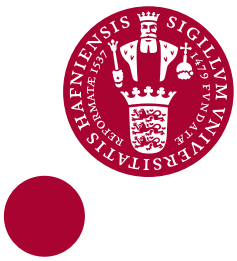

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Soil greenhouse gas emissions from inorganic fertilizers and recycled oil palm waste products from Indonesian oil palm plantations

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Abstract

A continuous rise in the global demand for palm oil has resulted in the large-scale expansion of oil palm plantations and generated environmental controversy. Efforts to increase the sustainability of oil palm cultivation include the recycling of oil mill and pruning residues in the field, but this may increase soil methane (CH_4) emissions. This study reports the results of yearlong field-based measurements of soil nitrous oxide (N_2O) and CH_4 emissions from commercial plantations in North Sumatra, Indonesia. One experiment investigated the effects of soil-water saturation on N_2O and CH_4 emissions from inorganic fertilizers and organic amendments by simulating 25 mm rainfall per day for 21 days. Three additional experiments focused on emissions from (a) inorganic fertilizer (urea), (b) combination of enriched mulch with urea and (c) organic amendments (empty fruit bunches, enriched mulch and pruned oil palm fronds) applied in different doses and spatial layouts (placed in inter-row zones, piles, patches or bands) for a full year. The higher dose of urea led to a significantly higher N_2O emissions with the emission factors ranging from 2.4% to 2.7% in the long-term experiment, which is considerably higher than the IPCC standard of 1%. Organic amendments were a significant source of both N_2O and CH_4 emissions, but N_2O emissions from organic amendments were 66%–86% lower than those from inorganic fertilizers. Organic amendments applied in piles emitted 63% and 71% more N_2O and CH_4, respectively, than when spread out. With twice the dose of organic amendments, cumulative emissions were up to three times greater. The (simulated) rainwater experiment showed that the increase in precipitation led to a significant increase in N_2O emissions significantly, suggesting that the time of fertilization is a critical management option for reducing emissions. The results from this study could therefore help guide residue and nutrient management practices to reduce emissions while ensuring better nutrient recycling for sustainable oil palm production systems.

KEYWORDS
methane, nitrogen fertilizer, nitrous oxide, nutrient management, organic amendment, plant residue

1 | INTRODUCTION

Oil palm plantations are rapidly expanding in South East Asia due to the increasing demand for palm oil as an edible oil and also as a source of biofuel raw material (Carlson et al., 2012; Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Lambin & Meyfroidt, 2011). Indonesia is the leading producer and exporter (>30%) of palm oil worldwide and the world's top supplier of palm oil-based biofuel after meeting European standard 14214 for biodiesel. The total harvested oil palm area in Indonesia is projected to reach 17 million hectares by 2025 (BPS, 2017; Sung, 2016). The anticipated increase to meet the growing production demands of the oil palm sector may lead to an increase in the amount and dose of fertilizers. The oil palm sector is the second largest user of inorganic fertilizers (NPK) in Indonesia (Heffer & Prud'homme, 2013). To increase the sustainability of the oil palm production system, it is often suggested to reduce the dependency on the mineral fertilizer and apply more organic waste generated in the production system to close nutrient cycles. The most commonly applied biomass in large-scale plantations are pruned fronds, empty fruit bunches (EFB) and old palm trunks (cut into small pieces and incorporated into the soil during replanting; Rahman et al., 2018). Furthermore, palm oil mill effluent (POME), which is the largest residual fraction from palm oil mills, is applied alone or co-composted with EFB and is known as enriched mulch (EMU). These organic amendments applied in different doses following different spatial layouts (band or patch application) to increase soil organic matter and improve soil properties compared to soils solely receiving regular applications of inorganic fertilizers. This has resulted in an increase in oil palm yields of between 16% and 21% (Comte et al., 2013; Tohiruddin & Foster, 2013). The push for more intensified management systems utilizing organic waste could have serious implications in terms of increased greenhouse gas (GHG) emissions, but the magnitude of such increases is not known (Aini, Hergoualc'h, Smith, & Verchot, 2015; Reay et al., 2012; Valin et al., 2013).

Among GHGs, nitrous oxide (N_2O) and methane (CH_4) are the most important in agriculture and account for approximately 12% of total global anthropogenic GHG emissions (IPCC, 2007, 2014; Mosier, Halvorson, Reule, & Liu, 2006), amounting to 60% and 50% of global N_2O and CH_4 emissions respectively (Smith et al., 2014). N_2O is mainly produced in soils by two microbial processes, nitrification (the oxidation of ammonium [NH_4^+] to nitrite [NO_2^-] or nitrate [NO_3^-]) and denitrification (the anaerobic reduction of NO_2^- or NO_3^- to gaseous nitric oxide [NO], N_2O or dinitrogen [N_2]) (Bouwman, Boumans, & Batjes, 2002). Increases in N inputs from mineral fertilizers or organic amendments are the main source of N_2O emissions. Increases in N_2O emissions of average 78% and 57% after application of mineral fertilizers and organic residues, respectively, have been reported from sugarcane fields in Brazil (Neto, Galdos, Feigl, & Cerri, 2016). In addition, it has been reported that soil water content and available organic carbon (C) from soil organic matter or applied organic amendments influence denitrification rates, with higher soil water content restricting O_2 diffusion into the soil, thus increasing N_2O emissions through denitrification (Jäger, Stange, Ludwig, & Flessa, 2011; Wolf & Russow, 2000). On the other hand, methanogenesis which is the main process involving CH_4 production from degraded organic compounds (Husted, 1994), that can be directly reduced by the application of N fertilizers which can stimulate competing nitrate-reducing bacteria, resulting lower organic carbon availability on the one hand but can also increase N_2O production. Indirectly, stimulation of plant growth by NH_4^+- or NO_3^--based fertilizers can enhance CH_4 production by increasing organic C availability for fermenting microbes delivering methanogenic substrates (Bodelier, 2011). However, some studies suggest that well-balanced combinations of different fertilizers and organic amendments can provide a trade-off between maintaining crop yield and minimizing GHG emissions., Uptake of atmospheric CH_4 by methanotrophs should be facilitated while at the same time N_2O emissions can be kept to a minimum by providing a greater variety of C and N compounds to the microorganisms (Brenzinger, Drost, Korthals, & Bodelier, 2018; Ho et al., 2015). Therefore, it is important to understand the significance of fertilizer type, dose, methods and timing of application on emissions from oil palm plantations. It is not clear whether the emission factors are constant with respect to these variables (type, dose, water) and which type, dose or combinations of fertilizers are better in terms of minimizing emissions jeopardizing productivity.

As far the authors are aware, no studies have investigated the potential emission patterns from this complex fertilizer management regime, combining inorganic fertilizers and organic amendments in oil palm production systems. According to Pardon et al. (2016), there is a lack of data on GHG emissions which limits the knowledge necessary for analysing N budgets and optimizing fertilization on oil palm plantations. Until now, very few trials have been carried out on mineral soils. Those that have been conducted include studies from Indonesia (Ishizuka et al., 2005; Sakata et al., 2015) and Papua New Guinea (Murom, 2007). These studies were severely constrained by a very limited sampling (five times), a short duration (17 and 30 days) or an absence of information on fertilizers. Recently, Aini et al. (2015) investigated N_2O emissions from land-use conversion from forest to smallholder oil palm plantation, fertilized with only 33 kg ha^{-1} $year^{-1}$, which is less than the amount usually applied in large-scale plantations. Furthermore, no studies on N_2O and CH_4 emissions from organic amendments have been carried out on oil palm plantations on mineral soils.

