocks are higher whereas soil bulk density is lower in the frond-stacked area than the palm circle and inter-row. The effective cation exchange capacity and pH, influenced by the applied lime as well as from decomposed leaf litter, are higher in the palm circle and frond-stacked area than the inter-row (Table S3.1) (Formaglio et al. 2020).

This oil palm management experiment had started in November 2016 – a 2 × 2 factorial design of two fertilization rates and two weeding methods: conventional fertilization – herbicide weeding (ch), conventional fertilization – mechanical weeding (cw), reduced fertilization – herbicide weeding (rh), and reduced fertilization – mechanical weeding (rw). These four treatments were randomly assigned to four plots (50 m × 50 m each) in a block and there were four replicate blocks (Fig. 3.1). Within each plot, we selected two subplots in the inner 30 m × 30 m area and each subplot included the three management zones where all measurements were carried out (Fig. 3.1).

Conventional fertilization rates were 260 kg N, 50 kg P, and 220 kg K ha^{-1} yr^{-1}, commonly practiced in large-scale oil palm plantations in Jambi, Indonesia (Formaglio et al. 2020). Reduced fertilization rates were 136 kg N, 17 kg P, and 187 kg K ha^{-1} yr^{-1}, equal to the nutrients exported by fruit harvest (detail calculation given by Formaglio et al. 2021). The fertilizer sources were urea, triple superphosphate, muriate of potash or NPK-complete.

For herbicide weed control, glyphosate was used at a rate of 1.5 L ha^{-1} yr^{-1} in the palm circle (split into quarterly applications in each year) and 0.75 L ha^{-1} yr^{-1} in the inter-row (spilt into two applications per year). Mechanical weeding used a brush cutter with the same weeding frequencies as the herbicide applications. All treatments received the same rates of lime (426 kg dolomite ha^{-1} yr^{-1}) and micronutrients (142 kg micro-mag ha^{-1} yr^{-1} with 0.5% B_2O_3, 0.5% CuO, 0.25% Fe_2O_3, 0.15% ZnO, 0.1% MnO and 18% MgO), applied only on the palm circle.

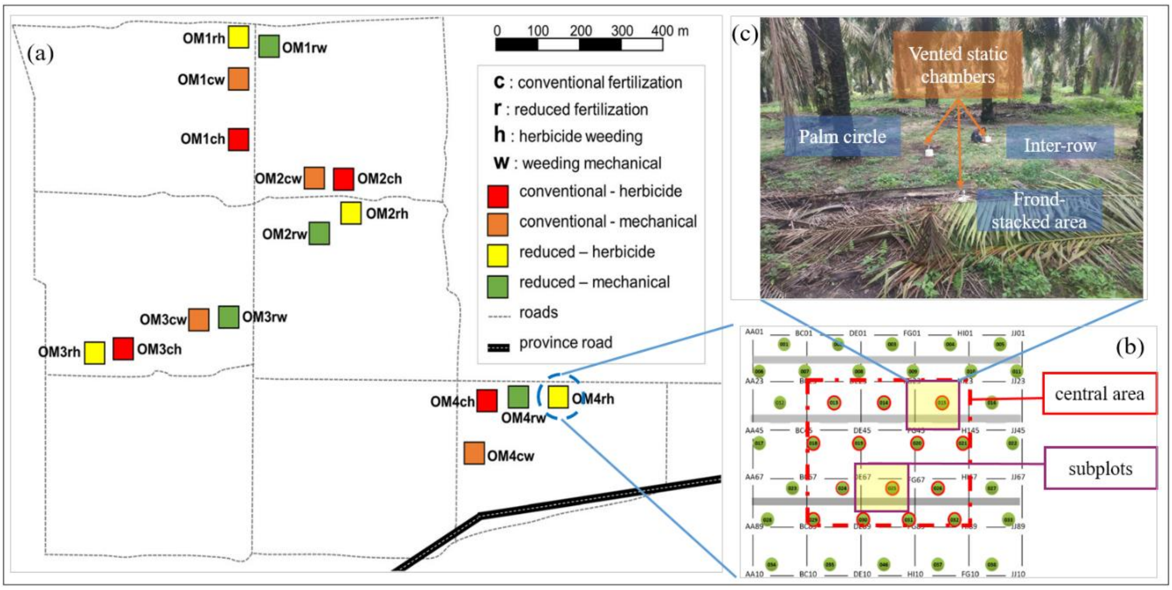

Fig. 3.1 Experimental set-up. A 2 × 2 factorial experiment design with four blocks (OM1–4) within which are the four treatments (each plot was 50 m × 50 m; ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding) (a). Two subplots were selected in the central 30 m × 30 m area in each plot (b). In each subplot, soil GHG flux measurements were conducted at each management zone (palm circle, inter-row, and frond-stacked area) using vented static chambers (c)

3.3.2. Soil greenhouse gas fluxes

Soil CO_2, N_2O, and CH_4 fluxes were measured monthly from July 2019 to June 2020, using vented static chambers. Measurement schedules were random among plots (i.e. 16 plots, each with two subplots that each encompassed three management zones) such that we covered the temporal variability of soil GHG fluxes (e.g. peak of soil N_2O emissions during two weeks following fertilization (conducted in April and October of each year), as observed in our earlier study (Hassler et al, 2017). During the year-round measurement, chamber bases (0.04 m^2 area) were installed permanently at each management zone (i.e. palm circle, inter-row, and frond-stacked area) in all subplots of 16 plots (Fig. 3.1), totaling to 96 chambers, by inserting these into the soil at approximately 0.02 m depth. On a measurement day, the chamber bases were covered for 28 minutes with polyethylene covers (11 L total volume) that were equipped with a Luer-lock sampling port. Four gas samples (23 mL each) were taken using syringes at 1, 10, 19, 28 minutes following chamber closure and injected into pre-evacuated 12 mL glass vials (Labco Exetainers, Labco Limited, Lampeter, UK) with rubber septa. On each monthly measurement, 384 gas samples were taken (i.e. 16 plots × 2 subplots × 3 management zones × 4 chamber headspace-sampling intervals). As a check for possible leakage, we also stored standard gases into pre-evacuated 12 mL glass vials in the same period as the field gas samples. All gas samples were transported by air to the Goettingen University, Germany for analysis.

Gas samples were analyzed using a gas chromatograph (SRI 8610C, SRI Instruments Europe GmbH, Bad Honnef, Germany) equipped with a flame ionization detector to measure CH_4 and CO_2 concentrations (with a methanizer) as well as an electron capture detector for N_2O analysis (with a make-up gas of 5% CO_2–95% N_2). Soil CO_2, N_2O, and CH_4 fluxes were calculated from the linear change in concentrations with chamber closure time and adjusted with the measured air temperature and atmospheric pressure during sampling. We found that the concentrations of all standard gases stored in the same duration as the field gas samples stayed the same as those in the standard gases at our laboratory. The quality check for each flux measurement was based on the linear increase of CO_2 concentrations with chamber closure time ($R^2 \geq 0.9$). For soil CH_4 and N_2O, all flux measurements (including zero and negative fluxes) were included in the data analysis. For an overall value of soil CO_2, N_2O, and CH_4 fluxes in a plot, fluxes were weighted by the areal coverages of the three management zones (see above). Area-weighted annual soil CO_2, N_2O, and CH_4 fluxes were estimated based on trapezoidal extrapolations between measured fluxes and sampling day intervals.

3.3.3. Soil variables

Concurrent with soil GHG flux measurement, soil temperature, mineral N, and moisture content in top 5 cm depth were determined. Soil temperature was recorded using a portable thermometer (Greisinger GMH 3210, Greisinger Messtechnik GmbH, Regenstauf, Germany). At about 1 m away from each chamber, soil samples were collected and pooled from the two subplots for each management zone. Part of each soil sample was added to a prepared bottle containing 150 mL 0.5 M K_2SO_4 for immediate mineral N extraction. Upon arrival at the field laboratory, the bottles were shaken for 1 hour, filtered and the extracts were immediately frozen. The remaining soil sample was oven-dried at 105 °C for 24 h to determine the gravimetric moisture content, which was used to calculate the dry mass of the soil extracted for mineral N. The soil moisture was the expressed as water-filled pore space (WFPS), using the mineral soil particle density of 2.65 g cm^{-3} and the average soil bulk density in the top 5 cm (1.23 g cm^{-3} in the palm circle, 1.20 g cm^{-3} in the inter-row, and 0.52 g cm^{-3} in the frond-stacked area). In April and May 2020, we were unable to conduct WFPS and mineral N measurements due to restrictions from COVID-19 pandemic. The frozen extracts were transported by air to Goettingen University and analyzed for NH_4^+ and NO_3^- concentrations using continuous flow injection colorimetry (SEAL Analytical AA3, SEAL Analytical GmbH, Norderstedt, Germany).

3.3.4. Global warming potential estimation

The GWP of this $\geq$ 18-year-old, large-scale oil palm plantation was estimated based on Malhi et al. (1999), as also used in our earlier work in agricultural land use (Quiñones et al. 2022). First, the net primary production (NPP) was estimated as the sum of aboveground biomass C production, fruit biomass C production, frond litter biomass C input, root biomass C production, and root litter biomass C input. Within the inner 30 m × 30 m area per plot, stem height, harvested fruit weight, and the number of pruned fronds per palm were recorded during 2017–2020 (Iddris et al. 2023). Aboveground biomass per palm was calculated using the allometric growth equation (Asari et al. 2013): kg biomass $palm^{-1}$ = 71.797 × palm stem height – 7.0872; and biomass production per palm was the difference in biomass between two consecutive years. Annual aboveground biomass C production (g C m^{-2} yr^{-1}) = annual biomass production per palm (kg $palm^{-1}$, 2019–2020) × planting density (142 palms ha^{-1}) × tissue C concentration (0.41 g C g^{-1}) × 10^{-1} (for unit conversion). Annual fruit biomass C production (g C m^{-2} yr^{-1}) = annual fruit harvest per palm (kg $palm^{-1}$, mean of 2019–2020) × planting density × tissue C concentration (0.63 g C g^{-1}) × 10^{-1}. Frond litter biomass C input (g C m^{-2} yr^{-1}) = annual litter production per palm (kg $palm^{-1}$, mean of 2019–2020) × planting density × tissue C concentration (0.47 g C g^{-1}) × 10^{-1}. Data of root biomass C production (140 g C m^{-2} yr^{-1}) and root litter biomass C input (45 g C m^{-2} yr^{-1}) were taken from Kotowska et al. (2015).

Second, the net ecosystem productivity (NEP) was calculated as NEP (g C m^{-2} yr^{-1}) = heterotrophic respiration – (NPP – fruit biomass C) (Malhi et al. 1999; Quiñones et al. 2022). Our measured soil CO_2 fluxes included both autotrophic and heterotrophic respirations. We assumed 70% heterotrophic contribution to soil CO_2 flux, based on a long-term quantification in a forest in Sulawesi, Indonesia (van Straaten et al. 2011). As the frond litter also contributes to heterotrophic respiration upon decomposition, we assumed this fraction to be 80% of frond litter biomass C, based on the frond-litter decomposition rate in the same plantation (Iddris et al. 2023). Third, the GWP (g CO_2-eq m^{-2} yr^{-1}) = (NEP × 3.67) + (soil N_2O fluxes × 298) + (soil CH_4 fluxes × 25), of which 3.67 is C to CO_2 conversion and 298 and 25 are CO_2-equivalents of N_2O and CH_4, respectively, for a 100-year time horizon (IPCC 2006). Negative and positive symbols indicate the direction of the flux: (−) for C uptake and (+) for C export or emission from the plantation.

3.3.5. Statistical analysis

The mean value of two subplots for the soil GHG fluxes and soil temperature were used to represent each plot and management zone on each sampling day. The normality of distribution and equality of variance were first tested using Shapiro-Wilk's test and Levene's test, respectively. Linear mixed-effects (LME) models with Tukey's HSD test were used to assess the differences in soil GHG fluxes and soil variables (WFPS, soil temperature, and mineral N content) among treatments (Crawley 2013). In the LME models, management (2 × 2 factorial of fertilization rates, weed control and their interaction) was considered as the fixed effect whereas plot and sampling day were taken as random effects and statistical analysis were conducted for each management zone. As there were no significant differences among treatments, we tested differences among the three management zone across treatments; for the latter, management zone was the fixed effect in the LME model and plot and sampling day were random effects. We also assessed if there were seasonal differences, and the year-round measurements were categorized into dry (precipitation ≤ 80 mm $month^{-1}$) and wet seasons; this was conducted for each management zone, and season was the fixed effect and plot and sampling day were random effects om the LME model. For all the above analyses, the LME models further included a variance function that allows variance heteroscedasticity of the fixed effect, and/or a first-order temporal autoregressive process that assumes decreasing auto-correlation between sampling days with increasing time difference, if these improve the model performance based on Akaike information criterion. The model residual was checked using diagnostic plots and finally soil CO_2 and N_2O fluxes, and soil NH_4^+ and NO_3^- concentrations were re-analyzed after log-transformation as the model residual distributions approximated the normal distribution.

The relationships between soil GHG fluxes and soil variables were determined by Spearman's Rank correlation test. Correlations tests were conducted on the means of the four replicate plots on each measurement day for each management zone (n = 144 for soil temperature, from 4 treatments × 3 management zones × 12 monthly measurements; n = 120 for WFPS and mineral N content, from 4 treatments × 3 management zones × 10 monthly measurements). All data analyses were performed using the R version 4.0.5 (R core Team 2021). The statistical significance for all the tests was set at $p \leq 0.05$.

3.4. Results

3.4.1. Soil greenhouse gas fluxes and global warming potential

Soil CO_2 emissions from the palm circle and frond-stacked area were higher in the wet season than in the dry season ($p \leq 0.03$; Fig. S3.1). Soil N_2O emissions from the palm circle sharply increased after fertilizer application and returned to background levels after two months (Fig. S3.2). Excluding the direct effects after fertilization, the palm circle had higher soil N_2O emissions in the wet season than the dry season ($p = 0.03$; Fig. S3.2). Soil CH_4 uptake was higher in the dry season than the wet season in all three management zones ($p \leq 0.01$; Fig. S3.3). The frond-stacked area showed consistent CH_4 uptake throughout the measurement period whereas 33% and 17% of measured soil CH_4 fluxes in the palm circle and inter-row, respectively, were net CH_4 emissions (Fig. S3.3).

Reduced and conventional management had comparable soil CO_2 emissions (fertilization, weeding and interaction: $p \geq 0.13$), N_2O emissions (fertilization, weeding and their interaction: $p \geq 0.14$), and CH_4 fluxes (fertilization, weeding and their interaction: $p \geq 0.26$) in each management zone (Table 3.1). However, there were clear differences in soil GHG fluxes among the three management zones. The palm circle had the highest soil N_2O emissions and lowest soil CH_4 uptake ($p \leq 0.01$; Table 3.1); the inter-row had the lowest soil CO_2 and N_2O emissions ($p \leq 0.01$; Table 3.1); the frond-stacked area had the highest soil CO_2 emissions and CH_4 uptake ($p \leq 0.01$; Table 3.1). The palm circle accounted for 25%, the inter-row for 45%, and the frond-stacked area for 30% of the annual soil CO_2 emissions (Fig. 3.2). The palm circle comprised 79% of the annual soil N_2O emissions although it only accounted for 18% of the plantation area (Fig. 3.2). The frond-stacked area with 15% areal coverage contributed to 41% of the annual soil CH_4 uptake and the palm circle with 18% of plantation area contributed 5% of the annual soil CH_4 uptake (Fig. 3.2).

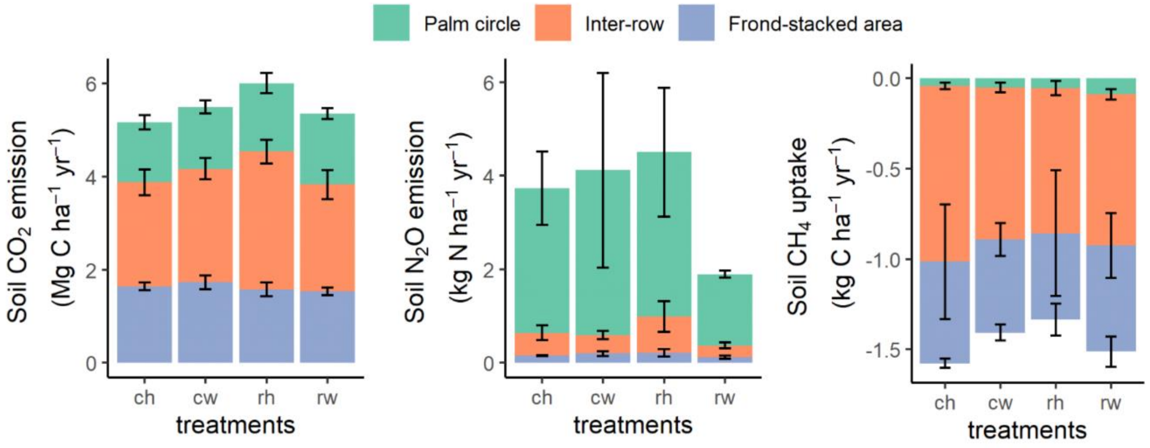

Fig. 3.2 Annual soil CO_2, N_2O, and CH_4 fluxes (means ± SE, *n* = 4 plots), weighted by the areal coverages of the palm circle (18%), inter-row (67%), and frond-stacked area (15%) under different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding. Annual soil N_2O emissions from rh were calculated excluding three extreme outliers: 5311 and 4325 µg N m^{-2} h^{-1} in the palm circle and 1934 µg N m^{-2} h^{-1} in the frond-stacked area. Annual soil CO_2, N_2O, and CH_4 fluxes were not statistically tested since these are trapezoidal extrapolations between measurement periods

We calculated the GWP across 16 plots (Fig. 3) as there were no significant differences in soil GHG fluxes among treatments (Table 1). Additionally, the reduced and conventional management had also comparable fruit yield during four years (2017–2020) of treatments (fertilization, weeding and their interaction: $p \geq 0.07$; Table S3.2). The NPP was larger than the soil heterotrophic respiration (which was assumed to be 70% of the measured soil respiration + 80% C emissions from decomposition of frond litter; see Methods), but 62% of this NPP was removed from the field via fruit harvest (Fig.3). Thus, this oil palm plantation turned into a net C source (i.e. positive NEP value; Fig. 3.3). Summing the NEP, soil N_2O emissions and soil CH_4 uptake in terms of CO_2 equivalent (100-year time horizon; see Methods), the GWP of this ≥ 18-year-old, large-scale oil palm was contributed by 55% soil N_2O emissions and only counterbalanced by < 2% soil CH_4 sink (Fig. 3.3).