Against the backdrop of a continuous boom in palm oil demand and production and sustainability concerns in the palm oil sector, the present research investigated the effect of inorganic fertilizers, recycled oil palm waste products and rainfall on soil N_2O and CH_4 emissions from a commercial oil palm plantation in Sumatra, Indonesia. The specific research questions were: (a) To what extent does rainfall after fertilization affect N_2O and CH_4 emissions? (b) What are the differences in the emission factors of different doses of inorganic fertilizers and their combinations with organic amendments compared to the IPCC's default value? (c) What is the effect of various organic amendments applied at different doses and spatial layout on N_2O and CH_4 emissions, and is there an interaction between C and N application that leads to higher N_2O and CH_4 emissions? (d) Will higher loading rate of organic amendments (varying in the spatial layout of application) lead to disproportionately greater increases in emissions (due to low oxygen in piles)? and (e) What are the relative contributions to global warming potential (GWP) of N_2O and CH_4 from different inorganic fertilizers and organic amendments applied on the oil palm plantation?

The specific hypotheses were that (a) rainfall directly after fertilization increases N_2O and CH_4 emissions, (b) the emission factors for different type of organic and inorganic fertilizers differ significantly, (c) organic amendments increase CH_4 emissions but reduce N_2O emissions, whereas inorganic fertilizers reduce CH_4 emissions but increase N_2O emissions, (d) organic amendments applied in piles as a spatial layout increase GHG emissions than when these are spread out and (e) the combination of organic and inorganic fertilizers decreases GWP.

2 | MATERIALS AND METHODS

2.1 | Site description

Field experiments were conducted on a 13 year old oil palm plantation for a full year at the Bah Lias Research Station (BLRS) located on the coastal plains east of Medan in North Sumatra, Indonesia (3°10'58"N, 99°17'18"E) (Figure 1). The climate is humid tropical with a mean annual temperature of 26.2°C and precipitation of 2,125 mm, with a maximum rainfall occurring between September and November (BLRS meteorology station). The dry season usually spans from February to July and the wet season is between August and January. The monthly rainfall and average air and soil temperatures during the experimental period are given in Figure 2. The highest rainfall during the study period was recorded in October 2013 (400 mm). Less than 100 mm rainfall was recorded in the months of January, February, March, June and July 2014. The coldest month was December 2013 and the highest air temperature was recorded in June 2014. The average soil temperature in the experimental plot during the study period ranged between 23°C and 27°C (Figure 2). The soil at BLRS is classified as red-yellow podzolic (Ultisol) with a sandy clay loam texture with 26% clay, 11% silt and 63% sand (Gerritsma & Soebagyo, 1999). Soil samples were collected from the field and the average bulk density measured in the topsoil (0–15 cm) was 1.31 g/cm^3 with an organic C content of 10.4 g/kg soil, N content of 1.3 g/kg and C:N ratio of 7.8. The average elevation of the experimental site is 7 m above sea level with slightly acidic (pH = 5) soil (BLRS soil laboratory).

2.2 | General management of the oil palm plantation at BLRS

The oil palms were planted in 2000 in a staggered design 9 m apart at a density of 135 palms/ha. The plantation was divided into four distinct types of surface management: weeded circle, inter-row zone, frond stack (FS) zone and harvesting path, corresponding to approximately 16%, 33%, 18% and 33%, respectively, of the area of the oil palm plantations (Figure S1). The weeded circle was a weed-free area in an approximately 2 m around each trunk. The inter-row zone lay between two rows of palms where grass and ferns grew freely and abundantly. During the establishment of the plantation, legume cover crops were planted here. The harvesting path was on the other side of the palm row and was always kept free of litter. At every harvest, pruned fronds were piled on the space between two palms in the FS zone. Inorganic fertilizers (urea:rock phosphate:muriate

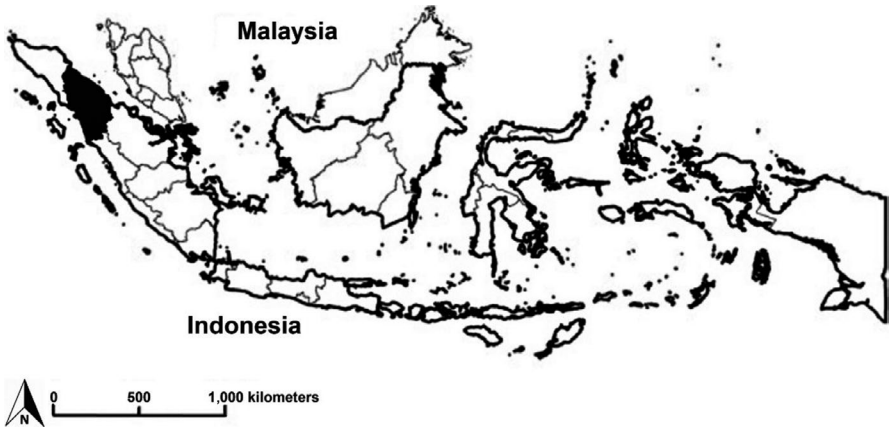


FIGURE 1 Location map of the study area (highlighted in black) in Sumatra, Indonesia

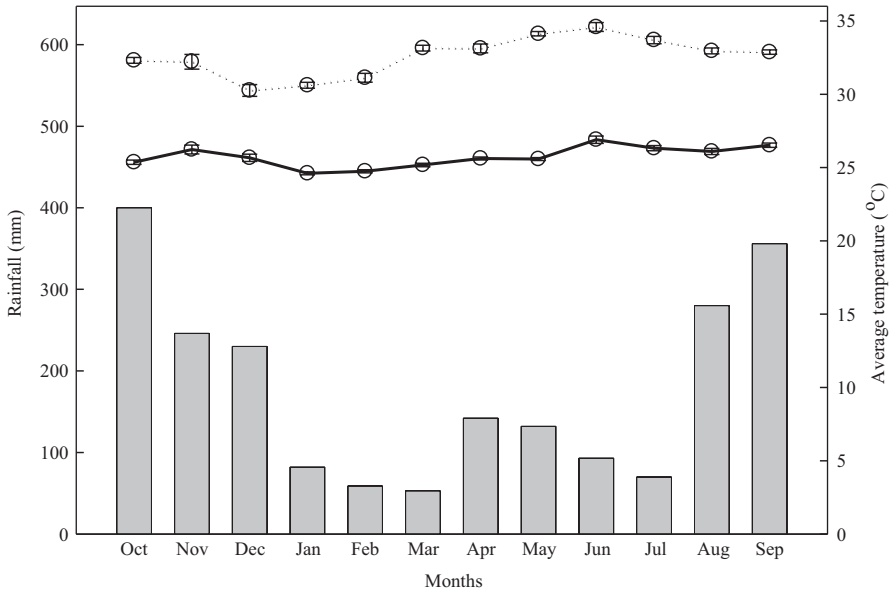


FIGURE 2 Monthly rainfall and average air (dotted line) and soil (solid line) temperature at the study site during the study period (2013–2014)

of potash = 1:1:1) were broadcasted homogenously (mature oil palm roots spread along 640 cm horizontally) twice a year by hand spreading, excluding a 1 m circle around each palm base that covers approximately 96% of the entire area. Application of other fertilizers (zinc, boron, magnesium) was based on the palm growth stage and nutrient status, as evaluated by foliar analysis. The fertilizer type depended on market availability. Yield residues, for example EFB, were also applied to the outer area of the weeded circle at the early stage of the plantation, depending on availability. The average fresh fruit bunch (FFB) production of the study field was 23–28 Mg/ha.