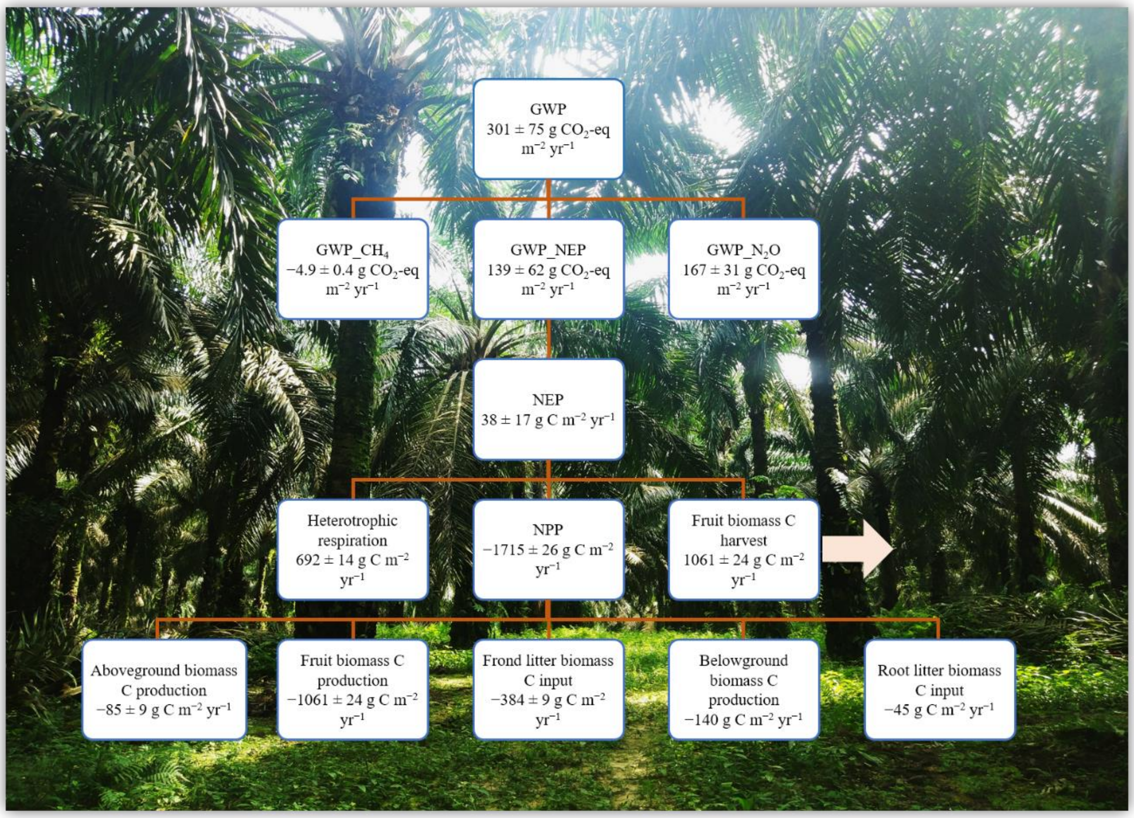

Fig. 3.3 Ecosystem net global warming potential (GWP) from an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia (means ± SE, *n* = 16 plots). Negative and positive symbols indicate the direction of the flux: (-) for C uptake and (+) for C export or emission from the plantation. Net primary productivity (NPP, g C m^{-2} yr^{-1}) = aboveground biomass C production + fruit biomass C + frond litter biomass C + belowground biomass C production + root litter biomass C. Aboveground biomass C production = annual biomass production per palm (2019–2020) × planting density × tissue C concentration. Annual fruit biomass C = annual fruit production per palm (mean of 2019–2020) × planting density × tissue C concentration. Frond litter biomass C = annual litter production per palm (mean of 2019–2020) × planting density × tissue C concentration. Belowground biomass C production and root litter C were taken from oil palm sites in the same area (Kotowska et al. 2015). Net ecosystem productivity (NEP, g C m^{-2} yr^{-1}) = heterotrophic respiration – (NPP – fruit biomass C) (Malhi et al. 1999; Quiñones et al. 2022). Heterotrophic respiration was assumed to be 70% of soil respiration (van Straaten et al. 2011) + 80% from decomposition of frond litter (Darras et al. 2019). GWP (g CO_2-eq m^{-2} yr^{-1}) = NEP_in CO_2 + N_2O_CO_2-eq + CH_4_CO_2-eq, whereby the CO_2-equivalents for N_2O and CH_4 are their annual fluxes multiplied by 298 and 25, respectively, for a 100-year time frame (IPCC 2006)

Table 3.1 Soil CO_2, N_2O, and CH_4 fluxes (means ± SE, *n* = 4 plots) from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from July 2019 to June 2020

Soil greenhouse gas	Management zones	Treatments				across treatments	LME model p-values numDF = 1, denDF = 12		
		ch	cw	rh	rw		Fertilization	Weeding	Interaction
CO_2 flux ($\mathrm{mg\ C\ m^{-2}\ h^{-1}}$)	Palm circle	82.06 ± 9.95	84.27 ± 8.70	92.32 ± 12.69	93.51 ± 5.70	88.04 ± 4.48 b	0.95	0.94	0.89
	Inter-row	38.54 ± 4.73	41.46 ± 3.41	50.34 ± 4.14	39.86 ± 5.31	42.55 ± 2.32 c	0.31	0.47	0.13
	Frond-stacked area	126.21 ± 6.23	132.95 ± 11.17	120.23 ± 11.15	117.95 ± 6.57	124.33 ± 4.34 a	0.21	0.89	0.65
	area-weighted	59.52 ± 3.49	62.60 ± 2.05	68.38 ± 6.37	61.23 ± 4.45	62.93 ± 2.14	0.55	0.66	0.22
N_2O flux ($\mathrm{\mu g\ N\ m^{-2}\ h^{-1}}$)	Palm circle	198.96 ± 53.70	219.50 ± 131.74	301.90 ± 121.53 (205.17 ± 85.71) [a]	91.47 ± 7.55	202.96 ± 46.14a	0.38	0.16	0.31
	Inter-row	10.14 ± 3.94	7.40 ± 1.56	13.67 ± 5.56	4.48 ± 1.13	8.92 ± 1.81 c	0.90	0.14	0.26
	Frond-stacked area	12.82 ± 0.98	16.12 ± 4.26	37.50 ± 26.14 (17.73 ± 6.98) [a]	9.74 ± 2.91	19.04 ± 6.59 b	0.38	0.47	0.62
	area-weighted	44.53 ± 8.18	46.56 ± 24.31	69.13 ± 28.67	20.93 ± 1.87	45.29 ± 9.67	0.53	0.20	0.07
CH_4 flux ($\mathrm{\mu g\ C\ m^{-2}\ h^{-1}}$)	Palm circle	−2.89 ± 1.19	−3.19 ± 1.63	−3.74 ± 2.46	−5.97 ± 1.70	−3.95 ± 0.87 a	0.26	0.66	0.29
	Inter-row	−16.94 ± 5.39	−14.06 ± 1.69	−14.13 ± 6.27	−14.46 ± 2.98	−14.90 ± 2.03 b	0.89	0.66	0.84
	Frond-stacked area	−42.53 ± 1.93	−38.89 ± 3.36	−36.09 ± 6.59	−44.66 ± 6.44	−40.54 ± 2.39 c	0.88	0.73	0.28
	area-weighted	−18.25 ± 3.74	−15.89 ± 1.42	−15.55 ± 4.75	−17.46 ± 2.97	−16.79 ± 1.57	0.98	0.73	0.58

For each soil greenhouse gas, different letters within each column indicate significant differences among management zones across treatments (2^2 factorial ANOVA with linear mixed-effects models and Tukey HSD test at $p \le 0.05$); numDF and denDF are numerator and denominator degrees of freedom, respectively.

ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

[a] For soil N_2O fluxes, values in parenthesis excluded two extreme outliers in the palm circle (5311 and 4325 µg N m^{-2} h^{-1}) and one extreme outlier in the frond-stacked area (1934 µg N m^{-2} h^{-1})

3.4.2. Soil variables

Fertilization and weeding treatments did not affect soil temperature (fertilization, weeding and their interaction: $p \geq 0.21$) and WFPS (fertilization, weeding and interaction: $p \geq 0.24$) in each management zone (Table 3.2). Soil NO_3^- concentration was lower in reduced than conventional fertilization, particularly in the frond-stacked area ($p \leq 0.01$; Table 3.2). There was an interaction effect of fertilization and weeding on soil NH_4^+ concentration in the frond-stacked area ($p = 0.02$; Table 3.2); however, neither fertilization nor weeding solely affect soil NH_4^+ concentration in any of the management zones ($p \geq 0.08$; Table 3.2). Across treatment plots, the three management zones showed comparable soil temperature while the palm circle and inter-row had higher WFPS than the frond-stacked area ($p \leq 0.01$; Table 3.2). The soil NH_4^+ and NO_3^- concentrations in the palm circle and frond-stacked area were larger than the inter-row ($p \leq 0.01$; Table 3.2).

Soil CO_2 emissions were positively correlated with WFPS in the palm circle (rho = 0.37, $p = 0.02$) and frond-stacked area (rho = 0.72, $p \leq 0.01$; Fig. 3.4a) and were positively correlated with soil temperature in the frond-stacked area (rho = 0.60, $p \leq 0.01$) and inter-row (rho = 0.29, $p = 0.05$; Fig. 3.4b). Soil N_2O emissions were positively correlated with soil mineral N in the palm circle (rho = 0.58, $p \leq 0.01$) and inter-row (rho = 0.32, $p = 0.04$; Fig. 3.4f). Soil CH_4 uptake decreased with increase in WFPS in all three management zones (rho = 0.44–0.81, $p \leq 0.01$; Fig. 3.4g). In the frond-stacked area, soil CH_4 uptake decreased with increase in soil temperature (rho = 0.54, $p \leq 0.01$; Fig. 3.4h) but increased with increase in soil mineral N (rho = −0.40, $p = 0.01$; Fig. 3.4i); also in the frond-stacked area, a positive relationship between soil temperature and WFPS was observed (rho = 0.37, $p = 0.02$; Fig. 3.4j). We did not found any other significant correlations between soil GHG fluxes and the measured soil variables.

Table 3.2 Soil temperature, water content, and mineral N concentrations (means ± SE, *n* = 4 plots) measured in the top 5 cm from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from July 2019 to June 2020

Soil factors	Management zones	Treatments				Across treatments	LME model p-values numDF = 1, denDF = 12		
		ch	cw	rh	rw		Fertilization	Weeding	Interaction
Soil temperature (°C)	Palm circle	26.2 ± 0.2	26.2 ± 0.2	26.3 ± 0.2	26.2 ± 0.1	26.2 ± 0.1 a	0.44	0.57	0.55
	Inter-row	26.1 ± 0.2	26.2 ± 0.2	26.2 ± 0.1	26.0 ± 0.1	26.1 ± 0.1 a	0.89	0.91	0.21
	Frond-stacked area	26.1 ± 0.1	26.2 ± 0.1	26.2 ± 0.1	26.1 ± 0.1	26.2 ± 0.1 a	0.66	0.93	0.21
Water-filled pore space (%)	Palm circle	38.8 ± 2.5	35.6 ± 2.3	34.9 ± 2.9	40.4 ± 2.1	37.5 ± 1.2 a	0.89	0.71	0.32
	Inter-row	34.4 ± 3.0	35.4 ± 1.4	36.5 ± 1.5	36.9 ± 1.9	35.8 ± 1.0 a	0.53	0.71	0.74
	Frond-stacked area	25.2 ± 2.4	26.7 ± 3.0	27.9 ± 3.0	23.6 ± 1.1	25.8 ± 1.2 b	0.86	0.53	0.24
NH_4^+ (µg N g^{-1})	Palm circle	6.3 ± 5.1	15.2 ± 10.9	1.7 ± 0.8	13.7 ± 8.3	9.3 ± 3.6 a	0.42	0.08	0.64
	Inter-row	0.7 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.7 ± 0.1 c	0.24	0.84	0.26
	Frond-stacked area	1.8 ± 0.1	4.1 ± 1.9	2.3 ± 0.1	1.8 ± 0.1	2.50 ± 0.5 b	0.52	0.27	0.02
NO_3^- (µg N g^{-1})	Palm circle	5.2 ± 2.3	14.6 ± 6.1	4.5 ± 1.9	10.0 ± 4.7	8.6 ± 2.1 a	0.42	0.29	0.88
	Inter-row	0.4 ± 0.1	0.6 ± 0.2	0.6 ± 0.3	0.3 ± 0.1	0.5 ± 0.1 c	0.54	0.39	0.14
	Frond-stacked area	10.1 ± 2.5	14.1 ± 1.4	5.3 ± 1.0	3.6 ± 0.4	8.3 ± 1.3 b	<0.01	0.53	0.16

For each soil factor, different letters within each column indicate significant differences among management zones across treatments (2^2 factorial ANOVA with linear mixed-effects models and Tukey HSD test at $p \leq 0.05$); numDF and denDF are numerator and denominator degrees of freedom, respectively. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

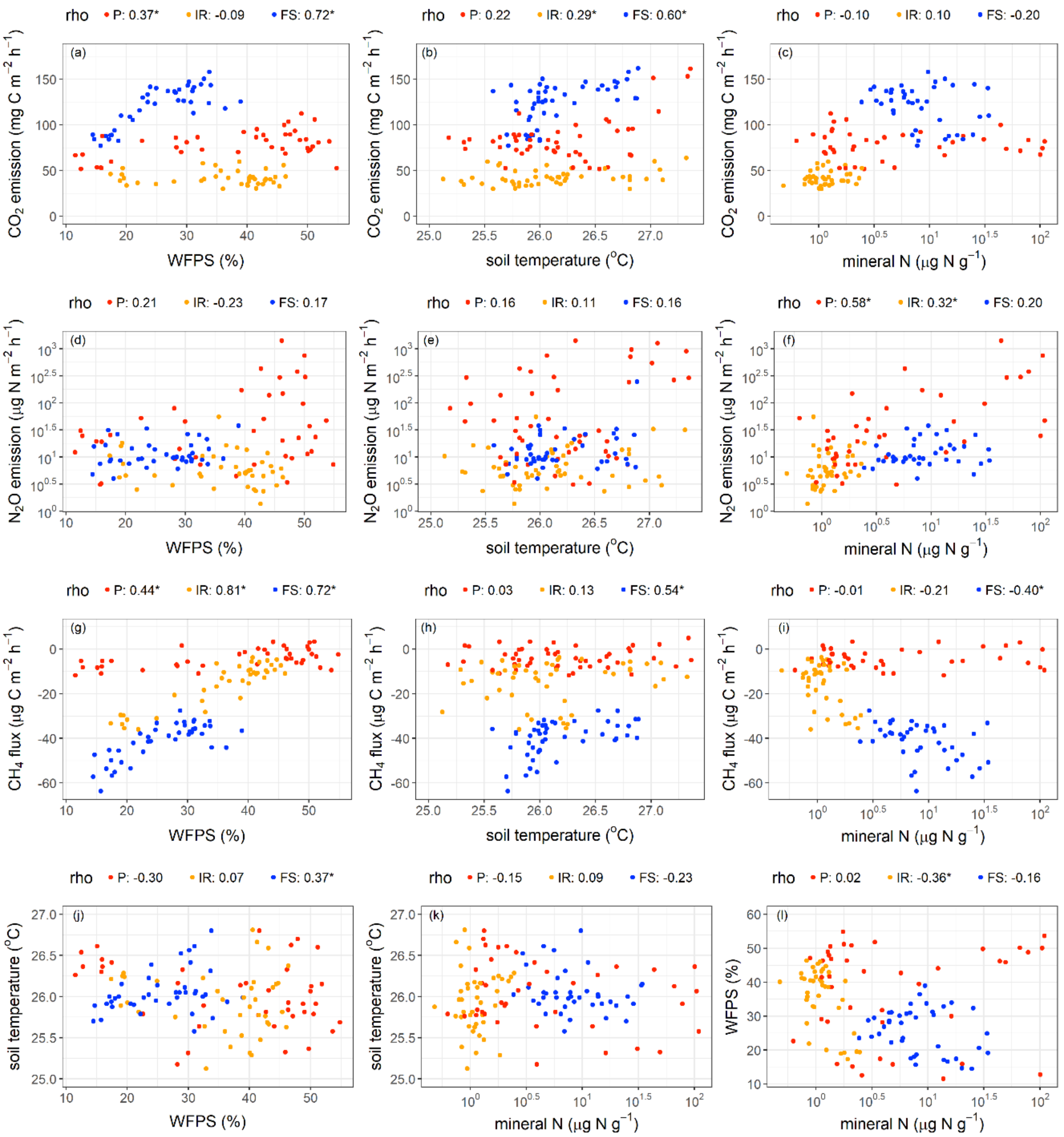

Fig. 3.4 Relationships among soil CO$_2$, N$_2$O, and CH$_4$ fluxes and soil factors. Spearman rank coefficients (rho) marked by * indicates $p \leq 0.05$. Each data point was the average of four replicate plots per treatment on each measurement period (*n* = 48 (i.e. 4 treatments × 12 months) for soil temperature; *n* = 40 (i.e. 4 treatments × 10 months) for soil water-filled pore space (WFPS) and total mineral N). P – palm circle, IR – inter-row, FS – frond-stacked area

3.5. Discussion

3.5.1. Soil CO_2 emissions

Area-weighted soil CO_2 emissions (Table 3.1) were only about one third of the soil CO_2 emissions from forests in the same study area (187–196 mg C m^{-2} h^{-1}; Hassler et al. 2015) but within the range reported for oil palm plantations on mineral soils in Southeast Asia (45–195 mg C m^{-2} h^{-1}; Hassler et al. 2015; Sakata et al. 2015; Aini et al. 2020; Drewer et al. 2021b). Specifically, soil CO_2 emissions from the inter-row were in the lower end of this range and soil CO_2 fluxes from the frond-stacked area were in the middle of this range. These earlier studies deployed different spatial sampling designs for measuring soil GHG fluxes from oil palm plantations. Sakata et al. (2015) measured soil CO_2 fluxes at 1 m away from the palm base and Hassler et al. (2015) measured soil CO_2 fluxes at 1.8–5 m away from the palm base. Aini et al. (2020) measured soil CO_2 fluxes from the fertilized area (within 1 m from the palm base) and unfertilized area whereas no information on sampling location was given by Drewer et al. (2021b). Measurement locations to represent spatial management zones should be stated when reporting soil GHG fluxes from oil palm plantations in order to facilitate comparisons as well as to warrant spatial extrapolation.

The three management zones differed in soil CO_2 fluxes caused by their differences in SOC (Table S3.1), microbial biomass (Fig. S3.4) as drivers of heterotrophic respiration, and root biomass (Nelson et al. 2014) that influences autotrophic respiration. In this mature large-scale oil palm plantation, senesced fronds have been piled on the frond-stacked area for more than a decade. This results in 40% larger SOC stocks (Table S3.1) and 3–5 times larger microbial biomass (Fig. S3.4) in the frond-stacked area than in the palm circle and inter-row (Formaglio et al. 2020, 2021). The positive correlation of microbial biomass C (MBC) to soil CO_2 fluxes (Fig. S3.4) supported our second hypothesis whereby differences in soil CO_2 emissions among management zones are driven in part by microbial biomass size and available organic C for heterotrophic respiration. Substantial heterotrophic respiration as well as presence of roots in the frond-stacked area (Rüegg et al. 2019; Dassou et al. 2021) explained its highest soil CO_2 emissions (Table 3.1). On the other hand, the palm circle has higher root biomass than the inter-row (Nelson et al. 2014), and higher soil CO_2 emissions from the palm circle than the inter-row (Table 3.1) may be caused by their disparate autotrophic respiration as their soil SOC stocks (Table S3.1) and MBC did not differ (Formaglio et al. 2021). However, in the same oil palm plantation, the different fertilization and weeding treatments, analyzed across the three management zones, did not influence soil MBC (Formaglio et al. 2021) as well as the fine root biomass in the top 10 cm depth (Ryadin et al. 2022) after one year of this management experiment. These findings support our first hypothesis whereby there was no short-term differences between reduced and conventional managements on soil CO_2 emissions. Nonetheless, we emphasize that the lower soil respiration in oil palm plantations compared to the forests (Hassler et al. 2015) is supported by its decreases in SOC (van Straaten et al. 2015; Allen et al. 2016), root and litter production (Kotowska et al. 2015) and microbial biomass (Allen et al. 2015; Formaglio et al. 2021). Also, the higher soil ^{15}N natural abundance and lower soil C:N ratio in oil palm plantations than the forests (Hassler et al. 2015; van Straaten et al. 2015) signify a highly decomposed organic matter which, combined with reduced SOC, suggest reduced available C for microbial biomass and heterotrophic activity (Allen et al. 2015; Formaglio et al. 2021).

The seasonal pattern of soil CO_2 emissions from land uses in Indonesia is commonly influenced by soil moisture (e.g. Hassler et al. 2015; van Straaten et al. 2011). In our present study, the positive correlation between soil CO_2 emissions and soil moisture (ranging from 10%–55% WPFS; Fig. 3.4a) depicted a reduced soil respiration during the dry season, particularly in the palm circle and frond-stacked area, suggesting diminished autotrophic and heterotrophic respiration in these management zones when soil moisture was low (Fig. 3.4a; Fig. S3.1). Previous studies show that autotrophic and heterotrophic respiration increase toward an optimum WFPS (e.g. WFPS between 50%–55%; Sotta et al. 2007; van Straaten et al. 2011). Unlike the previous study conducted in 2013 in the same area (Hassler et al. 2015), our measured WFPS did not reach beyond 55%, as the annual rainfall during our study year (2019–2020) was lower than in 2013 and the sandy clay loam texture of our present soil may facilitate well-drained conditions. Thus, we did not observe a parabolic relationship of soil CO_2 emissions with WFPS beyond 55% as observed by Hassler et al. (2015). Although we observed a positive relationship between soil CO_2 emissions and soil temperature (Fig. 3.4b), largely in the frond-stacked area, this maybe confounded by WFPS as the soil temperature and WFPS were auto-correlated (Fig. 3.4j). Thus, soil temperature was not a dominant controlling factor for the seasonal pattern of soil CO_2 emissions in this oil palm plantation where soil temperature also only varied narrowly during our measurement period (25–28 °C; Fig. 3.4b).

3.5.2. Soil N_2O emissions

Area-weighted soil N_2O emissions (Table 3.1) were within the range reported for oil palm plantations on mineral soils (8–117 $\mu g\ N\ m^{-2}\ h^{-1}$; Aini et al. 2015; Sakata et al. 2015; Hassler et al. 2017; Rahman et al. 2019; Drewer et al. 2021b). Specifically, the soil N_2O emissions from the unfertilized inter-row and frond-stacked areas at our site were close to the lower end of this range whereas those from the fertilized palm circle were larger than the upper end of this range (Fig. S3.2). This pattern supported our second hypothesis, whereby soil N_2O emission was primarily influenced by soil N availability (i.e. mineral N; Table 3.2; Fig. 3.4f). These pulses of N_2O emissions from the palm circle peaked at around two weeks following N fertilization and went down to the background emissions after at most eight weeks (Fig. S3.2) (Aini et al. 2015; Hassler et al. 2017; Rahman et al. 2019). Although both the inter-row and frond-stacked areas had no direct N fertilizer application, litter decomposition in the frond-stacked area resulted in higher gross rates of N mineralization and nitrification, indicating higher soil N availability, than the inter-row (Formaglio et al. 2021). This explained the higher soil N_2O emissions from the frond-stacked area than the inter-row (Table 3.1). However, these internal soil-N cycling processes provide slow release of mineral N as opposed to the pulse release of mineral N level from N fertilization, and hence the soil N_2O emissions and mineral N levels were larger in the palm circle than the frond-stacked area (Tables 3.1 and 3.2). These findings signified the main control of soil N availability on soil N_2O emissions (Fig. 3.4f) (Davidson et al. 2000). We did not observe a correlation of soil N_2O emissions with WFPS (Fig. 3.4d) possibly because our sandy clay loam soil was relatively dry to moist in the top 5 cm depth ($\leq$ 55% WFPS) during our measurement period. In sum, the direct N fertilizer application on the palm circle (although covering only 18% of the plantation area) caused the extremely high soil N_2O emissions (Fig. S3.2), accounting 79% of the annual soil N_2O emission at the plantation level (Fig. 3.2). Our findings highlight that the palm circle was a hot spot of soil N_2O emissions, and such management-induced spatial heterogeneity must be accounted for in accurately quantifying soil N_2O emissions from large-scale oil palm plantations.