2.3 | Field experiment

The experiments were conducted on 6 ha of land within BLRS, and all the experiments were spatially separated. For each treatment, 12 palms (4 rows × 3 palms) were randomly selected with two inter-rows and one harvesting path (Figure S1), corresponding to an area of 888 m^2 (32 m × 27 m). Control plots were also established for all experiments and gas measurements were taken on each sampling day according to the experiments.

2.3.1 | Experimental setup and gas sampling

The first experiment lasted 22 days, while the three other experiments lasted for the whole year (wet and dry seasons; Figure S2). An overview of the treatments and doses is given in Table 1. The quantity of each source (inorganic fertilizers in weeded circles and organic amendments in inter-row zones) for each treatment was weighed on a precision balance and applied specifically to the chamber area (1.8 × 1.2 m^2) with the rest applied on the whole field for production continuity of the plantations. The corners of the chamber location were marked with permanent metal sticks, and samples were collected from the same place each sampling day.

Experiment 1: The first experiment investigated the effect of water saturation on N_2O and CH_4 emissions, with the management implications from adjusting the timing of application based on predicted rainfall patterns. Rainfall was simulated by adding 25 mm of water every day using nozzle sprayers to represent heavy rainfall conditions when the soil reached saturated conditions. The experiment was conducted with a known dose of urea with and without water and EMU with and without water (Table 1) applied in the chamber area. The chambers were placed on the border of the weeded circle area (≥1 m from the palm base) and the inter-row area. For the control treatment (no fertilizer) with and without water, the chambers were placed in the inter-row area. Gas samples were taken 24 hr after the water had been added. All the sampling areas were protected from natural rainfall by a plastic roof (2 m height) supported by bamboo poles overnight and monitored during the day. The experiment was conducted with six treatments and three replicates for 22 days (total sampling days = 11) in the dry season.

Experiment 2: The second experiment was conducted with inorganic fertilizer (urea) in a split application in the wet and dry seasons with four replicates for 261 days following a specific schedule (Figure S2). Urea was applied at the common dose at BLRS (186 kg N ha^{-1} $year^{-1}$); a high dose (250 kg N ha^{-1} $year^{-1}$) of urea was also applied to investigate the dose effect on GHG emissions from oil palm plantations and the control received no fertilizer. The known doses of fertilizers were spread evenly on the sampling areas where the chambers were placed (≥1 m from the palm base). Gas samplings were performed almost every day for the first week after fertilizer application, twice a week for 3 weeks in the wet and dry seasons, and once a month for the rest of the year

TABLE 1 Overview of the treatment doses expressed per year

Experiments and duration	Treatments	Treatment codes	Application amount						
			Inorganic fertilizer	Organic amendments					
			Field dose (N kg/ha)[a]	Field dose (tonnes/ha)[a]	Placement in inter-row area	Application area coverage (%)	Concentration in application area[b]		
							(tonne/ha)	Total N (kg/ha)	Total C (kg/ha)
Experiment 1 12.6.2014–4.7.2014	Urea with added water	U + W	135	—	—	—	—	135	58
	Urea without water	U – W	135	—	—	—	—	135	58
	EMU with added water	E + W	—	20	—	100	20	126	3,150
	EMU without water	E – W	—	20	—	100	20	126	3,150
	Control with added water	C + W	—	—	—	—	—	—	—
	Control without water	C – W	—	—	—	—	—	—	—
Experiment 2 23.10.2013–5.7.2014	Urea	U186	186	—	—	—	—	194	81
		U248	248	—	—	—	—	259	108
	Control	C2	Unfertilized	—	—	—	—	—	—
Experiment 3 16.10.2013–1.7.2014	Urea + enriched mulch	EM5 + U63	63	5	1 m band	6.1	82	582	12,942
		EM5 + U126	126	5	1 m band	6.1	82	646	12,969
		EM10 + U63	63	10	1 m band	6.1	164	1,098	25,857
	Control	C3	Unfertilized	—	—	—	—	—	—
Experiment 4 30.10.2013–2.7.2014	Enriched mulch	EM5p	—	5	in patch	1.3	387	2,438	60,953
		EM10b	—	10	2 m band	12.0	82	518	12,947
		EM15b	—	15	2 m band	12.0	124	778	19,451
		EM20b	—	20	2 m band	12.0	164	1,036	25,893
	Empty fruit bunches	EF40b	—	40	2 m band	12.0	329	1,185	61,890
		EF80b	—	80	2 m band	12.0	658	2,370	123,760
	Frond stacks	FSs	—	7	Spreading	12.0	53	236	9,061
		FSpi	—	7	Pile	1.2	549	2,427	93,364
	Control	C4	Unfertilized	—	—	—	—	—	—

[a]Total amount applied per hectare in the system.

[b]The actual concentration (loading rate) on the application area.

in all the treatments ($n = 34$) (Figure S2). Gas samples were also collected from the control treatment with four replicates simultaneously with the other treatments.

Experiment 3: The third experiment focused on the combined effect of organic amendments (EMU) and inorganic fertilizer (urea). The known doses of EMU (Table 1) were spread evenly on the sampling areas where the chambers were placed (inter-row). Gas samplings commenced after application of EMU almost daily during the first week and continued for 1 month. After 1 month, the first split of urea was applied on the top of the EMU and the second split of urea was applied in the dry season. Gas samplings were performed almost every day for the first week after urea application and twice a week for 3 weeks in the wet and dry seasons, and once a month for the rest of the year ($n = 39$) (Figure S2). Gas samples were also taken from the control (without EMU and urea) plots (in inter-row) with four replicates.

Experiment 4: In the fourth experiment, nine treatments (including the control) were carried out with four replicates for 261 days. Fresh organic amendments (EMU, EFB and pruned frond) were applied to the inter-row zone in the wet season at different doses and using various spatial layouts (band, patch, pile) according to the treatments. The FS zone was already covered with previously pruned old frond, as recommended for Indonesian oil palm plantations. The organic amendments applied in inter-row zones as follows:

FS: After harvesting, freshly pruned fronds were collected from the field and applied in a pile following the traditional method of FS application at BLRS, and the same amount of FS was applied by spreading in 2 m bands in the inter-row zones following best management practice (Donough, Witt, & Fairhurst, 2009).

EFB: Fresh EFB were collected from the nearby LONSUM mill and applied immediately in 2 m bands in the inter-row zones on the experimental field.

EMU: Enriched mulch consisting of a partially decomposed organic residue mixture of pressed EFB (17%) and POME (83%). A known amount of POME was sprayed every day over the pressed EFB for 30 days. After 30 days, the EMU was taken to the experimental field and applied immediately to the inter-row zone with the different spatial layouts (2 m band, patch).

The chemical properties of the organic amendments used in the experiments are presented in Table 2. For all the treatments, the doses of organic amendments (Table 1) were spread evenly on the sampling areas in the chambers (inter-row) in a different spatial layout (band, patch, spreading or pile). No other inorganic fertilizers were applied on these fields. Gas sampling from the treatment plots started after organic amendments were applied in the field and continued for 261 days with a total of 22 sampling days (regular sampling for the first 10 days, twice a month for the next 2 months and once a month for the rest of the year; Figure S2).

On each sampling date, large static chambers (1.8 m × 1.2 m × 0.86 m) made of plastic were tightly fitted to the base to measure GHG fluxes in the field and an internal fan was used in each chamber to homogenize the chamber atmosphere during sampling (Rahman et al., 2017; Wolter, Prayitno, & Schuchardt, 2004). The airtightness of the chambers was tested using infrared gas analysis (WMA-2 CO_2 analyser, PP Systems, UK) (Ly, Jensen, Bruun, & de Neergaard, 2013) and CO_2 leakage was found to be minimal (<1%) over a deployment time of 2 hr. Gas samples were collected during the day between 9 a.m. and 11 a.m. to minimize the diurnal effect (Rahman et al., 2015). The chambers were placed for 60 min, during which time four gas samples were collected in 20 min intervals at time 0, 20, 40 and 60 min. Gas samples were taken using a 10 ml syringe and injected into an evacuated 3 ml vial (12.5 mm diameter, Labco Ltd., UK).

2.4 | Gas analysis and calculation of fluxes

The concentrations of N_2O and CH_4 gases were simultaneously analysed by using a gas chromatograph (Bruker 450-GC 2011) equipped with detectors for N_2O and CH_4. N_2O was determined by a separate electron capture detector operated at 350°C, a flame ionization detector was operated at 300°C for CH_4 analysis and the oven temperature was set at 50°C. Helium (99.99%) and (argon + 5% CH_4) were used as carrier gases of N_2O and CH_4, respectively, with a flow rate

TABLE 2 Chemical properties of the organic amendments used in the experiments

Properties[a]	Dry matter (%)	C:N ratio	Total C	Total N	Cellulose	Hemicellulose	Lignin	NH_4^+-N	NO_3^--N
			% dry matter					mg/kg dry matter	
Empty fruit bunches	40	54	47	0.9	37	26	19	292	2.24
Enriched mulch	35	25	45	1.8	37	16	25	79	3.00
Frond stacks	34	38	50	1.3	33	22	23	58	2.01

[a]Total C and total N were determined using isotope ratio mass spectroscopy (IR-MS). NH_4^+ and NO_3^- concentrations were analysed using a flow injection analyser (FIA star™ 5000 analysers, Denmark). Fibre analysis (cellulose, hemicellulose and lignin) was determined according to Van Soest (1963) using an ANKOM 220 fibre analyser (de Neergaard, Hauggaard-Nielsen, Jensen, & Magid, 2002).

of 60 ml/min. Certified reference N_2O and CH_4 gases were used for quality control and calibration during analyses. N_2O (N_2O-N) and CH_4 (CH_4-C) fluxes were calculated according to Smith and Conen (2004).

Data points were excluded if the linear regression value (R^2) of gas concentrations from t0 to t60 was below 0.80 (Pandey et al., 2014).

The cumulative N_2O (N_2O-N) and CH_4 (CH_4-C) emissions were calculated for each replicate per treatment separately from the integration of the area under the curve of each measurement point. The area between two adjacent intervals on the measurement days was calculated by trapezoid formula following Ly et al. (2013).

The total cumulative N_2O (N_2O-N) and CH_4 (CH_4-C) emissions for each replicate per treatment were calculated for 261 days as the sum of the emissions $A_{t(ab)}$ for all time intervals.

The N_2O and CH_4 emission factors from different treatments were calculated according to the methodology proposed by the IPCC (2006):

$$EF_N = \left(\frac{\sum N_2O - \sum N_{Control}}{N_{appl}}\right) \times 100,$$

$$EF_C = \left(\frac{\sum CH_4 - \sum C_{Control}}{C_{appl}}\right) \times 100$$

where $\sum N_2O$ and $\sum CH_4$ are the cumulative N_2O-N and CH_4-C emissions from each treatment, $\sum N_{Control}$ and $\sum C_{Control}$ are the cumulative N_2O-N and CH_4-C emissions from the control plot, and N_{appl} and C_{appl} are the amounts of N and C applied in the field all expressed in kg N ha^{-1} and kg C ha^{-1}.

The CO_2-equivalent (CO_2-eq) GWP over a 100-year period was calculated for each replicate per treatment. For the calculation of CO_2-eq GWP, cumulative N_2O-N and CH_4-C were converted to N_2O and CH_4. The total cumulative emissions of N_2O and CH_4 were multiplied by a factor of 298 and 34 (for a 100 year time horizon), respectively, to convert N_2O and CH_4 into CO_2-eq, with the inclusion of climate-carbon feedback (Myhre et al., 2013), following the equation below:

$$\text{Total } CO_2\text{-eq GWP} = \text{Total } N_2O\text{-N} \times \frac{44}{28} \times 298 + \text{Total } CH_4\text{-C} \times \frac{16}{12} \times 34$$

2.5 | Additional measurements

During gas sampling, the soil (5 cm depth) and air temperatures, atmospheric pressure (Garmin PSmap 64 s) and soil moisture (%) were recorded in each treatment field on each sampling day. Rainfall data were collected from the BLRS weather station. EFB, EMU and FS samples were collected from the nearby mill and from different sampling points from the fields and mixed to provide a composite sample. The composite samples were oven dried, weighed at BLRS and sent to the University of Copenhagen for chemical analysis. (C:N ratio, total N and fibre). Soil samples were also collected from the sampling plots, and analysed for soil physical and chemical properties at the BLRS soil laboratory.

2.6 | Statistical analysis

Statistical analyses were performed using Statistical Analysis System (SAS) software version 9.4 (SAS Institute Inc., NC). Normality and homogeneity of residual variances were checked using the Shapiro–Wilk test and Levene's test, respectively, and data were log-transformed if necessary. For all experiments, differences between the treatments' effect on GHG emissions (total cumulative emission and CO_2-eq GWP) were tested by analysis of variance (ANOVA) with the general linear models (GLM) procedure in SAS. The significant F-value was determined at the 95% level ($p < 0.05$). In the event of significance in ANOVA, means were compared using the Tukey's honestly significant difference test. Moreover, in experiment one, a mean comparison of water treatments with their non-water treatment variant were also assessed separately. Results are reported as means ± 1 *SD*. Pearson correlation coefficients were analysed using the PROC CORR procedure to determine the correlations between different variables. Simple linear and polynomial regressions were also performed to estimate the relationship between different variables and GHG emissions.

3 | RESULTS

3.1 | GHG emissions after application of inorganic fertilizers and organic amendments

3.1.1 | The interaction of inorganic fertilizers and organic amendments with water

The N_2O fluxes were higher in treatments with simulated rainwater than in those without (Figure 3). The treatment with urea and simulated rainwater produced higher N_2O fluxes than any of the other treatments. N_2O fluxes increased immediately after fertilizer application and reached a peak on day 6, and subsequently, all the treatments with simulated rainwater showed a decreasing trend until day 15. After day 15, N_2O emissions from the treatments were as low as the control except for the U + W treatment which remained high until 22 days. EMU application did not increase N_2O emissions. The lowest fluxes were observed from the control treatment without simulated rainwater.