The large and comparable soil N_2O emissions between the conventional and reduced fertilization treatments (Table 3.1; Fig. 3.2) were contrary to our first hypothesis. However, this finding was consistent with the soil N availability, i.e. mineral N (Table 3.2) as well as gross and net rates of soil N mineralization and nitrification, which did not differ among treatments during 1–4 years of this management experiment (Formaglio et al. 2021; unpublished data of net N mineralization and nitrification rates). These results implied a substantial legacy effect of the past decade of conventional management (high fertilization rate and herbicide application) prior to the start of this management experiment. It is important to note that our reduced fertilization treatment was still 1.5–3 times higher than the N fertilization rates in smallholder oil palm plantations, and these reduce fertilization treatment displayed 2–4 times larger soil N_2O emissions than the smallholder plantations (Hassler et al. 2017). Also, the soil mineral N levels in this large-scale oil palm plantation were larger in any of the management treatments (Table 3.2) compared to smallholder oil palm plantations (Hassler et al. 2017). In the reduced fertilization treatment, soil mineral N was possibly not the limiting factor for N_2O production, since the peaks of soil N_2O emissions following fertilization in both reduced and conventional fertilization treatments were comparable (Fig. S3.2). This supports the conclusion of Formaglio et al. (2020) that the decadal over-fertilization of this large-scale oil palm plantation causes large stocks of mineral N, leached below the root zone, and despite four years of reduced fertilization mineral N stored at deeper depths can contribute to microbial production of N_2O. These findings imply the need to adjust fertilization rates with age of oil palm plantation to maintain good yield while reducing the environmental impact. Apparently, years of over fertilization can have lasting effects well beyond the period when fertilization management changes. As the palm circle is a hotspot of N_2O emissions, improved nutrient management in this zone may have the potential to minimize fertilizer-induced N_2O emissions, e.g. through application of slow-release N fertilizers, use of nitrification inhibitors, adjusting N application rate with age of the plantation, and understory vegetation to take up and recycle excess mineral N (Sakata et al. 2015; Ashton-Butt et al. 2018; Cassman et al. 2019). Moreover, return of organic residues (empty fruit bunches or mill effluent) should be encouraged to improve nutrient retention and recycling, and to reduce dependency on chemical fertilizers (Bakar et al. 2011; Formaglio et al. 2021).

3.5.3. Soil CH_4 uptake

Area-weighted soil CH_4 uptake (Table 3.1) was comparable to CH_4 uptake reported for oil palm plantations (-15 ± 3 µg C m^{-2} h^{-1}) but lower than soil CH_4 uptake in forests on similar loam Acrisol soils in Jambi, Indonesia (-29 ± 12 µg C m^{-2} h^{-1}) (Hassler et al. 2015). The soil CH_4 uptake at our site was larger than that reported by Drewer et al. (2021a) (-3 ± 1 µg C m^{-2} h^{-1}) from ≤ 12 years old oil palm plantations on clay Acrisol soil in Malaysian Borneo, which they attributed to very high CH_4 emissions from a plot adjacent to a riparian area. Also, the soil CH_4 uptake at our site was larger than that reported by Aini et al. (2020) (ranging from -1 to 13 µg C m^{-2} h^{-1}) for an oil palm plantation on sandy clay loam Cambisol soil in Jambi, Indonesia, which they explained by the high WFPS (> 80%) during their measurement period. Clay content or soil texture is the main site factor that correlate positively to soil CH_4 fluxes(Veldkamp et al. 2013), indicating that the higher the clay content the lower is the soil CH_4 uptake. High clay content soils have a low proportion of coarse pores (Hillel 2003), which are important for gas diffusive transport. Furthermore, soils with high clay content have high water-holding capacity, which hinders gas diffusion from the atmosphere to the soil and limits CH_4 availability to methanotrophic activity in the soil (e.g. Keller and Reiners 1994; Veldkamp et al. 2013). Thus, the disparity of soil CH_4 uptake between our present site and these above-mentioned studies was attributed to their differences in soil texture or drainage status as well as rainfall conditions or WFPS during the measurement periods, which all influence CH_4 diffusion from the atmosphere to the soil and thereby its uptake.

The positive correlation between soil CH_4 fluxes and WFPS (Fig. 3.4g), which reflected the same spatial pattern and positive correlation between soil CH_4 fluxes and soil bulk densities (Fig. S3.5), was attributed to the reduction of CH_4 diffusion from the atmosphere to the soil with increases in WFPS and soil bulk density (e.g. Veldkamp et al. 2013; Tchiofo Lontsi et al. 2020; Martinson et al. 2021). Differences in soil bulk density that result from management practices in oil palm plantations (Table S1) (Formaglio et al. 2021) affect soil total porosity, WFPS and gas diffusivity (e.g. Keller and Reiners 1994; Hassler et al. 2015). The frond-stacked area has large SOC (Table S3.1) and low soil bulk density (Fig. S3.5) or high porosity (Formaglio et al. 2021), resulting in low WFPS (Table 3.2). Thus, with the high soil porosity in the frond-stacked area, gas diffusion may not limit CH_4 availability to methanothrophic activity in the soil, resulting in the highest soil CH_4 uptake among the management zones (Table 3.1). Where gas diffusion was favorable in the frond-stacked area, the increase in soil mineral N had increased CH_4 uptake (Fig. 3.4i), suggesting that mineral N availability enhanced CH_4 uptake once gas diffusion is not limiting (Veldkamp et al. 2013; Hassler et al. 2015). Conversely, the palm circle and inter-row have small SOC (Table S3.1) and high soil bulk density (Fig. S3.5) or low porosity (Formaglio et al. 2021), resulting in high WFPS (Table 3.2), which may have limited gas diffusion and possibly created anaerobic microsites, and thereby the occasional soil CH_4 emissions during the wet season (Fig. S3.3). Thus, the observation that soil mineral N did not influence soil CH_4 fluxes from the palm circle and inter-row (Fig. 3.4i) was possibly because gas diffusion limitation was the overriding factor controlling soil CH_4 uptake. Aside from improving the soil biochemical properties with the decadal piling of senesced fronds on the frond-stacked area (Table S3.1), which favor for increases in soil microbial biomass (Fig. S3.4) and N cycling rate (Formaglio et al. 2021), stimulating soil CH_4 sink or methanotrophic activity is one proof of the multiple benefits of conserving soil organic matter, e.g. its role on soil GHG abatement (Veldkamp et al. 2020). Foot traffic from management practices in the palm circle and inter-row as well as reduced litter inputs had increased soil bulk density and decreased SOC (Table S3.1), accompanied by reductions in microbial biomass and its activity (e.g. low soil N cycling rate; Formaglio et al. 2021), including reduced methanotrophic activity (Table 3.1). At the plantation level, the overall comparable soil CH_4 uptake between the reduced and conventional management treatments indicated that changes in fertilization rates and weeding methods did not yet affect the drivers of soil CH_4 uptake (e.g. comparable soil mineral N and WFPS among treatments; Table 3.2) at least during the first four years of this experiment. Instead, the spatial differences in soil CH_4 uptake suggest that restoring the function of soil as CH_4 sink should be geared towards increasing soil organic matter, e.g. alternating locations of piled fronds with unused inter-rows, returning empty fruit bunches and other processing by-products, and avoiding plant biomass burning in establishing the next generation oil palm plantation (Bakar et al. 2011; Carron et al. 2015; Bessou et al. 2017).

3.5.4. Global warming potential

The GWP of this $\geq$ 18-year-old, large-scale oil palm plantation (Fig. 3.3) was in the lower end of the estimate from another part of this plantation near a peat soil (GWP of 686 ± 353 g CO_2-eq m^{-2} yr^{-1}; Meijide et al. 2020). The slight difference between our estimated GWP and this previous study, aside from the latter's proximity to a peat soil, can be due to plantation age, different climatic conditions during separate study years, and different employed methods. First, as to plantation age, oil palm acts as a net C source one year after forest conversion with a net ecosystem exchange (NEE) of 1012 ± 51 g C m^{-2} yr^{-1} and becomes a net C sink at 12 years old (NEE of −754 ± 38 g C m^{-2} yr^{-1}; Meijide et al. 2020). However, C removed from the field via fruit harvest turns this plantation into a net C source (NEP of 146 ± 94 g C m^{-2} yr^{-1}; Meijide et al. 2020). At our study plots, the average annual yield during 2017–2020 across treatments (Fig. 3.3; Table S3.2) was higher than that of Meijide et al. (2020) (900 ± 49 g C m^{-2} yr^{-1}). Our estimated NEP (i.e. heterotrophic respiration – (NPP – fruit biomass C); Fig. 3.3) (Malhi et al. 1999; Quiñones et al. 2022; Iddris et al. 2023) was in the lower end of Meijide et al.'s (2020) NEP estimate. We attributed this small NEP to be due to large biomass and yield production as oil palm trees aged and also possibly due to reduced heterotrophic respiration as SOC had already decreased and reported to attain a steady-state low level after ~15 years from forest conversion (van Straaten et al. 2015). Secondly, the different climate conditions during our study year compared to the study by Meijide et al. (2020), may also have contributed to the differences in biomass and yield production as well as heterotrophic respiration. Our measurement period (2019–2020) had annual rainfall within the 10-year average, whereas Meijide et al.'s (2020) study years (2014–2016) included a severe drought in 2015 caused by a strong El Niño Southern Oscillation that induced prolonged smog events in Jambi, Indonesia (Field et al. 2016). Drought combined with smoke haze reduce the productivity and CO_2 uptake in this oil palm plantation (Stiegler et al. 2019), supporting the low fruit yield measured by Meijide et al. (2020). Thirdly, our different estimation methods may have contributed to the small disparity between our GWP estimate and that by Meijide et al. (2020), who measured NEE by eddy covariance technique. Our method and theirs both have advantages and disadvantages; ours based on measurements of NPP components and assumption of heterotrophic respiration contribution to measured soil CO_2 emissions (van Straaten et al. 2011) was spatially replicated, inexpensive, and practicable to deploy without a need for electricity source in the field (Baldocchi 2014), e.g. for plot-scale experiment on different fertilization regimes and weeding practices.

As soil N_2O emissions contributed substantially (55%) to the GWP of this large-scale oil palm plantation while soil CH_4 sink had only minor offset (< 2%) (Fig. 3.3), reducing its GHG footprint could be achieved by decreasing soil N_2O emissions and increasing soil CH_4 uptake (see above). Finally, the large NPP of this ≥ 18-year-old, large-scale oil palm plantation and reduced heterotrophic respiration (due to reduced SOC after ~ 15 years from forest conversion; van Straaten et al. 2015) contributed to its small NEP that accounted 46% of the GWP. In the perspective of long-term oil palm management, extending the rotation period from 25 years to 30 years to prolong accumulation of plant biomass C (Meijide et al. 2020), avoiding large biomass loss during establishment of the next generation oil palms (e.g. not burning but leaving cut palm trees on the field), and enhancing SOC stocks will reduce the GHG footprint of oil palm plantations.

3.6. Conclusions

During the first four years of this management experiment, soil GHG fluxes, GWP, and yield in reduced fertilization with mechanical weeding remained similar to conventional fertilization with herbicide application, signifying the strong legacy effect of over a decade of high fertilization regime prior to the start of our experiment in this mature oil palm plantation. Reducing soil N_2O emissions is the key to reducing GHG footprint in this oil palm plantation as soil N_2O emissions contributed substantially to the GWP of this oil palm plantation. The palm circle and frond-stacked area both showed high mineral N availability, but the palm circle was driven by the high fertilization rates and rendering it as a hotspot of soil N_2O emissions. In contrast, the frond-stacked area support high root and microbial biomass, low soil N_2O emissions and high soil CH_4 uptake. Thus, reasonably expanding the frond-stacked area and returning organic residues from oil palm fruit processing in order to reduce dependency on chemical fertilizers will help reduce the GHG footprint while maintaining high production in oil palm plantations.

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3.8. Appendix

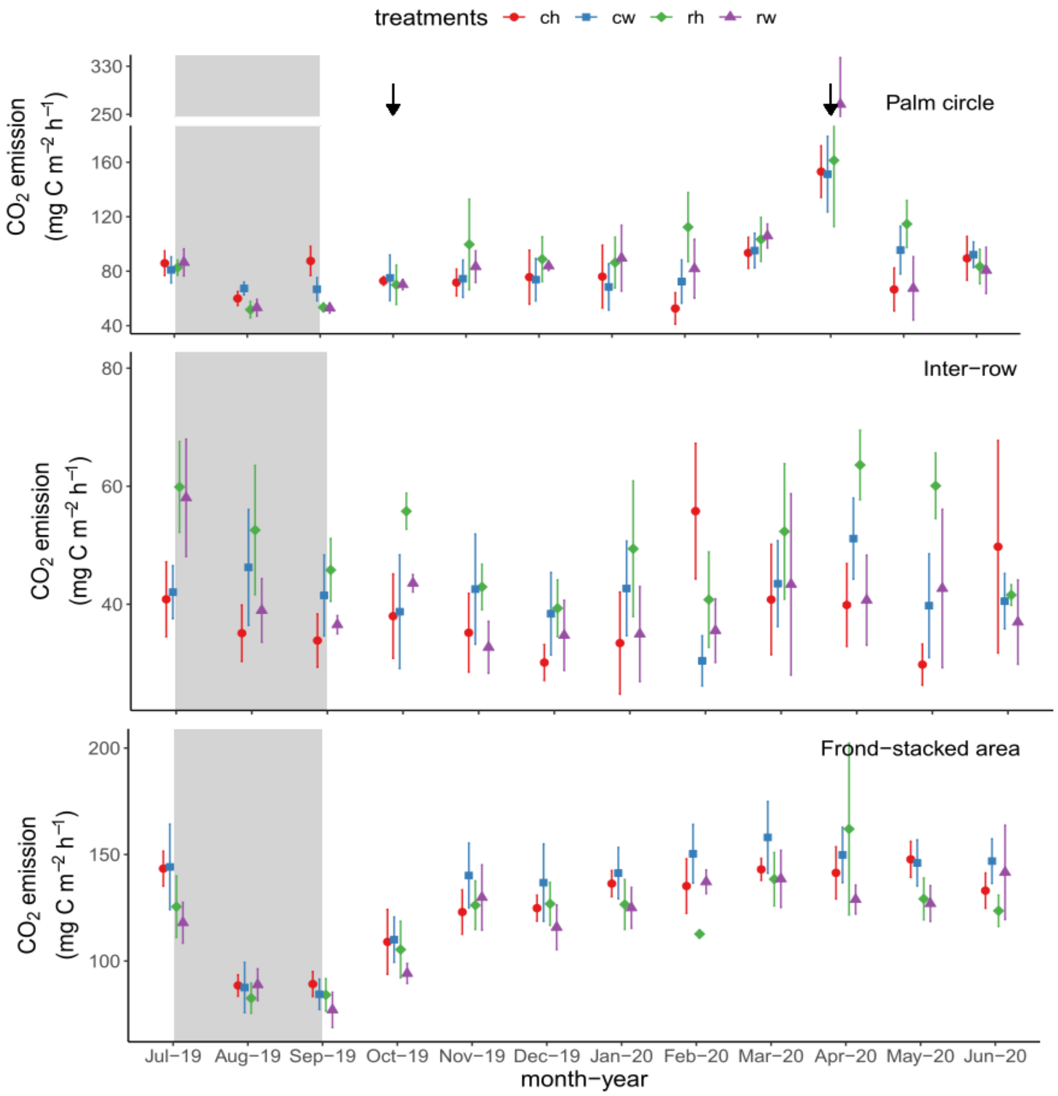

Fig. S3.1 Soil CO_2 emissions (mean ± SE, *n* = 4 plots) from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from July 2019 to June 2020. Gray shadings mark the dry season (precipitation ≤ 80 mm month^{-1}) and black arrows indicate fertilizer applications on the palm circle. Note the different y-axis ranges for the three management zones. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

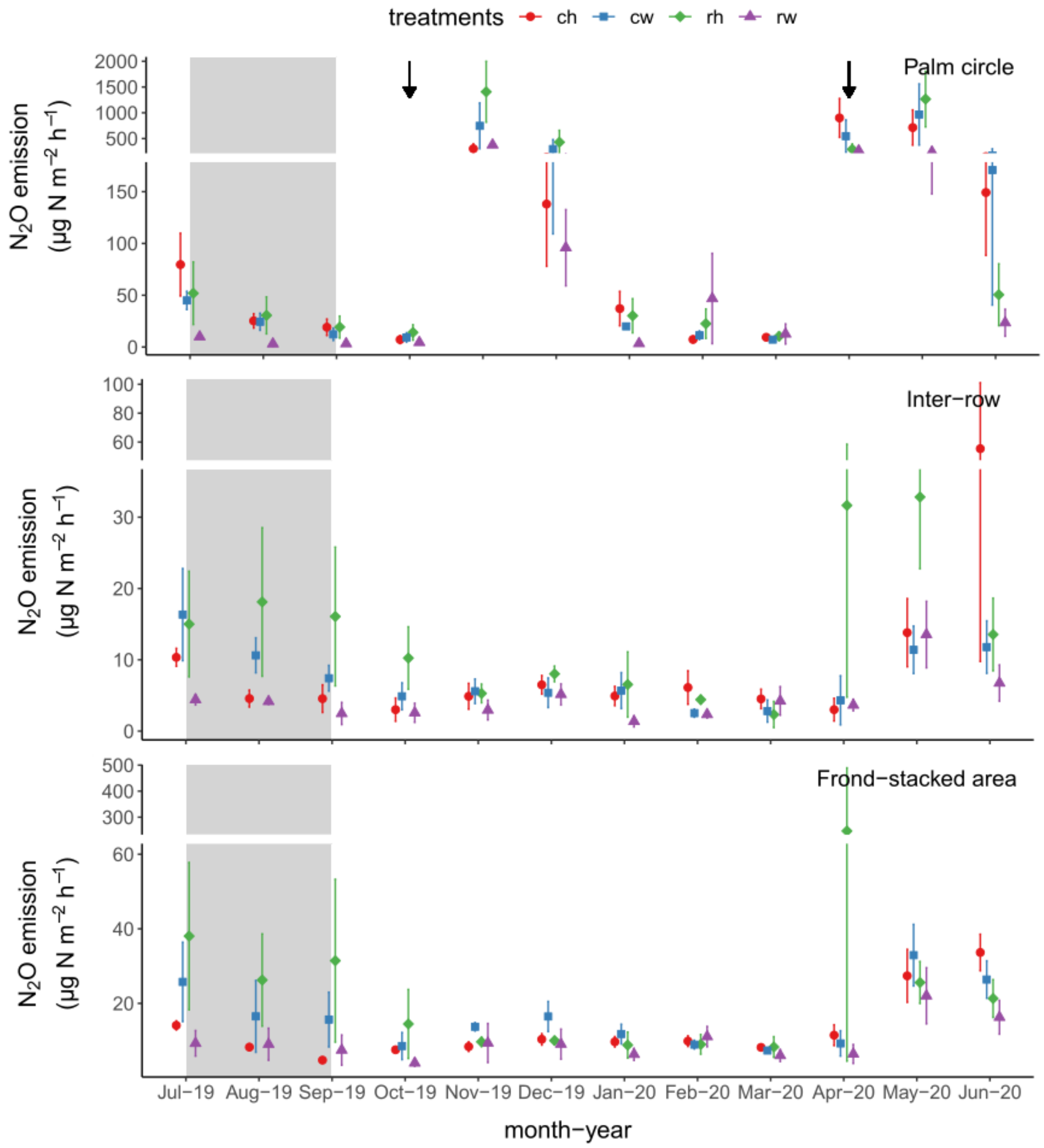

Fig. S3.2 Soil N_2O emissions (mean ± SE, n = 4 plots) from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from July 2019 to June 2020. Gray shadings mark the dry season (precipitation ≤ 80 mm month^{-1}) and black arrows indicate fertilizer applications on the palm circle. Note the different y-axis ranges for the three management zones. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