The highest CH_4 peak (5.6 mg CH_4-C m^{-2} day^{-1}) was observed from the EMU treatment with simulated rainwater on day 4 after EMU application. However, negative CH_4 fluxes were also observed from all the treatments without EMU with simulated rainwater throughout the whole sampling period (Figure 3).

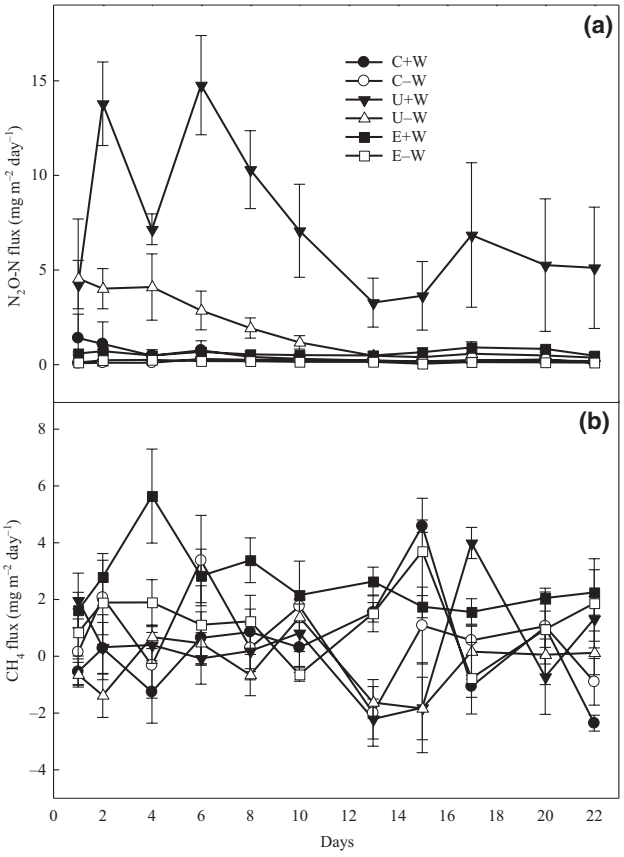
Cumulative N_2O emissions from the urea and EMU with simulated rainwater were significantly ($p < 0.05$) higher than their counterpart treatment without simulated rainwater (Figure 3). The highest N_2O emission over 22 days (158 mg N_2O-N m^{-2}) was observed for the urea with simulated rainwater treatment, which was 77% higher than its counterpart treatment without water (U-W). The cumulative N_2O emissions were lowest in the control and EMU without rainwater treatment.

Cumulative CH_4 emission from the treatment with EMU and simulated rainwater was significantly ($p < 0.05$) higher than the treatment with EMU without simulated rainwater (Figure 3) (56 mg CH_4-C m^{-2}). Cumulative negative emissions were observed from the treatment of urea without water.

All the treatments with simulated rainwater showed significantly ($p < 0.01$) higher CO_2-eq GWP than their respective treatments without water (Figure 3). The urea with simulated rainwater treatment had the highest CO_2-eq GWP of all the treatments. EMU with simulated rainwater showed a significantly higher GWP than the EMU without rainwater treatments and the control treatments. In all the treatments, the relative increase in N_2O emission due to water was significantly positive ($p < 0.01$; Table S1), with GWP dominated more by N_2O emission than by CH_4 emission. Only in the treatment of EMU with simulated rainwater did CH_4 contribute considerably to GHG emissions (one third of the total).

3.1.2 | Effect of inorganic fertilizers on N_2O emissions

The dynamics of N_2O fluxes over the sampling time were greatly affected by the amount and type of fertilizer applied and the season (wet or dry) (Figure 4). In the wet season, N_2O



(c)

Treatments	Cumulative N_2O-Nemission (mg/m^2)	*p* value	Cumulative CH_4-Cemission (mg/m^2)	*p* value
C+W	9.29±10[a]	0.47	11.75±5[a]	0.56
C-W	4.36±12[a]		14.69±8[a]	
U+W	157.94±9[a]	0.02	5.86±6[a]	0.08
U-W	36.32±11[b]		–5.41±7[a]	
E+W	13.70±7[a]	0.01	56.27±3[a]	0.01
E-W	3.29±9[b]		24.05±6[b]	

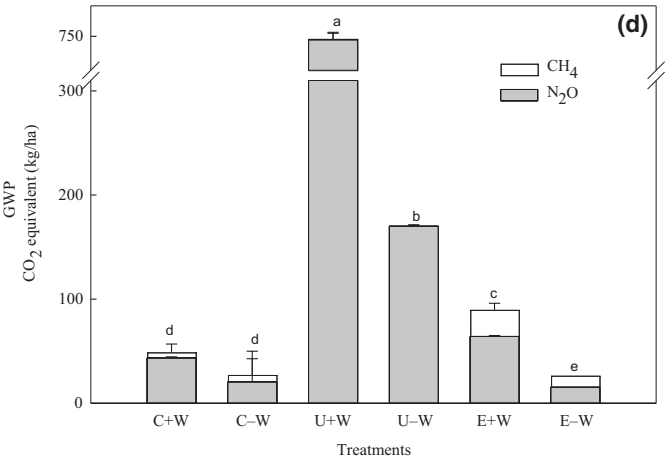


FIGURE 3 (a) N_2O-N flux, (b) CH_4-C flux, (c) cumulative N_2O-N and CH_4-C emissions, and (d) CO_2-eq GWP from the experimental treatments for 22 days in controlled conditions in the field. Treatments: C + W = control with simulated rainwater; C – W = control without simulated rainwater; U + W = urea with simulated rainwater; U – W = urea without simulated rainwater; E + W = enriched mulch with simulated rainwater; E – W = enriched mulch without simulated rainwater. Cumulative emissions represent mean ± 1 *SE* ($n = 3$). Different letters indicate a significant difference between simulated rainwater treatments and their counterparts without water treatments with Tukey's range test; the same letters show a nonsignificant difference (c, d). Error bars (a, b, d) indicate 1 *SE* ($n = 3$) and different letters indicate a significant difference in total CO_2-eq GWP (d) between treatments with Tukey's range test ($p < 0.05$)

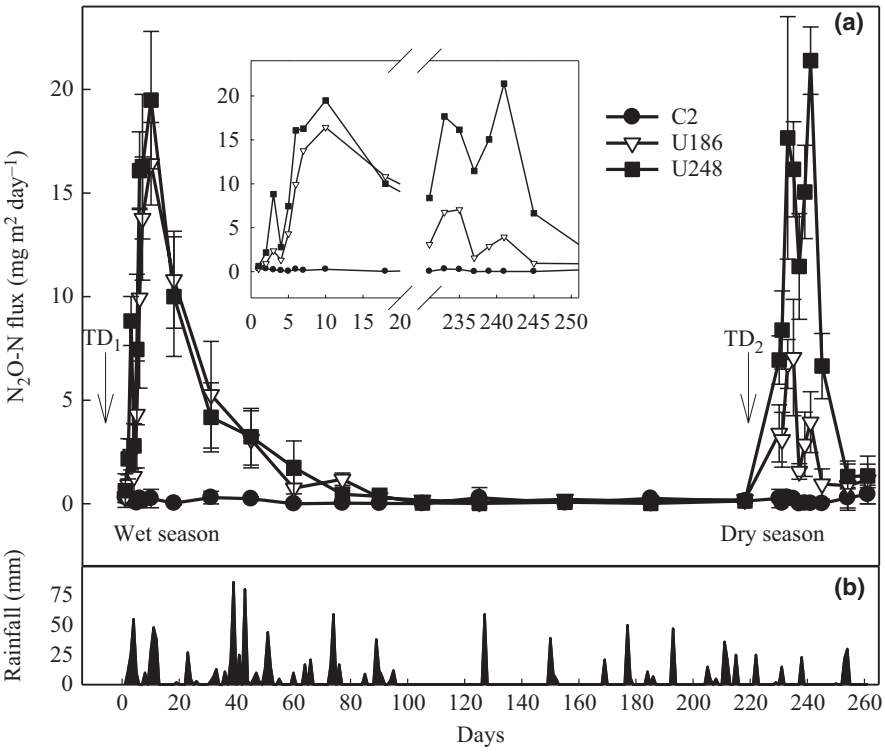


FIGURE 4 (a) N_2O-N fluxes from the three treatments (U186 = 186 kg N in urea ha^{-1} $year^{-1}$, U248 = 248 kg N in urea ha^{-1} $year^{-1}$ and C2 = control [no fertilizer]) during the 261 day sampling period. TD1 (day 1) and TD2 (day 229) represent the first and second split of urea applications. The insert is an enlargement of the plot for improved visibility. Error bars indicate 1 *SE* ($n = 4$). (b) Rainfall during the sampling period

fluxes increased immediately after the first sampling day following fertilizer application. N_2O emissions from both urea treatments increased steadily until the peak fluxes were attained on day 10 after application and subsequently declined. The effect of urea fertilizers lasted for about 60 days. N_2O fluxes remained negligible until the second fertilizer application at 230 days.

After the second split of fertilizer application during the dry season, N_2O fluxes again increased rapidly. The treatment with a low N dose (U186) reached its peak after 5 days, whereas U248 treatment reached its peak after 10 days of fertilizer application. The high N dose of urea had the highest peak (21 mg N m^{-2} day^{-1}) in the dry season. The greatest total cumulative N_2O emissions during the 261 days were observed from treatment U248, followed by U186 and the control treatments, with emissions of 7.34, 5.12 and 0.38 kg N2O-N ha^{-1} respectively (Table 3). The emission factor was highest in the treatment with the higher dose of urea (2.69%) compared to the lower dose of urea (2.44%) (Table 3), with a 17% coefficient of variation.

3.1.3 | Effect of the combination of inorganic fertilizers and organic amendments on GHG emission

Significant effects ($p < 0.05$) of urea and EMU were detected on total cumulative N_2O and CH_4 emissions (Table 3, experiment 3). During the wet season, all treatments showed a similar trend of N_2O flux after application of the organic amendment (EMU) for the first 32 days (Figure 5). All treatments reached their peak 3 days after EMU application, with the highest peak (3 mg N_2O-N m^{-2} day^{-1}) from the EM5 + U126 treatment and decreased afterwards. N_2O fluxes increased strongly after the first and second urea applications in both the wet and dry seasons. In the wet season, except for the control, all three treatments reached their peak 4–5 days after urea application, with the highest peak from the EM5 + U126 treatment at 16 mg N_2O-N m^{-2} day^{-1}. Thirty days after urea application, fluxes (all treatments) were very low and remained so until the second urea application in the dry season. Similarly, N_2O fluxes reached a peak on day 4 and day 11 after urea application during the dry season, with the EM5 + U126 treatment displaying the highest peak at 8 mg N_2O-N m^{-2} day^{-1}, which was 50% lower than in the wet season. Following the peak from 247 days onwards, fluxes decreased gradually, and negligible fluxes were recorded for the remainder of the season. The treatment with 10 tonnes of EMU/ha showed similar flux to 5 tonnes of EMU/ha with the same amount of urea. Treatment EM5 + U126 showed the highest cumulative N_2O emissions (4.10 kg N_2O-N ha^{-1}), which were 39% and 50% higher than treatments EM10 + U63 and EM5 + U63 respectively. Similarly, the highest emission factor (0.58) was also found from treatment EM5 + U126, which was 66% and 52% higher than the emission factor of treatments EM10 + U63 and EM5 + U63 respectively.

For CH_4 emissions, the highest peak (22 mg CH_4-C m^{-2} day^{-1}) was observed from treatment EM5 + U126 in the wet season following 4 days of EMU application. Negative CH_4 fluxes were also observed in all treatments throughout

TABLE 3 Average emission, total cumulative emission and the emission factor for 261 days

		Average daily flux[b]		Total cumulative emission		Emission factor	
		N_2O-N	CH_4-C	N_2O-N	CH_4-C	N_2O-N	CH_4-C
Experiments	Treatments[a]	mg m^{-2} day^{-1}		kg/ha		%	
Experiment 2	U186	1.96	−0.16	5.12 ± 0.2^{a}	-2.72 ± 0.2	2.44	
	U248	2.81	−0.13	7.34 ± 0.1^{a}	-3.41 ± 0.1	2.69	
	C2	0.14	0.09	0.38 ± 0.1^{c}	0.23 ± 0.1	—	
Experiment 3	EM5 + U63	0.78	0.69	2.03 ± 0.2^{b}	1.79 ± 0.2^{a}	0.28	0.012
	EM5 + U126	1.57	0.15	4.10 ± 0.2^{a}	0.39 ± 0.1^{b}	0.58	0.001
	EM10 + U63	0.97	0.52	2.52 ± 0.1^{b}	1.37 ± 0.1^{a}	0.20	0.008
	C3	0.12	0.11	0.40 ± 0.1^{c}	0.30 ± 0.1^{b}	—	—
Experiment 4	EM5p	0.65	1.64	1.70 ± 0.3^{b}	4.29 ± 0.5^{cd}	0.05	0.006
	EM10b	0.19	1.43	0.50 ± 0.1^{cd}	3.74 ± 0.6^{cd}	0.02	0.026
	EM15b	0.49	1.47	1.27 ± 0.1^{bc}	3.84 ± 0.7^{cd}	0.11	0.018
	EM20b	0.69	2.67	1.81 ± 0.4^{b}	6.97 ± 0.8^{c}	0.14	0.026
	EF40b	0.62	6.55	1.62 ± 0.3^{b}	17.09 ± 1.4^{b}	0.10	0.027
	EF80b	2.51	14.90	6.54 ± 0.6^{a}	38.88 ± 3.2^{a}	0.26	0.031
	FSs	0.27	0.65	0.70 ± 0.1^{cd}	1.70 ± 0.2^{d}	0.14	0.015
	FSpi	0.44	1.11	1.14 ± 0.1^{bc}	2.91 ± 0.4^{d}	0.03	0.003
	C4	0.15	0.12	0.39 ± 0.1^{d}	0.34 ± 0.1^{e}	—	—

Note: Cumulative emissions represent as mean ± 1 *SE* ($n = 4$). Within the column, the values with different letters indicate a significant difference with Tukey's range test ($p < 0.05$) between the treatments within each experiment and the same letters show a nonsignificant difference.