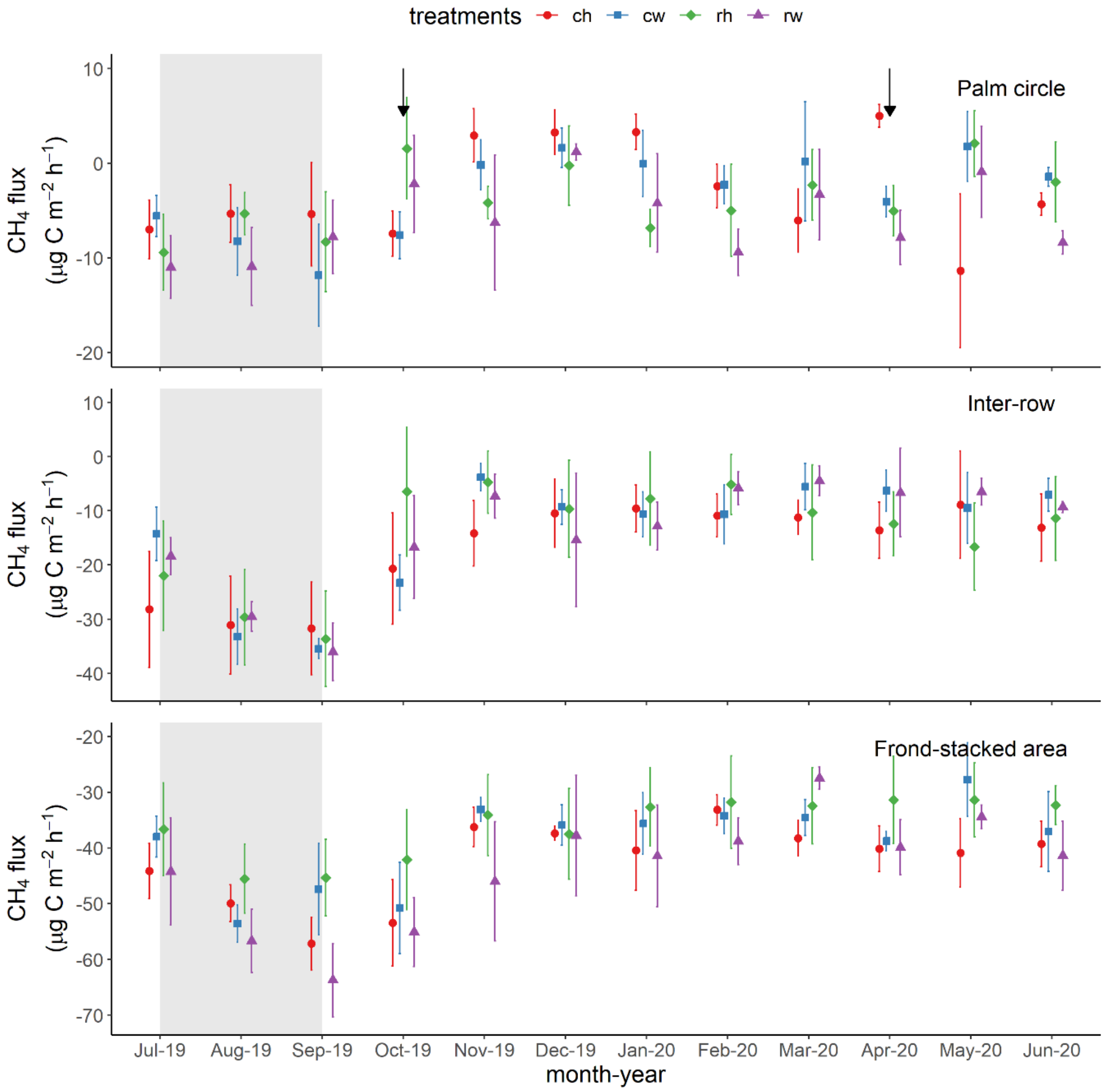

Fig. S3.3 Soil CH_4 fluxes (mean ± SE, *n* = 4 plots) from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from July 2019 to June 2020. Gray shadings mark the dry season (precipitation ≤ 80 mm month^{-1}) and black arrows indicate fertilizer applications on the palm circle. Note the different y-axis ranges for the three management zones. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

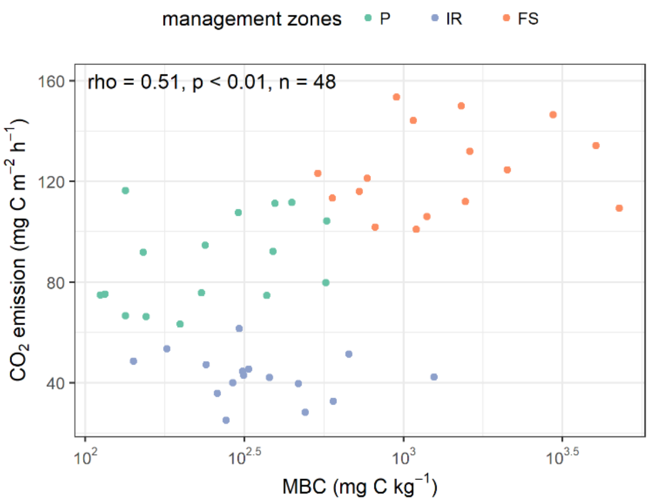

Fig. S3.4 Spearman rank correlation between soil CO_2 emissions and microbial biomass carbon (MBC). Each data point for soil CO_2 emissions was the average of 12-monthly measurements and MBC was measured once in 2018, as reported by Formaglio et al. (2021). P – palm circle, IR – inter-row, FS – frond-stacked area

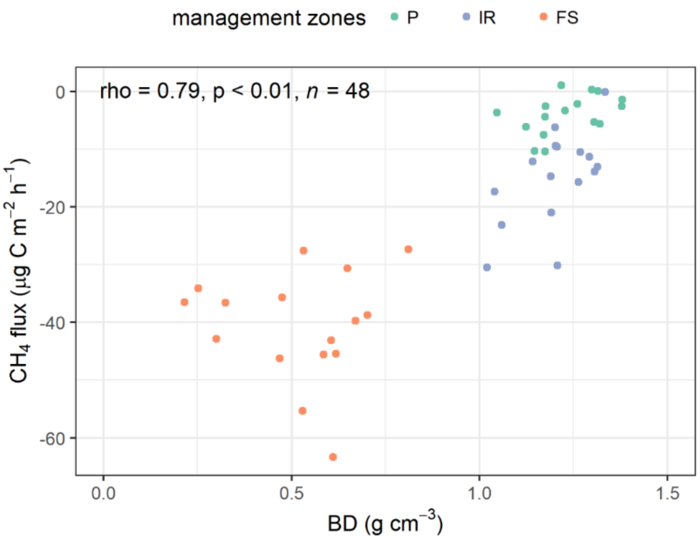

Fig. S3.5 Spearman rank correlation between soil CH_4 fluxes and soil bulk density (BD). Each data point for soil CH_4 fluxes was the average of 12-monthly measurements and BD was measured once in 2018 (Formaglio et al. 2021). P – palm circle, IR – inter-row, FS – frond-stacked area

Table S3.1 Soil biochemical and physical characteristics (means ± SE, *n* = 16 plots) in 0–50 cm depth determined in 2018 and soil texture in the 50–150 cm depth determined in 2021, reported for each management zone in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia

characteristics	Palm circle	Inter-row	Frond-stacked area
Soil organic C (kg C m^{-2})	6.2 ± 0.6 b	6.4 ± 0.2 b	9.1 ± 0.8 a
Total N (g N m^{-2})	402 ± 31 b	426 ± 15 ab	571±39 a
ECEC ($mmol_{charge}$ kg^{-1})	35 ± 2 a	18 ± 1 b	28 ± 2 a
pH (1:4 soil-to-H_2O)	5.05 ± 0.08 a	4.81 ± 0.05 b	5.00 ± 0.08 ab
Bulk density (g cm^{-3})	1.37 ± 0.01 a	1.36 ± 0.01 a	0.89 ± 0.01 b
Clay (%)	23.30 ± 1.31 a	23.60 ± 1.00 a	25.47 ± 1.37 a
Silt (%)	7.80 ± 1.19 a	7.73 ± 1.23 a	6.47 ± 1.21 a
Sand (%)	68.90 ± 1.52 a	68.67 ± 1.35 a	68.07 ± 1.97 a

ECEC: effective cation exchange capacity. For each parameter, different letters indicate significant differences among management zones (one-way ANOVA with Tukey HSD at $p \leq 0.05$). Except for soil texture, soil characteristics were reported by Formaglio et al. (2020)

Table S3.2 Cumulative fruit yield from 2017–2020 (means ± SE, *n* = 4 plots) in different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia

Treatments	Cumulative yield (Mg ha^{-1})			
	2017	2018	2019	2020
ch	26.64 ± 1.91	57.55 ± 2.74	83.41 ± 3.63	114.60 ± 4.26
cw	31.24 ± 1.12	66.51 ± 1.57	96.75 ± 3.55	130.37 ± 4.45
rh	28.18 ± 2.35	56.31 ± 4.86	86.59 ± 5.21	116.01 ± 6.20
rw	29.38 ± 4.69	60.62 ± 5.35	90.94 ± 5.25	118.50 ± 5.92

There are no significant differences among treatments for each column (2^2 factorial ANOVA; fertilization: p = 0.35–0.96; weeding control: p = 0.07–0.32; interaction: p = 0.23–0.57). ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

Chapter 4

Reduced fertilization with mechanical weeding decreases soil nitrogen leaching losses and maintains the high yield in a mature large-scale oil palm plantation

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4.1. Abstract

Conventional management of oil palm plantations, involving high fertilization rate and herbicide application, results in high yield but with a high risk of nutrient leaching losses. This study aimed to assess a practical alternative to conventional management, namely reduced fertilization with mechanical weeding, to decrease soil element leaching without sacrificing production. We established a full factorial experiment with two fertilization rates (conventional and reduced fertilization, equal to nutrients exported via fruit harvest) and two weeding methods (herbicide and mechanical), each with four replicate plots, since 2016 in a mature large-scale oil palm plantation in Indonesia. Soil element leaching at 1.5 m soil depth were measured during 2019–2020 from three management zones (the palm circle, inter-row, and frond-stacked area). In conventional management, the annual element leaching in this oil palm plantation were 46 kg N ha^{-1} yr^{-1}, 22 kg Al ha^{-1} yr^{-1}, 23 kg Ca ha^{-1} yr^{-1}, 9 kg K ha^{-1} yr^{-1}, 9 kg Mg ha^{-1} yr^{-1}, and 9 kg Na ha^{-1} yr^{-1}. Compared to the conventional fertilization, reduced fertilization decreased dissolved N leaching by 74%, Al leaching by 60%, and K leaching by 73%. Among the management zones, the fertilized palm circle had higher dissolved N, Al, Ca, K, Mg, and Na leaching losses than the inter-row and frond-stacked area. Although fertilization and weeding treatment did not affect DOC leaching but reduced fertilization had a higher area-weighted DOC:DON ratio in soil-pore water compared to conventional fertilization. This study show for the first time that reduced fertilization with mechanical weeding decreased N, Al, and K leaching losses without sacrificing the high yield in large-scale oil palm plantation after 4 years of treatment. Our results support that reduced fertilization with mechanical weeding can contribute to the sustainability of large-scale oil palm plantations.

Keywords: Fertilization management; Tree cash crop plantation; Weeding practices; Nitrogen budget

4.2. Introduction

Rapid oil palm expansion has been a significant driver of land-use change in the tropics over the past several decades, especially in Southeast Asia (Meijaard et al. 2018; Vancutsem et al. 2021). Between 1989 and 2013, 45% of established oil palm plantations in Malaysia and Indonesia, the two largest palm oil producers, were transformed from forests (Vijay et al. 2016). This change in land use has been shown to have negative impacts on ecosystem multifunctionality, including decreases in C storage (Kotowska et al. 2015; van Straaten et al. 2015), nutrient cycling and retention (Allen et al. 2015; Kurniawan et al. 2018), water and energy fluxes (Manoli et al. 2018), and biodiversity losses (Clough et al. 2016). Yet oil palm plays an important role in the global vegetable oil supply because oil palm is the most productive oil crop, yielding four to ten times more than soy, rapeseed, or sunflower per unit area (Thomas et al. 2015). Presently, oil palm meets approximately 35% of global vegetable oil consumption using less than 10% of the oil crops land (Meijaard et al. 2018). Large-scale oil palm plantations (> 50 ha planted area and owned by corporations) have much higher productivity than in smallholder oil palm plantations (< 50 ha per household, most around 2 ha and owned by individuals) (Monzon et al. 2021), but this is largely dependent on conventional intensive management practices, such as high rates of fertilizer and herbicide application during the life cycle of the oil palm plantation (25-30 years). A significant long-term effect of such excess fertilization under conventional management practices is nutrient leaching losses (Banabas et al. 2008; Tung et al. 2009).

Nitrogen fertilization rate is the most important factor controlling N leaching losses under specific climate and land use (Wang et al. 2019; Huddell et al. 2020). In agriculture ecosystems, soil N leaching increases with an increase in N surplus (applied N fertilizer – N remove through harvest) (Goulding 2000; Tamagno et al. 2022). Highly mobile NO_3^- is the dominant form of leached soil N, partly because most soil aggregates have a negative charge and hence cannot hold it tightly (Schlesinger and Bernhardt 2013). Highly weathered tropical soils, such as Ferralsols, Acrisols, Lixisols, and Nitisols have pH-dependent charges and show anion exchange capacity (AEC) at acidic pH (Veldkamp et al. 2020). Thus, NO_3^- is not lost directly through leaching in soils with AEC but is absorbed in the soil profile. In fertilized tropical agricultural ecosystems, large NO_3^- stocks in subsoil has been widely reported (Rasiah et al. 2003; Neill et al. 2013; Tully et al. 2016; Huddell et al. 2022). Although low-activity soil clays with positively charge have the ability to adsorb substantial amounts of NO_3^-, it is inevitable that NO_3^- will leach beyond the root zone when high rates of N fertilizer are applied continuously. On the one hand, the soil anion adsorption capacity from the root zone is limited. On the other hand, other anions, such as Cl^-, and SO_4^{2-} from fertilizer or rainfall, can displace NO_3^- from soil adsorption sites (Formaglio et al. 2020). For example, Dong et al. (2022) found that NO_3^- leaching at 1 m soil depth increased from 27 kg N ha^{-1} yr^{-1} in the first fertilization year to 88 kg N ha^{-1} yr^{-1} in the second fertilization year in a previously 10-year unfertilized Ferric Acrisol soil with AEC. NO_3^- leaching is a significant path of N losses in fertilized tropical agriculture (Huddell et al. 2020) and has a detrimental impact on the environment, such as eutrophication which poses a threat to the safety of drinking water (Wang et al. 2013). However, there is a paucity of field data on N leaching losses, which is a major cause of uncertainty in N budgets of oil palm plantations (Pardon et al. 2016).

NO_3^- leaching is accompanied by an equal charge loss of cations (Jiang et al. 2018; Kurniawan et al. 2018; Formaglio et al. 2020). Many cations like Ca, Mg, and K are essential nutrients for plants and play an important role in buffering soil pH (Schlesinger and Bernhardt 2013). Oil palm plantations are widely distributed on highly weathered acidic tropical soil with low base saturation (Sheil et al. 2009), and Al^{3+} can be the major cation in soil-pore water (Formaglio et al. 2020). The low availability of soil base cations affects oil palm yield, and high Al^{3+} concentration threatens oil palm root growth and metabolism (Ratnasari et al. 2017; Panggabean et al. 2021). This results in oil palm plantations relying on micronutrient fertilizers and lime to replenish cations that are exported via fruit harvest, and to stabilize soil pH to reduce the impact of soil acidification on oil palm. Thus, reducing NO_3^- leaching through optimizing fertilization rates without sacrificing yield in oil palm plantations can reduce negative environmental impacts and reliance on micronutrient fertilizers and lime.

Leaching of dissolved organic C (DOC) is a significant flux in the terrestrial C budget and in tropical ecosystems, it is estimated that 22% of terrestrial net ecosystem productivity is exported to aquatic systems as leached DOC (Nakhavali et al. 2021). Soil organic matter decomposition, root exudates, and litter decomposition produce large amounts of DOC in the soil (Evans et al. 2005; Möller et al. 2005). At the same time, plenty of DOC is immobilized by soil microorganisms or absorbed to clay minerals in subsoil (Kalbitz et al. 2000). The relative rates of DOC production and consumption determines the DOC leaching fluxes. Fertilization affects plant rhizosphere C flux (Giardina et al. 2004), soil C mineralization rates (Koehler et al. 2009), and microbial biomass (Baldos et al. 2015) in tropical forests, and can potentially affect soil DOC production and consumption. Herbicide application results in the complete removal of understory vegetation resulting in decreased plant species diversity (Guynn Jr et al. 2010; Qi et al. 2020) which can in turn affect soil DOC input from understory plants (Lange et al. 2020). Conversion of forests to smallholder oil palm plantations has been shown to result in increases in soil DOC leaching (Kurniawan et al. 2018). However, the effect of different oil palm management intensity on soil DOC leaching is still unknown.

The conventional management practices of fertilization, weeding, and pruning of senesced fronds within large-scale oil palm plantations usually result in three distinctive management zones: palm circle (fertilized and weeded), inter-row (not fertilized but weeded), and frond-stacked area (not fertilized or weeded but mulched with pruned frond) (Formaglio et al. 2020). The fertilized palm circle distributes dense root (Dassou et al. 2021). The unfertilized inter-row has little organic matter input and low soil fertility (Formaglio et al. 2020). The frond-stacked area receives nutrients input through litter decomposition and hence supports high fine root and microbial biomass (Dassou et al. 2021; Formaglio et al. 2021). The palm circle and inter-row have higher soil bulk density than the frond-stacked area due to frequent foot traffic (Formaglio et al. 2020), which consequently results in the frond-stacked area having the highest water infiltration rate among the management zones (Banabas et al. 2008). The different water infiltration and evapotranspiration among management zones result in their different soil drainage fluxes (Formaglio et al. 2020). The direct fertilizer application in the palm circle offers sufficient nutrients to oil palm but also presents higher risk of nutrient leaching than in the unfertilized inter-row and frond-stacked area (Formaglio et al. 2020). Therefore, differences in element concentrations in soil-pore water and drainage flux among management zones should be taken into consideration when assessing the nutrient leaching losses in oil palm plantations.

In this study, we assessed the dissolved N, cation element, and DOC leaching losses from conventional management (conventional fertilization – herbicide weeding) and reduced management (reduced fertilization, equal to nutrient exported via fruit harvest – mechanical weeding) by taking into consideration the different management zones in an ≥ 18-year-old, large-scale oil palm plantation (Fig. 4.1). During first four years of fertilization and weeding treatments, reduced management had comparable yield (Iddris et al. 2023), microbial biomass (Formaglio et al. 2021), and fine root biomass (Ryadin et al. 2022) as the conventional management. Therefore, we hypothesized that (1) reduced management, with relatively low N fertilization rate, will have lower soil N and cation elements leaching losses than the conventional fertilization, but soil DOC leaching will be comparable between the two management practices; (2) the fertilized palm circle will have higher soil N and cation elements leaching losses than the inter-row and frond-stacked area, but the three management zones will have comparable soil DOC leaching.

Fig. 4.1 An ≥ 18-year-old, large-scale oil palm plantation in Jambi, Indonesia (a). The three distinct zones resulting from field management practices in the oil palm plantation (b). Installation of suction cup lysimeters at 1.5 m depth in each management zone per replicate plot (c). Soil-pore water sampling from installed lysimeters, measured monthly from November 2019 to October 2020 during 3-4 years of this field experiment (d).

4.3. Materials and methods

4.3.1. Site description and experimental design

We conducted our study in a mature large-scale oil palm plantation in Jambi, Indonesia (1°43′8″ S, 103°23′53″ E, 73 m above sea level). The 2025 ha plantation was established between 1998 and 2002, and thus the oil palms were ≥ 18 years old during our measurement period from November 2019 – October 2020. Oil palms were planted at a density of 142 palms ha^{-1}, and spaced 8 m apart both within and between rows. The study area has an average annual air temperature of 26.9 ± 0.2 °C and average annual precipitation of 2078 ± 155 mm (2010–2020). During our measurement period, the annual precipitation was 2081 mm and the dry season was from June to August 2020 based on consecutive monthly precipitation of less than 130 mm month^{-1} (Fig. 4.2d). The soil is highly weathered Acrisol soil with sandy clay loam texture. The oil palm fine roots are mainly distributed in the top 0–1 m soil depth in the research area (Kurniawan et al. 2018). This plantation follows the conventional management in Jambi and forms three contrasting management zones in the interior of the plantation: (1) the palm circle, which is a 2 m radius from the palm base where fertilizers, lime and herbicides are applied; (2) the frond-stacked area, where senesced fronds are piled; and (3) the inter-row, which is the remaining area of the plantation where no fertilization is applied but its minimally weeded (Fig. S4.1; Formaglio et al. 2020). The palm circle account for 18% of the plantation area, the inter-row covers 67%, and the frond-stacked area covers the remaining 15% of the plantation area (Formaglio et al. 2020).

We established a field management experiment within this oil palm plantation in November 2016 with 2^2 factorial treatments of two fertilization levels and two weeding methods. The fertilization treatments consisted of conventional fertilization rates commonly applied in large-scale plantations (260 kg N, 50 kg P, and 220 kg K ha^{-1} yr^{-1}), and reduced fertilization rates based on quantified nutrients exported via fruit harvest (136 kg N, 17 kg P, and 187 kg K ha^{-1} yr^{-1}). Fertilizers were applied twice per year following weeding and raking of the palm circle. The fertilizer sources were urea, triple superphosphate, muriate of potash or NPK-complete. Lime (426 kg dolomite ha^{-1} yr^{-1}) and micronutrients (142 kg micro-mag ha^{-1} yr^{-1} with 0.5% B_2O_3, 0.5% CuO, 0.25% Fe_2O_3, 0.15% ZnO, 0.1% MnO and 18% MgO) were applied in the palm circle in all treatments. The weeding treatments included either the use of herbicides in the palm circle (1.5 L glyphosate ha^{-1} yr^{-1}, split into four applications per year) and in the inter-rows (0.75 L glyphosate ha^{-1} yr^{-1}, split into two applications per year), or the use of mechanical weeding via brush cutter, which was done in with the same management zones and frequency as the herbicide weeding. The full factorial design resulted in four treatments (Fig. S4.1): conventional fertilization – herbicide weeding (ch), conventional fertilization – mechanical weeding (cw), reduced fertilization – herbicide weeding (rh), and reduced fertilization – mechanical weeding (rw). The four treatments were randomly assigned on 50 m × 50 m plots replicated in four blocks (Fig. S4.1). Two subplots were selected within the inner 30 m × 30 m area of each plot, and each subplot included the three management zones where all measurements were carried out (Fig. S4.1). As a consequence of these management activities, soil organic C and total N stocks are higher whereas soil bulk density is lower in the frond-stacked area compared to the palm circle and inter-row. Effective cation exchange capacity and pH, influenced by the applied lime as well as from decomposed frond litter, are higher in the palm circle and frond-stacked area than the inter-row (Table S4.1) (Formaglio et al. 2020).

4.3.2. Soil-pore water sampling

We collected soil-pore water below the oil palm rooting zone by installing suction cup lysimeters (P80 ceramic, maximum pore size 1 µm; CeramTec AG, Marktredwitz, Germany) at 1.5 m depth in the three management zones of each subplot per plot. Lysimeters were installed by drilling a vertical hole in the soil using an auger and then connected to dark glass bottles with a tube. All the bottles were placed in plastic buckets that were buried in the ground to shield the bottles from direct sunlight. In total, we installed 96 lysimeters (16 plots × 2 subplots × 3 management zones) at least three months prior to the first sampling in order to restore the disturbed soil. Soil pore water was sampled by applying a 40 kPa vacuum (Kurniawan et al. 2018) to the lysimeters. The water samples stored in the bottles were collected weekly from November 2019 to October 2020, and then pooled every month for each subplot and management zone. All samples were deep-frozen after collection and were transported by air to the Goettingen University, Germany for analysis. The concentration of NH_4^+, NO_3^-, and TDN were measured using continuous flow injection colorimetry (SEAL Analytical AA3; SEAL Analytical GmbH, Norderstedt, Germany). DON was calculated as the difference between TDN and mineral N ($NH_4^+ + NO_3^-$). The concentration of DOC was determined using a total organic carbon analyzer (TOC-Vwp, Shimadzu Europa GmbH, Duisburg, Germany). The concentration of Na, K, Ca, Mg, Al, Fe, Mn, S, and P were measured using an inductively coupled plasma-atomic emission spectrometer (iCAP 6300; Thermo Fisher ScientificGmbH, Dreieich, German). Most values of Fe (< 0.003 mg L^{-1}), Mn (< 0.002 mg L^{-1}), and P (< 0.01 mg L^{-1}) were below the instrument detection limits, thus we did not include Fe, Mn and P leaching fluxes in our data analysis.

4.3.3. Soil water modeling and leaching fluxes

The water balance in this oil palm plantation was modeled for each management zone (Formaglio et al. 2020) using Expert-N software, version 5.0 (Priesack, 2005). To parameterize the model, we maintained the model settings of Formaglio et al. (2020) but used climatic data (solar radiation, air temperature, precipitation, relative humidity, and wind speed) that were collected during our study period from a climatological station located in the plantation. The model input parameters of soil (texture, bulk density, and hydraulic functions) and plant characteristics (height, leaf area index, root distribution) were taken from our earlier studies in these plots or nearby oil palm plantations (detailed information in Formaglio et al. 2020). The water balance was established based on the mass balance among precipitation, runoff, evapotranspiration, daily water drainage, and the change in soil water storage (Kurniawan et al. 2018). In the Expert-N model, evapotranspiration is calculated using the Penman-Monteith equation, runoff is based on soil texture, bulk density, and slope, and the vertical soil water movement is based on the Richards equation using soil hydraulic functions (Kurniawan et al. 2018; Formaglio et al. 2020).

The water balances for the three management zones were modeled using the same climate data but different soil and plant parameters in order to mimic disparities in water balance among the distinct management zones (Formaglio et al. 2020). We validated the model output by comparing the modeled soil matric potential with field-measured values (Fig S4.2). To measure the soil matric potential in the field, we randomly installed two tensiometers (P80 ceramic, maximum pore size 1 µm; CeramTec AG, Marktredwitz, Germany) at soil depths of 30 cm and 60 cm in each management zone in the four treatments, totaling 24 tensiometers (3 management zones × 4 treatments × 2 soil depths). The soil matric potential was recorded weekly from November 2019 to October 2020.

The monthly soil drainage flux (at 1.5 m soil depth) was the cumulative value of the daily fluxes from the model output. The monthly dissolved elements leaching fluxes from each management zone were calculated as monthly drainage flux multiplied by the soil-pore water element concentrations. The mean values for each plot were calculated by taking the area-weighted average of the three management zones (see above). The annual nutrient leaching fluxes was the sum of area-weighted monthly values.

4.3.4. Calculation of major N fluxes and stocks

We measured the weight of harvested fruit bunches, the number of pruned fronds and the height of palms within the inner 30 m × 30 m area of each replicate plot from 2019–2020. Annual N exported via fruit harvest (kg N ha^{-1} yr^{-1}) was calculated as fruit bunch yield per palm (mean of 2019–2020) × planting density (142 palms ha^{-1}) × N concentration of fruit bunches (0.38%; Formaglio et al. 2021). Annual N input from pruned frond leaves (kg N ha^{-1} yr^{-1}) was calculated as frond litter mass per palm (mean of 2019–2020) × planting density × N concentration of frond litter (1.44%; Kotowska et al. 2016). Nitrogen stock in woody biomass was calculated as the standing woody biomass per palm (mean of 2019–2020) × planting density × the tissue N concentration (0.65%; Siang et al. 2022). The standing woody biomass was estimated using allometric growth equation developed for oil palm plantations, based on the height of the oil palms (Asari et al. 2013).

We measured monthly soil N_2O emissions from July 2019 to June 2020, and soil extractable mineral N stock in 2021 within this oil palm plantation (Chen et al. unpublished data). Soil N stocks were taken from our earlier studies at the same plots (Formaglio et al. 2020), while data on rainfall N deposition was measured in 2013 in the same research area (Kurniawan et al. 2018).

4.3.5. Statistical analysis

Statistical tests of soil-pore water dissolved element concentrations and leaching fluxes were based on the mean of the two subplots that represent each replicate plot and management zone in each sampling month. We tested the data for normality of distribution using Shapiro-Wilk's test and for equality of variance using Levene's test. Linear mixed-effects (LME) models with Tukey's HSD test were used to assess the differences in monthly soil-pore water element concentrations and leaching fluxes among treatments (Crawley 2013). In the LME models, management treatments (fertilization, weeding, and their interaction) were considered as fixed effects and replicate plots and sampling days as random effects. Additionally, soil-pore water element concentrations and leaching fluxes were tested for differences among the three management zones using LME models with management zone as the fixed effect and replicate plots and sampling days as random effects. The variance function that allows variance heteroscedasticity of the fixed effect was included in the final LME models, if it could improve the model performance based on the Akaike information criterion. Following non-normal distribution of the model residuals, soil-pore water element concentrations were log-transformed and reanalyzed for differences among treatments and management zones. The effect of fertilization and weeding treatment on annual dissolved element leaching fluxes were tested using factorial ANOVA. The relationships between modeled and measured soil matric potential and between soil extractable NO_3^- stock and annual NO_3^- leaching were determined using Pearson correlation test. The Pearson correlation among soil-pore water element concentrations were also tested in each management zone. The statistical significance for all the tests was set at $P \leq 0.05$. All data analyses were performed using the R (version 4.0.5) open-source software (R core Team 2021).

4.4. Results and discussion

Our modeled drainage fluxes were reliable as indicated by the positive correlation between modeled and field measured soil water matric potential from both 30 cm and 60 cm soil depths in each management zone (Pearson's $r = 0.66–0.86$; $P < 0.01$; Fig. S4.2). In this study, we assumed all plots had the same drainage fluxes but the palm circle had lower drainage fluxes compared to the inter-row and frond-stacked area, which was caused by a combination of higher evapotranspiration, interception, and runoff in the palm circle (Table S4.2 and Fig. 4.2a–c). At the plot level, soil nutrient leaching losses among treatments resulted from the differences in concentrations of elements in soil-pore water, whereas the different element leaching from three management zones was influenced by both drainage fluxes and nutrient concentrations. Compared to conventional fertilization with herbicide weeding, reduced fertilization with mechanical weeding decreased dissolved N, Al, K leaching losses but increased the ratio of DOC:DON in soil-pore water. Among the management zones, the fertilized palm circle had higher dissolved N, Al, Ca, K, Mg, and Na leaching losses than the inter-row and frond-stacked area. Our results suggest that the rate of fertilization supersedes the important of solute transport flux in this oil palm plantation.

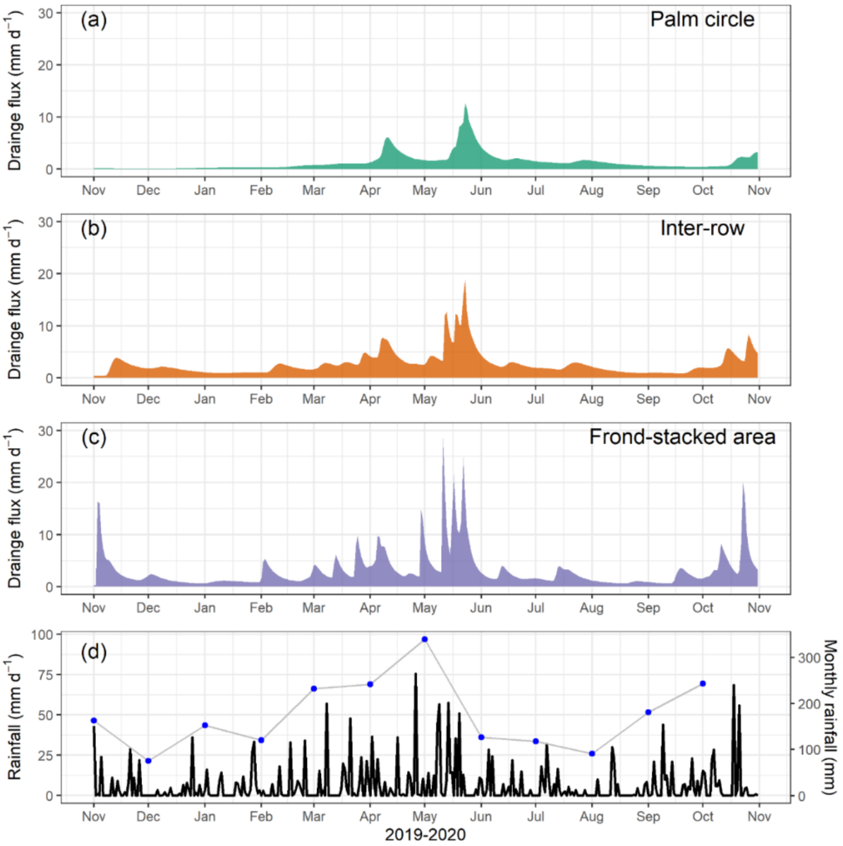

Fig. 4.2 Monthly water drainage at 1.5 m soil depth, simulated in each management zone: palm circle (a), inter-row (b), and frond-stacked area (c), and daily (black line) and monthly (blue circles) rainfall (d) from November 2019 to October 2020 in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia.

4.4.1. Reduced fertilization decreased N leaching losses

There was a significant effect of fertilization treatment on TDN leaching fluxes, whereas the effect of the weeding treatment was not significant (Table 4.1). Specifically, the reduction in fertilization rate in the reduced management decreased area-weighted monthly ($P \leq 0.01$; Table 4.1) and annual ($P \leq 0.02$; Table 4.2) NO_3^-, NH_4^+, DON leaching fluxes, supporting our first hypothesis. This is in line with studies in other agricultural systems that found significant decreases in N leaching following a reduction in the fertilization rate (e.g. Constantin et al. 2010; Min et al. 2011; Wang et al. 2019). The low N leaching fluxes under the reduced fertilization may be due to the low dissolved N concentrations in the soil-pore water ($P < 0.01$; Table S4.3), which was further reinforced by the significant decrease in soil extractable mineral N stocks within 0–1.5 m soil depth (Table S4.4) after more than 5 years of the reduced fertilization treatment. Compared to the conventional fertilization, reduced fertilization decreased TDN leaching by 43% during 0.5–1.5 years of this management experiment (Formaglio et al. 2020), and further decreased it by up to 74% after 3-4 years of the experiment (Table 4.2). These findings suggest that the application of fertilizer may be the most important factor influencing dissolved N leaching in oil palm plantations (Kurniawan et al. 2018).

Table 4.1 Dissolved nitrogen and dissolved organic carbon leaching fluxes (mean ± se, *n* = 4 plots) at 1.5 m soil depth from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from November 2019 to October 2020 during 3-4 years of this field experiment.

Dissolved N and C leaching	Management zones	Treatments				LME model *P*-values numDF = 1, denDF = 12		
		ch	cw	rh	rw	Fertilization	Weeding	Interaction
NO_3^- ($g\ N\ m^{-2}\ month^{-1}$)	Palm circle	1.23 ± 0.11	1.75 ± 0.57	0.53 ± 0.41	0.08 ± 0.05	< 0.01	0.55	0.22
	Inter-row	0.14 ± 0.02	0.16 ± 0.09	0.12 ± 0.09	0.02 ± 0.01	0.06	0.16	0.88
	Frond-stacked area	0.04 ± 0.01	0.11 ± 0.09	0.04 ± 0.02	0.01 ± 0.00	0.01	0.15	0.21
	Area-weighted	0.31 ± 0.03	0.43 ± 0.16	0.18 ± 0.13	0.02 ± 0.01	< 0.01	0.17	0.23
NH_4^+ ($g\ N\ m^{-2}\ month^{-1}$)	Palm circle	0.28 ± 0.16	0.52 ± 0.26	0.01 ± 0.00	0.09 ± 0.06	0.01	0.16	0.61
	Inter-row	0.010 ± 0.003	0.007 ± 0.001	0.010 ± 0.002	0.007 ± 0.000	0.91	0.62	0.65
	Frond-stacked area	0.006 ± 0.000	0.025 ± 0.019	0.007 ± 0.001	0.007 ± 0.000	0.97	0.94	0.90
	Area-weighted	0.058 ± 0.028	0.102 ± 0.050	0.010 ± 0.001	0.021 ± 0.010	< 0.01	0.29	0.37
Dissolved organic N ($g\ N\ m^{-2}\ month^{-1}$)	Palm circle	0.09 ± 0.02	0.15 ± 0.06	0.03 ± 0.02	0.01 ± 0.00	< 0.01	0.55	0.08
	Inter-row	0.003 ± 0.001	0.007 ± 0.004	0.005 ± 0.004	0.001 ± 0.000	0.07	0.68	0.34
	Frond-stacked area	0.002 ± 0.001	0.006 ± 0.005	0.002 ± 0.001	0.001 ± 0.000	0.08	0.79	0.37
	Area-weighted	0.018 ± 0.004	0.033 ± 0.011	0.009 ± 0.007	0.001 ± 0.001	< 0.01	0.44	0.12
Total dissolved N ($g\ N\ m^{-2}\ month^{-1}$)	Palm circle	1.59 ± 0.22	2.48 ± 0.69	0.57 ± 0.43	0.17 ± 0.08	< 0.01	0.25	0.31
	Inter-row	0.14 ± 0.02	0.16 ± 0.09	0.12 ± 0.09	0.02 ± 0.01	0.04	0.19	0.74
	Frond-stacked area	0.05 ± 0.01	0.14 ± 0.11	0.05 ± 0.02	0.01 ± 0.00	0.01	0.17	0.30
	Area-weighted	0.39 ± 0.04	0.58 ± 0.20	0.19 ± 0.14	0.05 ± 0.02	< 0.01	0.33	0.20
Dissolved organic C	Palm circle	0.7 ± 0.3	0.7 ± 0.3	0.4 ± 0.1	0.3 ± 0.1	0.50	0.11	0.96

(g C m^{-2} $month^{-1}$)	Inter-row	0.6 ± 0.03	0.7 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	0.96	0.26	0.99
	Frond-stacked area	0.6 ± 0.01	0.8 ± 0.2	0.7 ± 0.1	0.5 ± 0.05	0.81	0.58	0.12
	Area-weighted	0.6 ± 0.04	0.7 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.76	0.43	0.56

Statistical *P*-values are results from 2^2 factorial ANOVA with linear mixed-effects (LME) models; numDF and denDF are numerator and denominator degrees of freedom, respectively. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding.

Table 4.2 Annual element leaching fluxes (mean ± se, $n = 4$ plots) at 1.5 m soil depth from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from November 2019 to October 2020 during 3-4 years of this field experiment. Values are area-weighted averages of the three management zones.

Dissolved element leaching (kg ha^{-1} yr^{-1})	Treatments				Factorial ANOVA *P*-values numDF = 1, denDF = 12		
	ch	cw	rh	rw	Fertilization	Weeding	Interaction
NO_3^-–N	37.4 ± 3.3	51.5 ± 18.9	21.0 ± 16.0	2.8 ± 1.6	< 0.01	0.19	0.16
NH_4^+–N	6.9 ± 3.4	11.1 ± 5.2	1.2 ± 0.2	2.5 ± 1.3	0.02	0.36	0.98
Dissolved organic N	2.1 ± 0.5	3.8 ± 1.3	1.1 ± 0.8	0.2 ± 0.1	< 0.01	0.41	0.12
Total dissolved N	46.4 ± 4.3	66.3 ± 21.0	23.3 ± 16.8	5.5 ± 2.2	< 0.01	0.40	0.26
Dissolved organic C	70.8 ± 4.7	81.4 ± 8.5	67.3 ± 8.7	71.6 ± 8.7	0.38	0.33	0.62
Al	21.9 ± 9.5	39.9 ± 16.0	16.4 ± 11.2	8.2 ± 3.2	0.06	0.75	0.49
Ca	22.8 ± 6.5	20.4 ± 6.7	14.0 ± 3.8	15.1 ± 3.7	0.18	0.89	0.76
K	8.8 ± 1.6	10.3 ± 3.7	3.4 ± 1.0	1.8 ± 0.4	< 0.01	0.32	0.34
Mg	8.5 ± 3.3	7.6 ± 3.1	3.5 ± 0.4	6.0 ± 1.3	0.25	0.55	0.42
Na	8.5 ± 0.9	8.5 ± 1.8	6.7 ± 1.0	6.8 ± 1.2	0.19	0.88	0.91
S	1.1 ± 0.2	0.9 ± 0.3	0.7 ± 0.2	1.1 ± 0.5	0.59	0.80	0.44

Statistical *P*-values are results from 2^2 factorial ANOVA; numDF and denDF are numerator and denominator degrees of freedom, respectively. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding.

Among the management zones, the palm circle had higher NO_3^-, DON, and TDN leaching fluxes compared to the inter-row and frond-stacked area ($P < 0.01$; Table 4.1), although the drainage fluxes in the palm circle were 50% lower than in the inter-row and 57% lower than in the frond-stacked area (Fig. 4.2a-c), supporting our second hypothesis. The lower drainage flux in the palm circle were the result of high transpiration and runoff (Table S2), combined with decreased porosity (indicated by higher bulk density; Table S4.1) due to the presence of low organic matter resulting from the complete removal of underground vegetation and frequent foot traffic in the palm circle, hindering soil water infiltration (Moradi et al. 2015). Nevertheless, the direct application of fertilizer in the palm circle resulted in higher N solute concentrations, especially under the conventional management where the dissolved N concentrations were 10 times higher than that of the inter-row and frond-stacked area (Table S4.3). Indeed, Kurniawan et al. (2018) reported higher leaching of dissolved N in the fertilized area of a smallholder oil palm plantation compared to the frond-stacked area, which they attributed to higher concentrations of soluble N following fertilization. In contrast, Formaglio et al. (2020) found higher soil N leaching fluxes from the inter-row compared to the palm circle during 0.5–1.5 years of this management experiment, which they attributed to subsurface lateral flows of N from the palm circle to the inter-row. In their experiment, lysimeters for measuring the nutrient concentrations in the inter-row were installed less than 2 m away from the fertilized palm circle, compared to our installation of lysimeters approximately 4 m away from the palm circle. Thus, the close proximity of the fertilized palm circle to their measured N concentrations in the inter-row, coupled with the comparably higher drainage fluxes and precipitation during their study period may have contributed to the subsurface transport of N from the palm circle to the unfertilized inter-row. Despite the lack of fertilization and little organic matter input in the inter-row, soil-pore water TDN concentrations (Table S4.3) and leaching fluxes (Table 4.1) in this management zone was comparable to that of the frond-stacked area, which received numerous nutrient inputs such as N (Fig. 4.3) from the decomposition of nutrient-rich fronds (Kotowska et al. 2016). This observed lack of differences in N leaching losses may be due to the notable N retention ability of the frond-stacked area, as indicated by its higher SOC and N stocks (Table S4.1). Additionally, the frond-stacked area exhibited five times higher rates of mineral N immobilization, seven times larger microbial biomass N (Formaglio et al. 2021), and higher root biomass (Dassou et al. 2021) than the inter-row. These findings highlight the importance of considering the differences among management zones when evaluating nutrients leaching losses in oil palm plantations.