[a]The treatment labels are the same as in Table 1.

[b]Average flux of 261 days.

the whole sampling period (Figure 5). During the dry season, treatment EM10 + U63 had the highest peak, followed by treatments EM5 + U63 and EM5 + U126. As expected, the control treatment had the lowest CH_4 flux. The highest average flux of 3.09 mg CH_4-C m^{-2} day^{-1} was from treatment EM10 + U63. The highest total cumulative CH_4 emissions (1.79 kg CH_4-C ha^{-1}) were observed from treatment EM5 + U63. Similarly, the emission factor was highest in treatment EM5 + U63 (0.12), followed by treatments EM10 + U63 (0.04) and EM5 + U126 (0.01).

3.1.4 | Effect of organic amendments on GHG emission

Application of organic amendments significantly affected N_2O emissions from the oil palm plantations (Figure 6a). N_2O fluxes increased immediately after organic amendment application, reaching an early peak between 3 and 10 days after application, depending on the treatments. After reaching a peak, fluxes gradually decreased until day 40. Thereafter, all the treatments exhibited very low fluxes for the rest of the sampling period (Figure 6a).

By far the highest peak was observed from 80 tonnes EFB ha^{-1} $year^{-1}$ on the second day after application, being on average five times higher than any of the other treatments. Large fluxes in the other treatments were from 20 tonnes EMU ha^{-1} $year^{-1}$ with average daily flux 1.8 mg N_2O-N m^{-2} day^{-1} over the whole 261 day period. Application of 5 tonnes EMU ha^{-1} $year^{-1}$ in a patch showed an N_2O flux similar to the application of 15 and 20 tonnes ha^{-1} $year^{-1}$ in bands. Application of 10 tonnes EMU/ha in bands resulted in a much lower peak and a lower average N_2O flux, which was about four times lower than the other three. Application of 40 tonnes EFB ha^{-1} $year^{-1}$ and both doses (kg/m^2) of FS showed a similar trend of N_2O flux with double the emission rate.

A significant effect ($p < 0.05$) of the organic amendments was detected on total cumulative N_2O emissions (Table 3). The highest total cumulative N_2O emission was 6.54 kg N_2O-N/ha from treatment EF80b, which was four times higher than treatment EF40b. Among the EMU treatments, the lowest total cumulative N_2O emissions (0.50 kg N_2O-N ha^{-1}) from treatment EM10b were significantly lower ($p < 0.05$) than from treatments EM5p and EM20b (Table 3). However, no significant differences were observed between treatments EM5p, EM15b and EM20b. FS applied in a pile or spread in inter-row zones did not show any significant difference in total cumulative N_2O emission, but FSpi showed

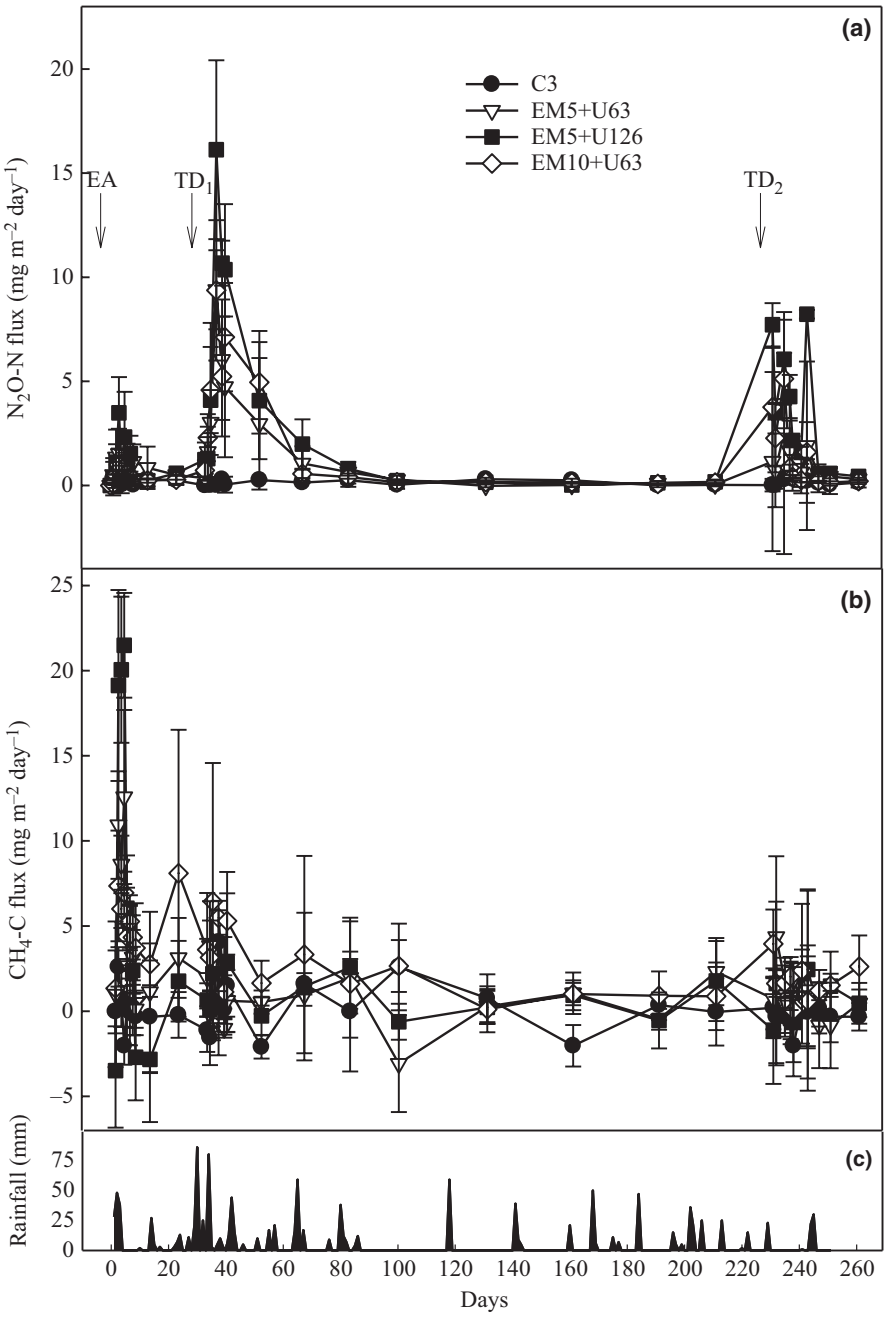


FIGURE 5 (a) N_2O-N and (b) CH_4-C fluxes from the four treatments: EM5 + U63 = (5 tonnes EMU + 63 kg N urea) ha^{-1} $year^{-1}$, EM5 + U126 = (5 tonnes EMU + 126 kg N urea) ha^{-1} $year^{-1}$, EM10 + U63 = (10 tonnes EMU + 63 kg N urea) ha^{-1} $year^{-1}$ and C2 = control for 261 days. EA = EMU application (day 1). TD1 (day 32) and TD2 (day 230) are the first and second applications of inorganic fertilizer respectively. Error bars indicate 1 *SE* ($n = 4$). (c) Rainfall during the sampling period.

a significantly higher cumulative emission than the control (Table 3).