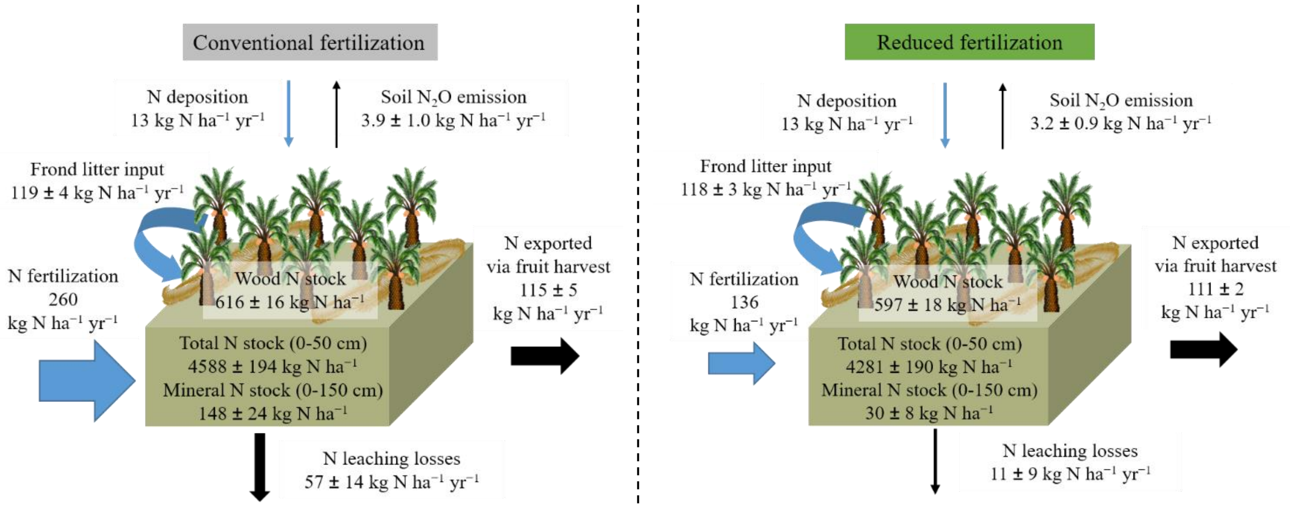

Fig. 4.3 Major nitrogen inputs and outputs from conventional and reduced fertilization treatments (mean ± se, $n = 8$ plots) in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured during 3-4 years of this field experiment. Rainfall N deposition was reported by Kurniawan et al. (2018). Soil N_2O emissions were measured monthly from July 2019 to June 2020 in this oil palm plantation (Chen et al. unpublished data). Nitrogen export from fruit harvest was the average fruit yield of 2019 and 2020 multiplied by the tissue N concentration (Formaglio et al. 2021). Nitrogen input from pruned frond leaves was the average frond litter mass of 2019 and 2020 multiplied by the tissue N concentration (Kotowska et al. 2016). Nitrogen stock in woody biomass was the average standing woody biomass of 2019 and 2020 multiplied by the tissue N concentration (Siang et al. 2022).

NO_3^- leaching represented 75% of the annual TDN leaching fluxes across the treatments (Table 4.2), indicating that NO_3^- was the main form of dissolved N leaching in this oil palm plantation, similar to results from other tropical forests and agriculture (e.g. Schewendenmann and Veldkamp 2005; Wakelin et al. 2011; Armour et al. 2013). In the conventional fertilization, the high levels of soil extractable NO_3^- stocks within the 0-1.5 m soil in the palm circle (Table S4.4) suggest a potentially high anion adsorption capacity in these highly weathered Acrisol soils, which had a low pH range of 4.8-5.0 (Table S4.1). Nevertheless, there was high NO_3^- leaching in the palm circle, especially in the conventional management with high fertilization rates (Table 4.1), indicating that soil NO_3^- adsorption in the root zone is limited. This suggest that long-term high rates of N fertilizer application and other anions (such as Cl^- and SO_4^{2-} from fertilizer or rainfall) displacement may still cause large amounts of N leaching beyond the root zone (Cameron et al. 2013). In the fertilized palm circle, the change from conventional to reduced fertilization treatment decreased TDN leaching fluxes by 82% (Table 4.1), while the contribution of the palm circle to the plantation's annual NO_3^- leaching losses decreased by 17% (Fig. 4.4c-d). Similarly, the fertilized palm circle accounted for 90% of annual NH_4^+ leaching losses in the conventional fertilization treatment, which was further reduced to 58% in reduced fertilization treatment (Fig. 4.4a-b). These results highlight that despite the area of the fertilized palm circle accounting for only 18% of the oil palm plantation, this management zone was the main area of N leaching, and thus optimizing fertilization rates was key to controlling N leaching in the plantation (Huddell et al. 2020). Soil mineral N leaching showed a similar temporal dynamic as drainage flux which was driven by heavy rainfall (Fig. 4.2 and 4.4). That implies fertilizer application should avoid periods of high rainfall. Annual soil NO_3^- leaching at 1.5 m soil depth was positively correlated with soil extractable NO_3^- stocks within 0–1.5 m soil (Pearson's $r = 0.91$; $P < 0.01$; Fig. 4.5), suggesting that soil extractable mineral N stock in the root zone may be a good indicator of potential N leaching in oil palm plantations under Acrisol soils. This may have broad practical implications for field measurement of N leaching losses because the determination of soil mineral N stock is easier compared to direct measurement of soil N leaching losses, especially when the spatial scale of observation is large.

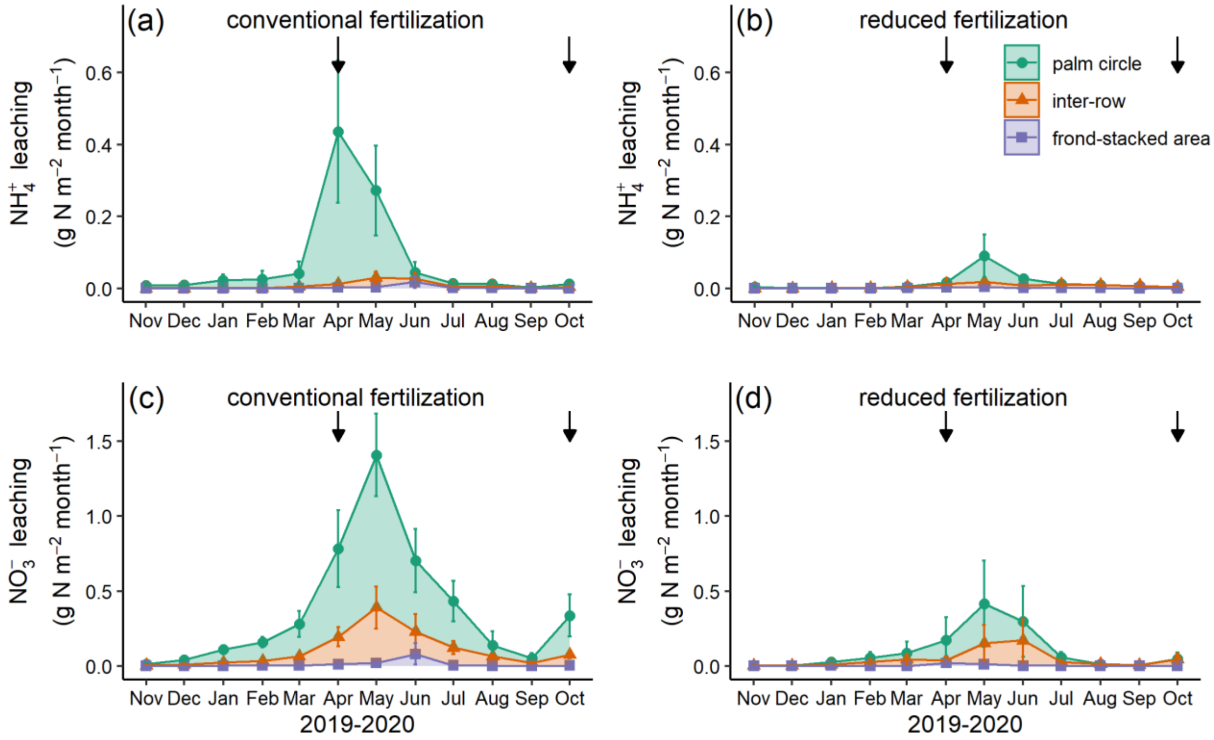

Fig. 4.4 Monthly soil NH_4^+ (a, b) and NO_3^- (c, d) leaching fluxes at 1.5 m depth from conventional (a, c) and reduced fertilization (b, d) (mean ± se, $n = 8$ plots) in an ≥ 18-year-

old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from November 2019 to October 2020 during 3-4 years of this field experiment. Black arrows indicate fertilization periods, applied only in the palm circle. Values are area-weighted by the three management zones.

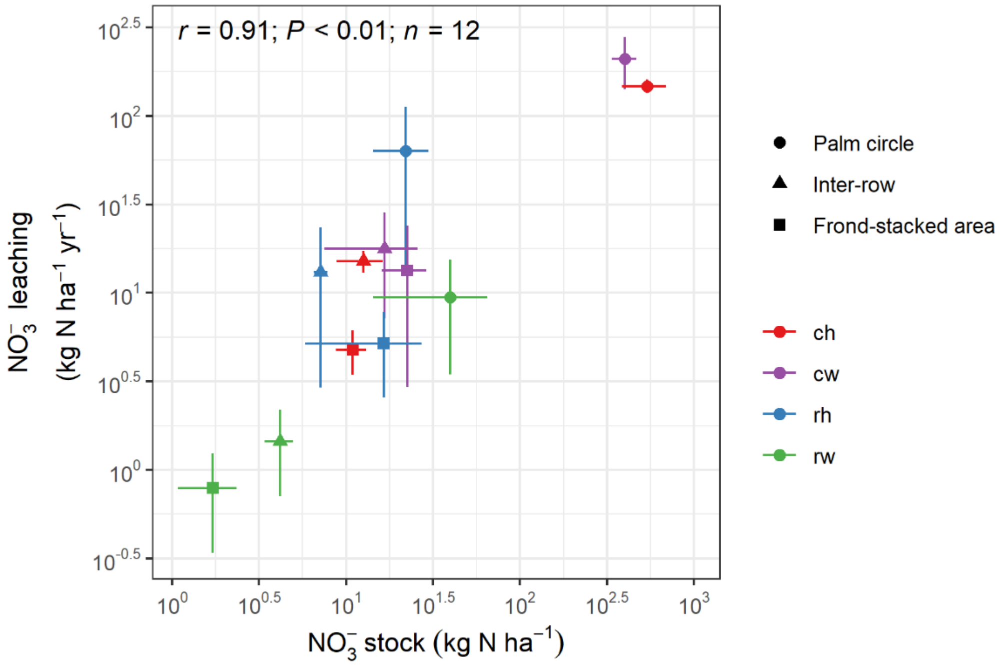

Fig. 4.5 Pearson correlation between annual NO_3^- leaching fluxes at 1.5 m soil depth, measured monthly from November 2019 to October 2020 during 3-4 years of this field experiment, and stocks of soil extractable NO_3^- within 0–1.5 m depth, measured in March 2021. Each data point was the average of four replicate plots per treatment for each management zone (*n* = 12). ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding.

During 3-4 years of this management experiment, the conventional and reduced fertilization treatments had comparable soil N_2O emission, N input from frond litter, and N exported via fruit harvest ($P \geq 0.53$; Fig. 4.3). Soil N leaching represented the most significant pathway of N loss in this oil palm plantation, which was ten times more than N losses via soil N_2O emission (accounted for 1.4–3.3% of applied N fertilizers) (Fig. 4.3). These highlight the importance of reducing N leaching losses because once reactive N is lost via leaching, it can cascade through natural ecosystems, causing series of environmental problems including N deposition and eutrophication (Galloway et al. 2003). The reduction in management intensity resulted in substantial decrease in the annual N leaching to N fertilizer application, with a reduction from 22% in the convention fertilization to only 8%

in the reduced fertilization treatment (Fig. 4.3). Our results suggest that on the one hand, the excess N applied in the conventional management are largely lost through leaching (Fig. 3), on the other hand, there is more efficient N retention and decreased environmental risks from N pollution in the reduced management system. Despite reduced fertilizer usage in reduced management, the oil palm yields were similar to the conventional management and profit significantly increased due to reductions in fertilizer costs (Iddris et al. 2023). Additionally, the replacement of herbicide application with mechanical weeding improved understory vegetation diversity in the reduced management, which significantly improved biodiversity (Darras et al. 2019; Iddris et al. 2023). In this mature oil palm plantation, the annual N return from senesced frond litter was comparable to the annual N exported via fruit harvest, or the annual N applied in the reduced fertilization treatment, representing an important N resource (Fig. 4.3). Frond mulching has been shown to improve soil N cycling (Formaglio et al. 2021), significantly reduce soil N_2O emissions (Chen et al. unpublished data) and N leaching losses (Table 4.3; Fig. 4.3), while the use of other organic amendments such as empty fruit bunches and palm oil mill effluents application can improve soil nutrient cycling and hydraulic properties (Bakar et al. 2011; Tao et al. 2016; Bessou et al. 2017). Thus, our results suggest that reducing fertilization rates, for example, to compensate for the quantity of nutrients exported through harvest, such as tested in this study, and the use organic amendments such as mulching of senesced frond litter are viable alternatives to current conventional management practices in reducing N leaching losses. The frond-stacked area accounted for about 15% of the plantation area in our site, thus, reasonably expanding the frond-stacked area may contribute to further reducing soil N leaching losses in oil palm plantations.

4.4.2. Reduced fertilization decreased Al and K leaching losses

The management intensity affected the leaching fluxes of K and Al, with generally higher leaching fluxes under the conventional management (Tables 4.2 and 4.3). In line with our first hypothesis, the conventional fertilization treatment had higher average monthly dissolved K and Al leaching fluxes ($P \leq 0.03$; Table 4.3) and higher annual K leaching fluxes ($P \leq 0.01$; Table 4.2) than the reduced fertilization. Additionally, the conventional fertilization had higher area-weighted soil-pore water dissolved K concentration than the reduced fertilization. Formaglio et al. (2020) found similar results of lower nutrient leaching fluxes in the reduced management during the first 0.5–1.5 years of this experiment, but this was mainly brought about by the effect of the weeding treatment. The replacement of herbicide application with mechanical weeding resulted in faster vegetation regrowth and increase in understory plant cover (Darras et al. 2019; Luke et al. 2019), which can increase organic matter input (Wardle et al. 2004) and the abundance and diversity of soil macrofauna (Ashton-Butt et al. 2018), altogether promoting efficient nutrient retention and recycling (Zhao et al. 2017). Iddris et al. (2023) provides evidence for significant increase in understory vegetation cover in the reduced management during four years of this management experiment, while Nouri et al. (2022) found significant decrease in nutrient leaching in Acrisol soils due to increased plant cover. However, we did not find an effect of mechanical weeding on nutrient leaching losses in this study. The high nutrient leaching losses under the conventional management largely resulted from the fertilized palm circle (Fig. 4.4a-d). This management zone was weeded four times per year and had very little to no plant cover (Darras et al. 2019). Thus, the high leaching losses of K and Al in the conventional compared to the reduced management was due to their higher solute concentrations in the conventional fertilization compared to reduced fertilization (Table S4.5). There was no significant effect of treatment on the leaching fluxes of Ca, Mg and Na (P > 0.18; Tables 4.2 and 4.3), which may be due to the similar rates of Ca and Mg application as lime and micronutrients in both the conventional and reduced fertilization treatments. In the reduced fertilization treatment, the decreased NO_3^- leaching losses was mainly accompanied by reduced Al^{3+} leaching losses (Table 4.2), which was due to the low soil pH (4.81-5.05; Table S4.1) in this oil palm plantation, as it was within the Al buffering range (Schlesinger and Bernhardt 2013).

The spatial pattern of cation element leaching fluxes among the three management zones was similar to that of the NO_3^- leaching losses (Tables 4.1 and 4.3). The palm circle had higher dissolved Al, Ca, K, Mg, and Na leaching fluxes than the inter-row and frond-stacked area (Table 3; $P < 0.05$), supporting our second hypothesis. Based on the rule of cation-anion balance in soil-pore water, the high leaching losses of negatively charged NO_3^- are accompanied by equally high leaching losses of positively charged cations (Dubos et al. 2017; Kurniawan et al. 2018). This was depicted by the positive correlation between cations and NO_3^- concentrations, especially in the palm circle (Table S4.6), and the high concentrations of Al, Ca, K, Mg, and Na in the soil-pore water ($P < 0.01$; Table S4.5). Formaglio et al. (2020) also found similar temporal leaching patterns between NO_3^- and Al, Ca, K, Mg, and Na. This result supported the conventional management practices of lime and micronutrient application in the palm circle because they supplement the concentrations of cation elements in the soil and suppress soil acidification caused by long-term N fertilizer application (Stumpe and Vlek 1991; Fageria and Baligar 2008).

Compared to the conventional fertilization, there was 15% less K fertilizer (33 kg K ha^{-1} yr^{-1}) applied in the reduced management. Nevertheless, the comparable oil palm yield among treatments (Iddris et al. 2023) and our findings of 73% decrease in K leaching losses in the reduced fertilization suggest a significant improvement in K fertilizer use efficiency in the reduced management. Al toxicity is known to limit soil fertility of acidic soils and impede plant development (Rahman and Upadhyaya 2020), and also have detrimental effect on humans (Igbokwe et al. 2019). Thus, the high Al concentrations and leaching losses at lower soil depths (Table S4.5) may pose some considerable risk of groundwater pollution. During the first 0.5–1.5 years of this management experiment, Al concentrations in 60% of measured soil-pore water samples (Formaglio et al. 2020) exceeded the upper limit of 0.2 mg L^{-1} for drinking water (WHO, 2017). After 3–4 years of this experiment, this reduced from 65% of the samples in conventional fertilization to 55% in reduced fertilization (Table S4.4). Using hydroponic experiments, Ratnasari et al. (2017) and Panggabean et al. (2021) showed that 100-300 mg L^{-1} Al aqueous solution can negatively affect the root growth of oil palm. However, due to the application of lime prior to each fertilization event, we did not find any soil-pore water samples with Al concentration over 100 mg L^{-1}. Nevertheless, the use of liming to amend the toxicity of Al (Jaiswal et al. 2018), especially in the highly fertilized conventional management is costly. Additionally, increasing scarcity of mineral fertilizers has resulted in global price increases, which are currently at near-record levels (Osendarp et al. 2022). Thus, the results of our study indicate that the reduced management is a practical and profitable alternative to current conventional management practices, as it not only delivers comparable yields at low management costs but also decreases the nutrient leaching losses of the oil palm plantation, thus significantly improving the environmental footprint of oil palm production.

Table 4.3 Dissolved element leaching fluxes (mean ± se, *n* = 4 plots) at 1.5 m soil depth from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from November 2019 to October 2020 during 3-4 years of this field experiment.

Element leaching ($g\ m^{-2}\ month^{-1}$)	Management zones	Treatments				LME model *P*-values numDF = 1, denDF = 12		
		ch	cw	rh	rw	Fertilization	Weeding	Interaction
Al	Palm circle	0.8 ± 0.5	1.6 ± 0.7	0.5 ± 0.3	0.3 ± 0.1	0.18	0.08	0.74
	Inter-row	0.05 ± 0.03	0.09 ± 0.07	0.07 ± 0.07	0.01 ± 0.00	0.19	0.21	0.66
	Frond-stacked area	0.03 ± 0.01	0.01 ± 0.00	0.03 ± 0.03	0.03 ± 0.01	0.60	0.22	0.41
	Area-weighted	0.18 ± 0.08	0.36 ± 0.26	0.14 ± 0.10	0.07 ± 0.03	0.03	0.95	0.84
Ca	Palm circle	0.75 ± 0.29	0.81 ± 0.31	0.46 ± 0.13	0.47 ± 0.20	0.06	0.45	0.52
	Inter-row	0.05 ± 0.02	0.02 ± 0.01	0.03 ± 0.01	0.01 ± 0.00	0.20	0.08	0.47
	Frond-stacked area	0.14 ± 0.05	0.10 ± 0.00	0.08 ± 0.01	0.21 ± 0.10	0.60	0.34	0.17
	Area-weighted	0.19 ± 0.05	0.18 ± 0.05	0.12 ± 0.03	0.13 ± 0.03	0.07	0.76	0.87
K	Palm circle	0.28 ± 0.09	0.44 ± 0.21	0.08 ± 0.04	0.04 ± 0.02	0.02	0.078	0.88
	Inter-row	0.023 ± 0.007	0.016 ± 0.003	0.016 ± 0.002	0.008 ± 0.001	0.07	0.18	0.50
	Frond-stacked area	0.050 ± 0.016	0.023 ± 0.005	0.023 ± 0.004	0.020 ± 0.005	0.75	0.18	0.54
	Area-weighted	0.074 ± 0.013	0.094 ± 0.039	0.028 ± 0.008	0.015 ± 0.003	< 0.01	0.11	0.74
Mg	Palm circle	0.29 ± 0.14	0.29 ± 0.12	0.10 ± 0.02	0.18 ± 0.07	0.07	0.17	0.91
	Inter-row	0.02 ± 0.01	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.11	0.28	0.71
	Frond-stacked area	0.04 ± 0.01	0.04 ± 0.01	0.03 ± 0.01	0.09 ± 0.06	0.40	0.44	0.47
	Area-weighted	0.07 ± 0.03	0.07 ± 0.03	0.03 ± 0.00	0.05 ± 0.01	0.15	0.48	0.81
Na	Palm circle	0.23 ± 0.05	0.28 ± 0.09	0.19 ± 0.03	0.21 ± 0.06	0.26	0.07	0.93

	Inter-row	0.04 ± 0.00	0.03 ± 0.01	0.03 ±0.00	0.02 ± 0.00	0.09	0.08	0.99
	Frond-stacked area	0.04 ± 0.01	0.03 ± 0.00	0.02 ± 0.00	0.04 ± 0.01	0.77	0.40	0.18
	Area-weighted	0.07 ± 0.01	0.08 ± 0.02	0.06 ± 0.01	0.06 ± 0.01	0.16	0.67	0.79
S	Palm circle	0.026 ± 0.008	0.016 ± 0.009	0.007 ± 0.002	0.011 ± 0.006	0.05	0.62	0.52
	Inter-row	0.005 ± 0.001	0.005 ± 0.002	0.005 ± 0.001	0.008 ± 0.003	0.19	0.67	0.55
	Frond-stacked area	0.011 ± 0.003	0.013 ± 0.005	0.008 ± 0.002	0.010 ± 0.004	0.58	0.87	0.75
	Area-weighted	0.009 ± 0.002	0.008 ± 0.002	0.006 ± 0.001	0.009 ± 0.004	0.75	0.96	0.58

Statistical *P*-values are results from 2^2 factorial ANOVA with linear mixed-effects (LME) models; numDF and denDF are numerator and denominator degrees of freedom, respectively. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding.

4.4.3. Fertilization and weeding treatment did not affect DOC leaching losses

The three management zones had comparable DOC leaching fluxes (Table 4.1), supporting our second hypothesis. However, similar to the findings of Kurniawan et al. (2018) in smallholder oil palm plantations, the fertilized palm circle had higher DOC concentrations in soil-pore water than the inter-row and frond-stacked area ($P < 0.01$; Table S4.3). The different DOC concentrations indicated the different net rates of DOC input and consumption in soil-pore water among the three management zones. We speculate that soil-pore water from both the palm circle and frond-stacked area had high DOC input because the palm circle accepts abundant root exudate, canopy leachates, and stemflow, while the decomposition of frond litter releases abundant DOC in the frond-stacked area (Evans et al. 2005; Versini et al. 2014; Wilcke et al. 2020). Thus, the difference in soil-pore water DOC concentrations between these two management zones mainly resulted from the consumption of DOC in the respective zones. DOC in soil-pore water can be adsorped by soil minerals or be consumed by soil microorganisms (Kalbitz et al. 2000; Schewendenmann and Veldkamp 2005), which is reflected in the decrease in soil-pore water DOC concentrations with increasing soil depth in tropical forests and plantations (e.g. Möller et al. 2005; da Costa et al. 2017; Wilcke et al. 2020). The palm circle and frond-stacked area had comparable soil texture (Table S4.1), implying their similar DOC adsorption ability. However, the frond-stacked area had 5.5 times higher microbial biomass C (Formaglio et al. 2021) and 41% higher soil CO_2 emission (Chen et al. unpublished data) than the palm circle, indicating a higher DOC consumption in the frond-stacked area compared to the palm circle. Such high use efficiency of DOC in the frond-stacked area could have resulted in the low soil-pore water DOC concentrations (Table S4.3). These results imply that mulching with senesced fronds can retain a tight soil C cycling, thereby facilitating efficient nutrient retention and cycling, and consequently reduce reliance on chemical fertilizers.

There was no effect of weeding or fertilization treatment on soil-pore water DOC concentrations (Table S4.3) and annual soil DOC leaching losses (Table 4.2), in line with our first hypothesis. As discussed above, soil-pore water DOC concentrations are affected by soil DOC input and consumption. Earlier findings in this experiment showed no significant difference in root biomass (Ryadin et al. 2022) and leaf litter decomposition rates (Iddris et al. 2023) among management treatments, which may have resulted in no significant change in soil DOC input between the different management intensities. The comparable microbial biomass C (Formaglio et al. 2021) and soil respiration (Chen et al. unpublished) among fertilization and weeding treatments also indicates no change in soil

DOC consumption. Thus, the comparable soil DOC input and consumption processes among treatments may have resulted in their comparable DOC concentrations. We found an effect of fertilization treatment on dissolved organic matter quality, signified by the different DOC:DON ratio between the conventional and reduced fertilization, similar to observation from a forest after chronic N addition (McDowell et al. 1998). The ratio of DOC:DON reflects the biodegradability of dissolved organic matter in the soil-pore water (Fellman et al. 2008). Reduced fertilization had a higher area-weighted DOC:DON ratio in soil-pore water compared to conventional fertilization ($P < 0.01$; Table S4.3), suggesting for the presence of N-rich organic matter in the conventional management, which may have been converted to N-poor organic matter in the reduced management due to the decreased fertilization rates (Wilcke et al. 2020). Moreover, the N-rich organic matter in soil-pore water was may preferentially degraded in reduced fertilization treatment because it is easily usable by microorganisms (Wilcke et al. 2020). Overall, the annual soil DOC leaching represented only 1% of the net ecosystem exchange (-7540 ± 380 kg C ha^{-1} yr^{-1}; Meijide et al. 2020). Compared to C losses via soil CO_2 emission (5.5 ± 0.2 Mg C ha^{-1} yr^{-1}; Chen et al. unpublished), soil DOC leaching (Table 2) represented a small C loss pathway in this oil palm plantation. Whereas, the different DOC:DON ratios indicated the changed soil organic matter composition in soil-pore water under different fertilization rates that will potentially affect soil microbial metabolism. Therefore, the effects of different management practices on soil organic matter stocks and quality need long-term observation.

4.5. Conclusions

Compared to conventional fertilization, reduced fertilization decreased dissolved N, K, and Al leaching losses while maintaining the high yield during the 3-4 years of this management experiment in this mature large-scale oil palm plantation. Among the management zones, the fertilized palm circle had higher dissolved N, Al, Ca, K, Mg, and Na leaching losses than the inter-row and frond-stacked area. Our results show that optimizing fertilizer application rate to avoid overuse of fertilizer is the key to reducing nutrient leaching in oil palm plantations. Moreover, frond litter is an important nutrient pool, and incorporating them and other organic residues from palm oil mills into nutrient management in order to reduce dependency on chemical fertilizers will help further reduce nutrient leaching losses while maintaining high production in oil palm plantations.

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4.7. Appendix

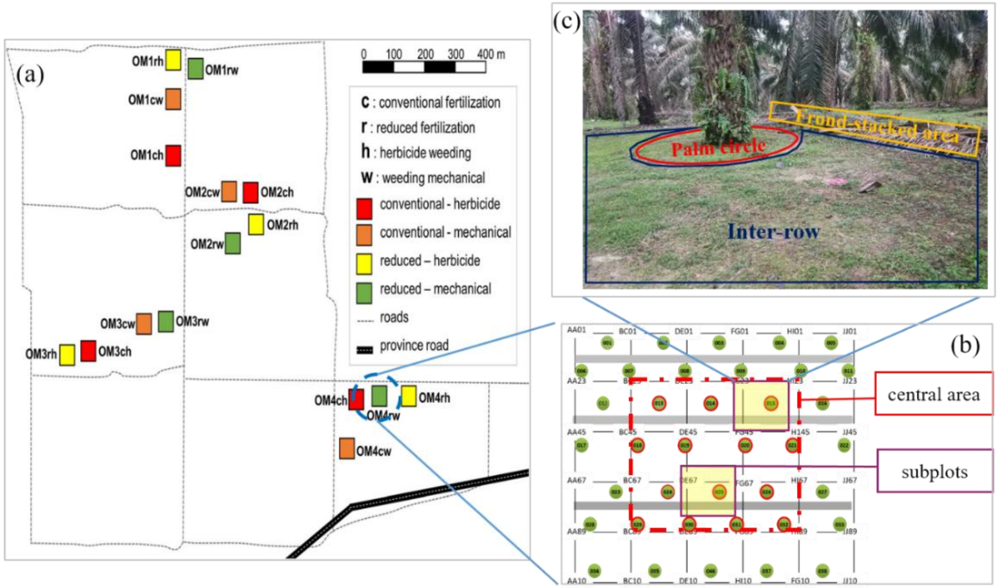

Fig. S4.1 Map of the 16 experimental plots, grouped in four blocks. Replicate plot codes are written in black and indicate the following: "OM" stands for "Oil palm Management experiment", numbers denote the block codes, and the small letters indicate the four different treatments (a). Two subplots with each containing the three management zones were selected in the central 30 m × 30 m area in each replicate plot for measurements (b). The three typical management zones in the oil palm plantation. Soil-pore water was sampled at 1.5 m depth using suction cup lysimeter in each management zone (palm circle, inter-row, and frond-stacked area) of each subplot from November 2019 to October 2020 during 3-4 years of this field experiment (c).

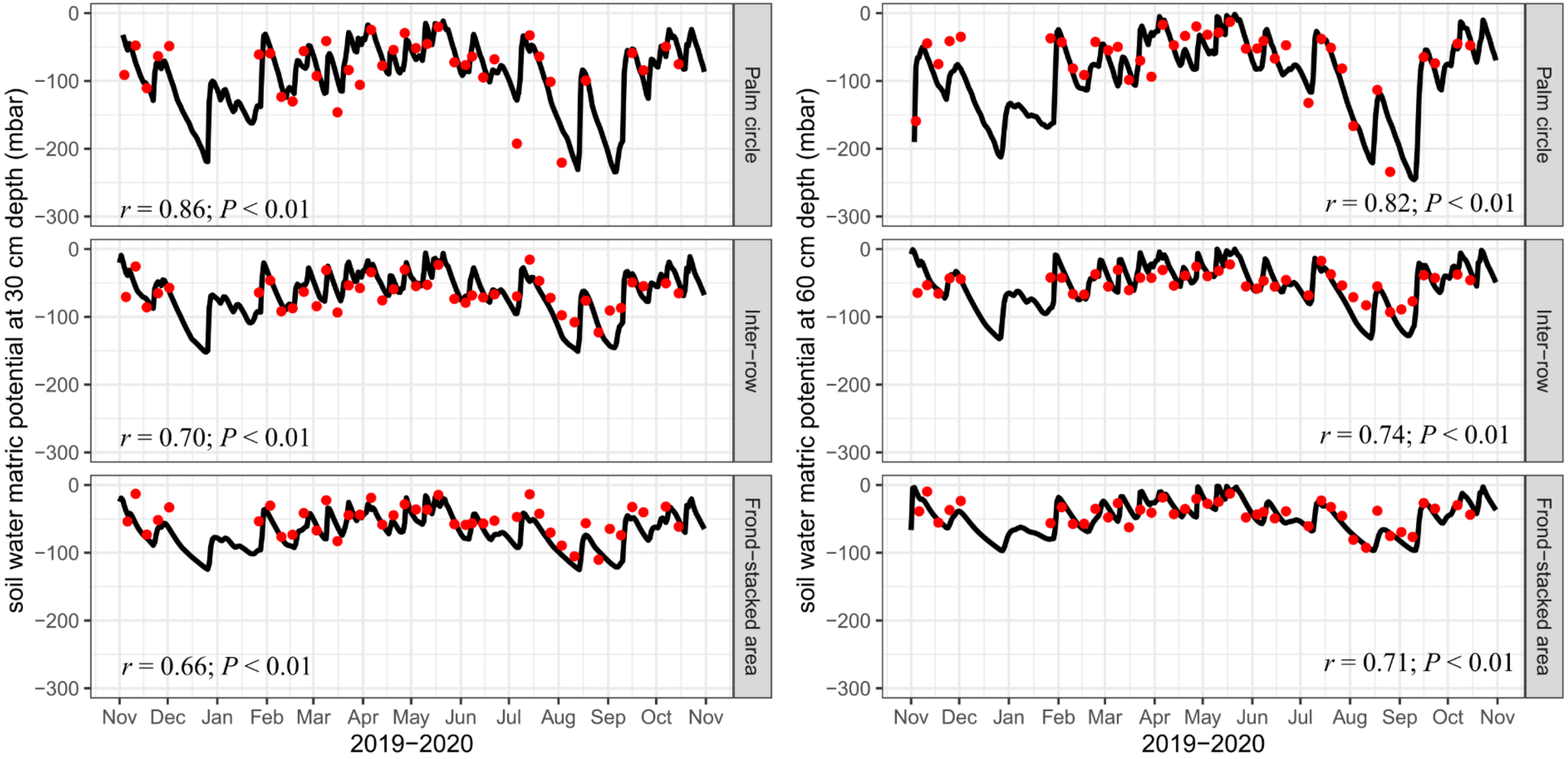

Fig. S4.2 Pearson correlation test between modeled (black line) and field-measured (red circles) soil water matric potential (n = 41 field measurements over 1 year) for each management zone at 30 cm (left panels) and 60 cm (right panels) depths in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia.

Table S4.1 Soil physical and biochemical characteristics (mean ± se, $n = 16$ plots) for each management zone, averaged across experimental treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia. Soil texture measured in the 50-150 cm of soil, whereas all the other parameters are for 0–50 cm soil depth.

Soil characteristics	Palm circle	Inter-row	Frond-stacked area
Soil organic C (kg C m^{-2})	6.2 ± 0.6^{b}	6.4 ± 0.2^{b}	9.1 ± 0.8^{a}
Total N (g N m^{-2})	402 ± 31^{b}	426 ± 15^{ab}	571 ± 39^{a}
ECEC ($mmol_{charge}$ kg^{-1})	35 ± 2^{a}	18 ± 1^{b}	28 ± 2^{a}
Base saturation (%)	48 ± 3^{a}	20 ± 2^{b}	46 ± 4^{a}
pH (1:4 soil-to-H_2O)	5.05 ± 0.08^{a}	4.81 ± 0.05^{b}	5.00 ± 0.08^{ab}
Bulk density (g cm^{-3})	1.37 ± 0.01^{a}	1.36 ± 0.01^{a}	0.89 ± 0.01^{b}
Clay (%)	23.30 ± 1.31^{a}	23.60 ± 1.00^{a}	25.47 ± 1.37^{a}
Silt (%)	7.80 ± 1.19^{a}	7.73 ± 1.23^{a}	6.47 ± 1.21^{a}
Sand (%)	68.90 ± 1.52^{a}	68.67 ± 1.35^{a}	68.07 ± 1.97^{a}

Means followed by different letters indicate significant differences among management zones (one-way ANOVA with Tukey HSD at $P \leq 0.05$). Except for soil texture, soil characteristics were reported by Formaglio et al. (2020).

Table S4.2 Annual water balance simulated from November 2019 to October 2020 for the three management zones in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia.

Water flux (mm yr^{-1})	Palm circle	Inter-row	Frond-stacked area	Area-weighted average
Precipitation	2081	2081	2081	2081
Transpiration	750	364	378	413
Evaporation	207	403	408	368
Interception	289	175	175	196
Runoff	123	62	0	60
Drainage (at 1.5 m depth)	500	1006	1171	940

Table S4.3 Dissolved nitrogen and dissolved organic carbon concentrations (mean ± se, *n* = 4 plots) in soil-pore water at 1.5 m depth from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from November 2019 to October 2020 during 3-4 years of this field experiment.

Dissolved N and C concentration	Management zones	Treatments				LME model *P*-values numDF = 1, denDF = 12		
		ch	cw	rh	rw	Fertilization	Weeding	Interaction
NO_3^- (mg N L^{-1})	Palm circle	38.6 ± 3.2	41.8 ± 11.5	16.1 ± 11.3	1.8 ± 1.1	<0.01	0.09	0.12
	Inter-row	3.0 ± 0.5	3.1 ± 1.7	2.3 ± 1.5	0.4 ± 0.2	0.05	0.16	0.97
	Frond-stacked area	1.0 ± 0.2	2.1 ± 1.3	1.0 ± 0.5	0.2 ± 0.1	<0.01	0.17	0.17
	Area-weighted	9.3 ± 0.5	10.0 ± 3.3	5.2 ± 3.6	0.6 ± 0.3	<0.01	0.07	0.14
NH_4^+ (mg N L^{-1})	Palm circle	7.0 ± 2.3	12.5 ± 6.3	1.1 ± 0.9	1.0 ± 0.5	<0.01	0.47	0.82
	Inter-row	0.19 ± 0.03	0.18 ± 0.03	0.30 ± 0.12	0.16 ± 0.01	0.75	0.47	0.32
	Frond-stacked area	0.16 ± 0.00	0.48 ± 0.31	0.21 ± 0.05	0.16 ± 0.00	0.94	0.98	0.06
	Area-weighted	1.4 ± 0.4	2.4 ± 1.2	0.4 ± 0.1	0.3 ± 0.1	<0.01	0.54	0.60
Dissolved organic N (DON) (mg N L^{-1})	Palm circle	2.25 ± 0.53	3.01 ± 0.78	0.70 ± 0.44	0.12 ± 0.05	<0.01	0.10	0.10
	Inter-row	0.07 ± 0.02	0.20 ± 0.14	0.12 ± 0.08	0.02 ± 0.01	0.09	0.73	0.57
	Frond-stacked area	0.05 ± 0.02	0.36 ± 0.30	0.04 ± 0.01	0.02 ± 0.01	0.07	0.64	0.62
	Area-weighted	0.46 ± 0.08	0.65 ± 0.14	0.24 ± 0.16	0.04 ± 0.01	<0.01	0.17	0.15
Total dissolved N (mg N L^{-1})	Palm circle	47.9 ± 5.5	57.3 ± 13.8	17.9 ± 11.5	3.0 ± 1.3	<0.01	0.12	0.14
	Inter-row	3.3 ± 0.5	3.5 ± 1.8	2.7 ± 1.6	0.5 ± 0.2	0.04	0.17	0.88
	Frond-stacked area	1.2 ± 0.2	2.9 ± 1.9	1.2 ± 0.5	0.4 ± 0.1	<0.01	0.25	0.18
	Area-weighted	11.2 ± 0.7	13.1±4.0	5.8 ± 3.7	1.0 ± 0.4	<0.01	0.11	0.19
	Palm circle	19.5 ± 5.7	17.3 ± 5.2	12.4 ± 2.3	7.7 ± 1.8	0.08	0.17	0.40

Dissolved organic C (DOC) (mg C L^{-1})	Inter-row	5.9 ± 0.7	6.3 ± 0.9	5.4 ± 1.2	6.6 ± 0.9	0.90	0.25	0.67
	Frond-stacked area	6.3 ± 0.1	8.9 ± 2.2	8.8 ± 1.3	6.1 ± 0.5	0.88	0.62	0.11
	Area-weighted	7.9 ± 0.9	8.6 ± 1.1	6.9 ± 0.9	6.7 ± 0.5	0.34	0.78	0.47
DOC-to-DON ratio	Palm circle	10 ± 3	6 ± 1	70 ± 46	138 ± 71	<0.01	0.53	0.17
	Inter-row	96 ± 20	138 ± 4	661± 615	426 ± 116	0.21	0.43	0.34
	Frond-stacked area	162 ± 47	207 ± 97	324 ± 123	410 ± 104	0.09	0.93	0.51
	Area-weighted	19 ± 3	15 ± 3	87 ± 35	265 ± 103	<0.01	0.182	0.08
pH	Palm circle	4.6 ± 0.3	5.1 ± 0.5	4.4 ± 0.2	4.6 ± 0.2	0.34	0.39	0.63
	Inter-row	4.7 ± 0.2	4.9 ± 0.3	4.8 ± 0.1	5.0 ± 0.2	0.68	0.42	0.84
	Frond-stacked area	5.0 ± 0.1	4.8 ± 0.0	5.0 ± 0.2	4.9 ± 0.3	0.71	0.33	0.99
	Area-weighted	4.7 ± 0.1	4.9 ± 0.3	4.8 ± 0.1	4.9 ± 0.2	0.92	0.50	0.85

Statistical *P*-values are results from 2 × 2 factorial ANOVA with linear mixed-effects (LME) models; numDF and denDF are numerator and denominator degrees of freedom, respectively. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding.

Table S4.4 Soil extractable nitrate stocks (mean ± se, *n* = 4 plots) within 0–1.5 m depth from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured in March 2021 after 4.5 years of this experiment.

	Management zones	Treatments				Factorial ANOVA *P*-values numDF = 1, denDF = 12		
		ch	cw	rh	rw	Fertilization	Weeding	Interaction
NO_3^- ($kg\ N\ ha^{-1}$)	Palm circle	536 ± 151	400 ± 65	22 ± 8	40 ± 25	< 0.01	0.78	0.60
	Inter-row	11 ± 2	22 ± 6	16 ± 11	2 ± 1	< 0.01	0.15	< 0.01
	Frond-stacked area	13 ± 4	17 ± 9	7 ± 1	4 ± 1	0.02	0.36	0.30
	Area-weighted	106 ± 29	90 ± 12	16 ± 6	9 ± 5	< 0.01	0.30	0.30

Statistical *P*-values are results from 2 × 2 factorial ANOVA; numDF and denDF are numerator and denominator degrees of freedom, respectively. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding.

Table S4.5 Dissolved elements concentrations (mean ± se, $n = 4$ plots) in soil-pore water at 1.5 m depth from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from November 2019 to October 2020 during 3-4 years of this field experiment.

Elements Concentration (mg L^{-1})	Management zones	Treatments				LME model *P*-values numDF = 1, denDF = 12		
		ch	cw	rh	rw	Fertilization	Weeding	Interaction
Al	Palm circle	23.0 ± 13.6	39.8 ± 17.6	14.3 ± 9.4	6.5 ± 3.1	0.40	0.86	0.46
	Inter-row	1.4 ± 0.7	1.7 ± 1.2	1.4 ± 1.3	0.2 ± 0.1	0.16	0.21	0.58
	Frond-stacked area	0.7 ± 0.4	0.3 ± 0.1	0.7 ± 0.6	0.6 ± 0.2	0.58	0.17	0.49
	Area-weighted	5.3 ± 2.2	8.6 ± 3.6	4.3 ± 3.2	1.4 ± 0.6	0.07	0.68	0.53
Ca	Palm circle	20.1 ± 5.7	21.9 ± 6.6	16.0 ± 5.3	11.6 ± 5.3	0.16	0.36	0.40
	Inter-row	1.3 ± 0.4	0.5 ± 0.2	0.9 ± 0.5	0.5 ± 0.1	0.16	0.13	0.41
	Frond-stacked area	2.9 ± 0.9	2.3 ± 0.2	1.9 ± 0.3	4.6 ± 1.8	0.65	0.34	0.24
	Area-weighted	5.0 ± 1.1	4.6 ± 1.2	4.0 ± 1.5	3.1 ± 0.9	0.18	0.49	0.86
K	Palm circle	12.9 ± 1.6	15.5 ± 6.8	5.2 ± 1.7	1.2 ± 0.6	0.02	0.10	0.81
	Inter-row	0.6 ± 0.2	0.5 ± 0.1	0.4 ± 0.1	0.3 ± 0.0	0.08	0.24	0.62
	Frond-stacked area	1.2 ± 0.3	0.7 ± 0.2	0.7 ± 0.1	0.7 ± 0.2	0.77	0.20	0.60
	Area-weighted	2.9 ± 0.3	3.1 ± 1.2	1.4 ± 0.3	0.5 ± 0.2	<0.01	0.06	0.97
Mg	Palm circle	8.1 ± 3.2	8.2 ± 2.9	3.5 ± 0.4	4.0 ± 1.7	0.09	0.76	0.66
	Inter-row	0.5 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.2 ± 0.0	0.12	0.35	0.62
	Frond-stacked area	0.9 ± 0.3	0.9 ± 0.2	0.8 ± 0.2	2.1 ± 1.1	0.44	0.40	0.51
	Area-weighted	1.9 ± 0.7	1.8 ± 0.6	0.9 ± 0.0	1.2 ± 0.3	0.16	0.92	0.85
Na	Palm circle	5.5 ± 0.8	7.6 ± 2.0	5.8 ± 1.5	4.6 ± 1.3	0.25	0.85	0.35

	Inter-row	0.9 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.6 ± 0.1	0.02	0.02	0.76
	Frond-stacked area	0.8 ± 0.3	0.7 ± 0.1	0.5 ± 0.1	1.0 ± 0.2	0.95	0.31	0.24
	Area-weighted	1.8 ± 0.1	1.9 ± 0.4	1.6 ± 0.4	1.4 ± 0.2	0.11	0.62	0.63
S	Palm circle	0.99 ± 0.39	0.42 ± 0.16	0.27 ± 0.07	0.22 ± 0.11	0.07	0.17	0.76
	Inter-row	0.11 ± 0.02	0.10 ± 0.03	0.12 ± 0.03	0.21 ± 0.08	0.15	0.75	0.44
	Frond-stacked area	0.30 ± 0.07	0.31 ± 0.15	0.20 ± 0.05	0.25 ± 0.10	0.64	0.89	0.70
	Area-weighted	0.29 ± 0.07	0.18 ± 0.05	0.16 ± 0.04	0.22 ± 0.09	0.83	0.76	0.50

Statistical *P*-values are results from 2 × 2 factorial ANOVA with linear mixed-effects (LME) models; numDF and denDF are numerator and denominator degrees of freedom, respectively. ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding.

Table S4.6 Pearson correlations among element concentrations (mg L^{-1}) in soil-pore water at 1.5 m depth from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation, Jambi, Indonesia, measured monthly from November 2019 to October 2020 during 3-4 years of this field experiment. Correlation analysis were carried out for each management zone (the palm circle, inter-row, and frond-stacked area), using the average of 4 plots per treatment on each month; *n* = 48 (4 treatments × 12 months).

Palm circle

	NO_3^-	TDN	DON	DOC	Al	Ca	K	Mg	Na	S
NH_4^+	0.36[a]	0.64[b]	0.56[b]	0.62[b]	0.07	0.33[a]	0.77[b]	0.54[b]	0.38[b]	0.68[b]
NO_3^-		0.95[b]	0.56[b]	0.33[b]	0.64[b]	0.71[b]	0.21	0.62[b]	0.44[b]	0.22
TDN			0.69[b]	0.49[b]	0.56[b]	0.68[b]	0.43[b]	0.68[b]	0.48[b]	0.40[b]
DON				0.46[b]	0.39[b]	0.17	0.37[a]	0.20	0.18	0.18
DOC					0.06	0.33[a]	0.49[b]	0.46[b]	0.18	0.69[b]
Al						0.17	−0.15	0.05	0.54[b]	-0.17
Ca							0.24	0.93[b]	0.43[b]	0.44[b]
K								0.44[b]	0.13	0.68[b]
Mg									0.43[b]	0.70[b]
Na										0.29

Inter-row

	NO_3^-	TDN	DON	DOC	Al	Ca	K	Mg	Na	S
NH_4^+	−0.16	−0.04	0.00	0.13	−0.16	−0.10	−0.05	-0.11	-0.05	-0.19
NO_3^-		0.99[b]	0.48[b]	−0.05	0.77[b]	0.45[b]	0.36[a]	0.42[b]	0.46[b]	-0.46[b]
TDN			0.55[b]	−0.04	0.75[b]	0.44[b]	0.37[b]	0.41[b]	0.47[b]	-0.48[b]
DON				−0.06	0.33[a]	0.17	0.41[b]	0.22	0.34[a]	-0.22
DOC					−0.06	−0.11	−0.18	0.00	-0.05	0.03
Al						0.51[b]	0.31[a]	0.37[b]	0.51[b]	-0.26
Ca							0.72[b]	0.73[b]	0.71[b]	-0.03
K								0.75[b]	0.78[b]	-0.06
Mg									0.77[b]	-0.11
Na										-0.09

Frond-stacked area

	NO_3^-	TDN	DON	DOC	Al	Ca	K	Mg	Na	S
NH_4^+	0.93[b]	0.95[b]	0.34[a]	0.25	−0.06	0.00	0.06	-0.02	-0.02	0.08
NO_3^-		0.98[b]	0.26	0.15	0.13	−0.07	0.04	-0.09	-0.03	-0.02
TDN			0.43[b]	0.16	0.09	−0.06	0.12	-0.08	-0.02	0.02
DON				−0.03	−0.04	−0.01	0.48[b]	-0.01	0.06	0.13
DOC					−0.20	−0.29	−0.28	-0.27	-0.36[a]	0.20
Al						0.07	−0.08	0.09	0.14	-0.3[a]
Ca							0.13	0.96[b]	0.52[b]	-0.17
K								0.06	0.43[b]	0.19
Mg									0.40[b]	-0.18
Na										-0.09

[a]: $P \leq 0.05$; [b]: $P \leq 0.01$

Chapter 5

Synthesis

5.1. Key findings of this thesis and implications

5.1.1. Fertilization and weeding treatment

During 3-4 years of fertilization and weeding treatments in this ≥ 18-year-old, large-scale oil palm plantation, we find that compared to conventional management (conventional fertilization with herbicide weeding), reduced management (reduced fertilization with mechanical weeding) (1) maintains the high yield at 30 ± 1 Mg fresh fruit bunches ha^{-1} yr^{-1}; (2) increases nutrient response efficiency, i.e. NRE by 68%, PFP_P by 200%, and PFP_K by 22%, and profit by 15%; (3) decreases element leaching losses, i.e. N by 88%, K by 80%, and Al by 63%; (4) has comparable soil GHG fluxes (5.5 ± 0.2 Mg CO_2-C ha^{-1} yr^{-1}, 3.6 ± 0.7 kg N_2O-N ha^{-1} yr^{-1}, and −1.5 ± 0.1 kg CH_4-C ha^{-1} yr^{-1}) and GWP (3010 ± 750 kg CO_2-eq ha^{-1} yr^{-1}) (Fig. 5.1). Therefore, our results show that reduced management through improving nutrient response efficiency maintains the ecosystem’s food provision function and improves the water purification function in this oil palm plantation (Fig. 5.1). Compared to conventional management, reduced fertilization combined with mechanical weeding is a more sustainable management option for large-scale oil palm plantations.

The implications for sustainable oil palm plantations are that (1) optimize fertilizer application rate based on soil nutrient status, age of oil palm, and nutrients exported via fruit harvesting. That will reduce the environmental footprint and enhance the economic profit in oil palm plantations; (2) promoting mechanical weeding in oil palm plantations which can avoid the health risks associated with herbicide application without compromising yield and even improve profit in areas with low labor costs.

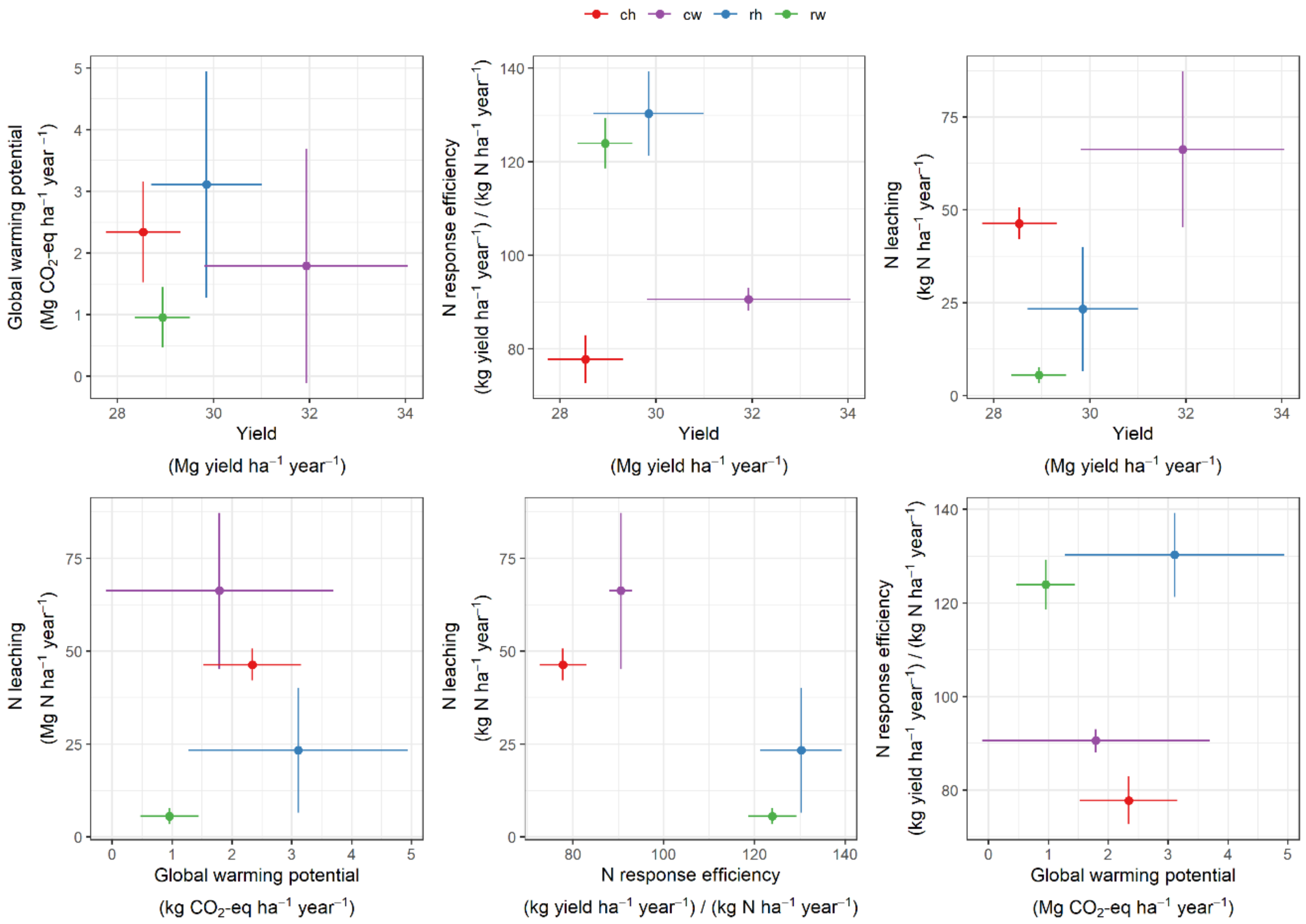

Fig 5.1 Relationships among yield, global warming potential, nitrogen response efficiency, and nitrogen leaching from different fertilization and weeding treatments in an ≥ 18-year-old, large-scale oil palm plantation (mean ± se, *n* = 4 plots). ch: conventional fertilization – herbicide weeding, cw: conventional fertilization – mechanical weeding, rh: reduced fertilization – herbicide weeding, rw: reduced fertilization – mechanical weeding

5.1.2. Management zones

Over a decade of management practices resulted in the three management zones showing different soil properties, therefore having different impacts on the multiple ecosystem's progresses in this ≥ 18-year-old, large-scale oil palm plantation. The palm circle maintains high soil nutrient availability through continuous macro- and micro-fertilizer application while bringing high soil N_2O emissions and nutrients leaching losses and low soil CH_4 uptake (Fig. 5.2). The inter-row area with little nutrient input and shows low soil fertility, soil N_2O emission, soil CH_4 uptake and nutrient leaching (Fig. 5.2). The frond-stacked area with much organic matter and nutrient input through litter decomposition which promotes soil nutrient cycling and retention capacity, therefore show high soil fertility and CH_4 uptake while low soil N_2O emission and nutrient leaching (Fig. 5.2). Overall, the frond-stacked area provides a suitable soil environment for oil palm growth while exhibiting the lowest environmental footprint among the three management zones.

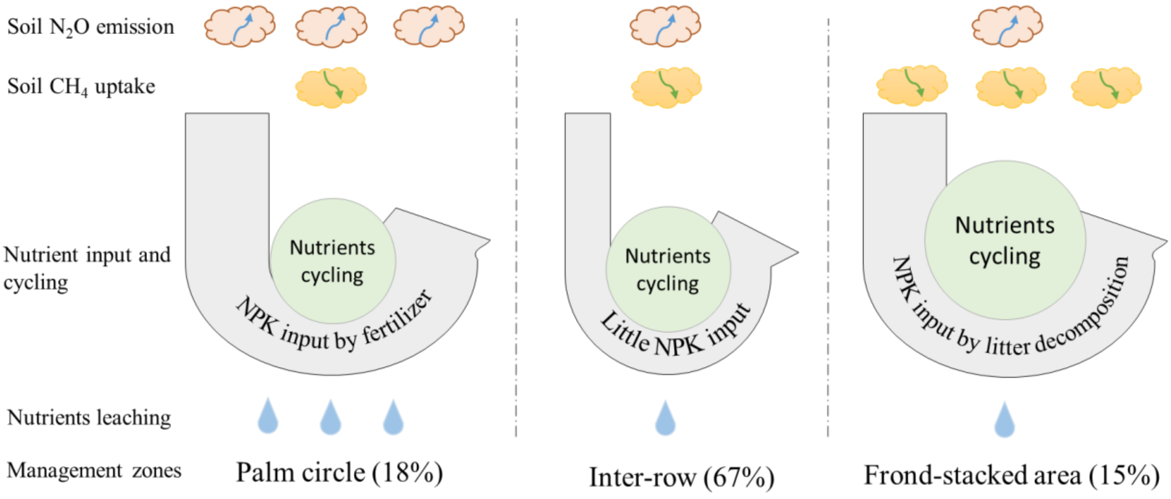

Fig. 5.2 Schematic diagram of the different characteristics in soil N_2O and CH_4 fluxes, nutrient input and cycling, and nutrients leaching among three management zones in large-scale oil palm plantations.

The implications for sustainable oil palm plantations are that (1) improving management practices in the fertilized palm circle where is a hotspot of soil N_2O emissions and nutrient leaching losses. For example, the application of slow-release N fertilizers, use of nitrification inhibitors, and keeping understory vegetation to take up excess nutrients (Sakata et al. 2015; Ashton-Butt et al. 2018; Cassman et al. 2019). (2) Protecting and increasing soil organic matter should be recommended to improve the ecosystem's GHG regulating and water purification function. For example, expanding the frond-stacked area through piled fronds in part of the inter-rows area, returning empty fruit bunches and other processing by-products, and avoiding plant biomass burning in establishing the next generation oil palm plantations (Bakar et al. 2011; Carron et al. 2015; Bessou et al. 2017).

5.2. Outlook

At present, a large number of oil palm plantations are in the first rotation cycle (Danylo et al. 2021). In the future, how to maintain the ecological function in the process of oil palm replantation is worth considering. The sustainable management of the next generation of oil palm plantations may meet new challenges. For example, in the second rotation cycle of oil palm plantations, some of the oil palms grow in the original frond-stacked area, while the other part of the oil palm will grow in the original inter-row area, whereas two management zones have apparent differences in soil nutrients availability (Fig. 5.3).

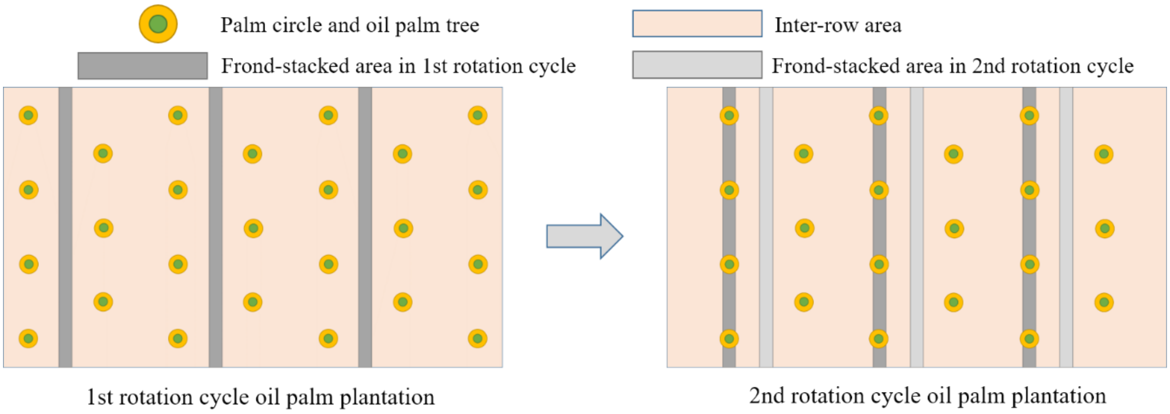

Fig. 5.3 Schematic diagram of management zones (the palm circle, inter-row, and frond-stacked area) in 1st and 2nd rotation cycle oil palm plantations.

Oil palm plantations are a complex agricultural ecosystem with long life cycles and many management practices. Optimization management practices are key to achieving sustainable oil palm plantations. In addition to the reduction of fertilizer application and the use of mechanical weeding instead of herbicide explored in this thesis, there are other proposed solutions to lessen the environmental impact in oil palm plantations. These explorations include oil palm agroforestry (Teuscher et al. 2016; Ashraf et al. 2019), cattle grazing to control weeds (Tohiran et al. 2017), applying empty fruits bunches (Bakar et al. 2011; Carron et al. 2015), applying coated fertilizer to replace conventional fertilizer (Sakata et al. 2015). However, these studies are usually carried out for a short period and/or only focus on partial ecological functions thus the long-term effect of those management practices on yield, profit, and ecosystem multifunctionality needs to be validated by long-term field multidisciplinary data. Furthermore, integrating knowledge and putting forward operable management practices to promote the sustainability of oil palm plantations is needed in the future.

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THESIS DECLARATION

I, Guantao Chen, hereby declare that I have completed all the five chapters of this dissertation entitled “Nutrient response efficiency, soil greenhouse gas fluxes, and nutrient leaching losses from a large-scale oil palm plantation under conventional and reduced management practices” by myself, and all references and data sources have been appropriately acknowledged. I have neither, nor will I, accept unauthorised outside assistance either free of charge or subject to a fee. I furthermore declare that this work has not been submitted elsewhere in any form as part of another dissertation procedure.

Göttingen, April 2023

(Guantao Chen)