The CH_4 fluxes were higher for the EFB treatments than for the EMU and FS treatments (Figure 6b). The EMU treatments exhibited an early emission peak, among which the 20 tonne EMU ha^{-1} $year^{-1}$ treatment showed the highest peak after 3 and 8 days of application. After 20 days, the emission was very low and even negative fluxes were recorded. However, EFB treatments showed a CH_4 peak 40 days after application, with the highest fluxes from EF80b followed by EF40b at flux rates of 105 and 35 mg CH_4-C m^{-2} day^{-1} respectively. The highest average of daily CH_4 flux (14 mg CH_4-C m^{-2} day^{-1}) was also observed from treatment EF80b (Table 3). Fluxes from both EFB treatments were similar to the other treatments after 87 days of application. The addition of FS resulted in very low CH_4 fluxes. Negative fluxes were recorded for all the treatments, especially in the dry season.

The highest cumulative CH_4 emission (38.88 kg CH_4-C/ha) was recorded from treatment EF80b (Table 3) followed by treatment EF40b. EFB treatments also showed significantly higher total cumulative CH_4 emissions than the other EMU and FS treatments. However, EMU treatments did not show any significant differences in cumulative CH_4 emission. FS applied in a pile or spread in the inter-row zones did not show any significant difference in total cumulative CH_4 emission but did show significantly

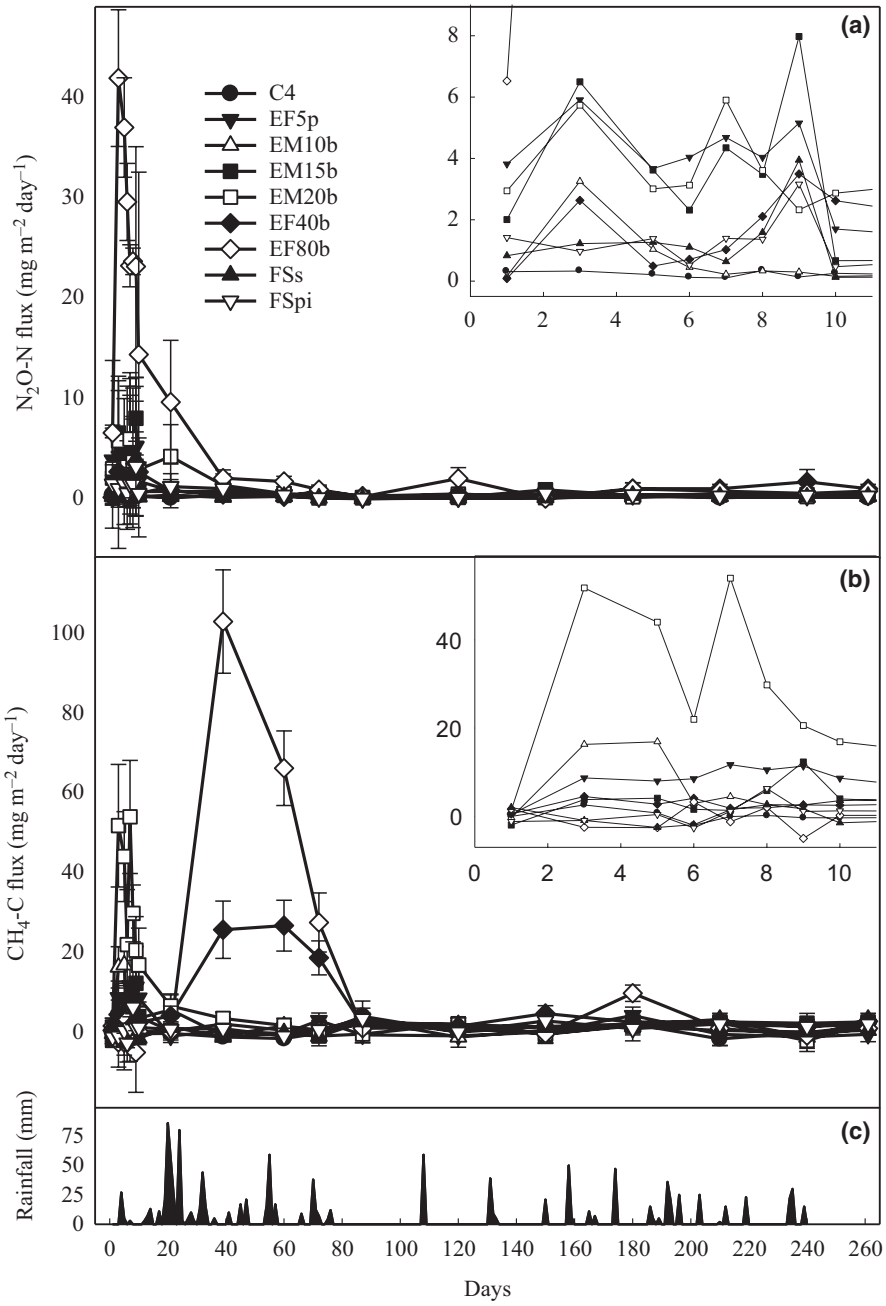


FIGURE 6 (a) N_2O-N and (b) CH_4-C fluxes from different treatments for 261 days (EM5p = 5 tonnes EMU ha^{-1} $year^{-1}$ in patch, EM10b = 10 tonnes EMU ha^{-1} $year^{-1}$, EM15b = 15 tonnes EMU ha^{-1} $year^{-1}$, EM20b = 20 tonnes EMU ha^{-1} $year^{-1}$, EF40b = 40 tonnes EFB ha^{-1} $year^{-1}$, EF80b = 80 tonnes EFB ha^{-1} $year^{-1}$, FSs = 7 tonnes FS ha^{-1} $year^{-1}$ spread, FSpi = 7 tonnes FS ha^{-1} $year^{-1}$ in pile and C4 = control). Error bars indicate 1 *SE* ($n = 4$). The inset is an enlargement of the figure. (c) Rainfall during the sampling period

lower emissions than EFB and the control. The lowest total cumulative N_2O and CH_4 emissions were observed from the control in which no organic amendments (Table 3) were applied.

The emission factors vary between 0.02% (EM10b) and 0.26% (EF80b) for N_2O-N and 0.003% (FSpi) and 0.031% (EF80b) for CH_4-C (Table 3).

3.2 | Global warming potential of the treatments

There were significant ($p < 0.05$) differences in GWP between the treatments (Figure 7). The highest GWP (N_2O + CH_4) was 4.4 Mg CO_2-eq/ha from the EF80b treatment, which was significantly higher than from all other treatments. It also contributed the most N_2O and CH_4 to CO_2-eq GWP of all the organic amendment treatments.

Among the organic amendments, the lowest net GWP by far was found from 10 tonnes EMU/ha applied in a 2 m band (0.4 Mg CO_2-eq/ha), and FS spreading in the inter-row area (0.4 Mg CO_2-eq/ha), followed by FS applied in a pile (0.6 Mg CO_2-eq/ha). Both EFB treatments had a significantly higher net GWP than the FS treatments. Experiments 2 and 3 confirmed that a higher dose of urea showed a higher GWP, with a higher share of N_2O. In experiment 2, treatment U248 had the highest net GWP.

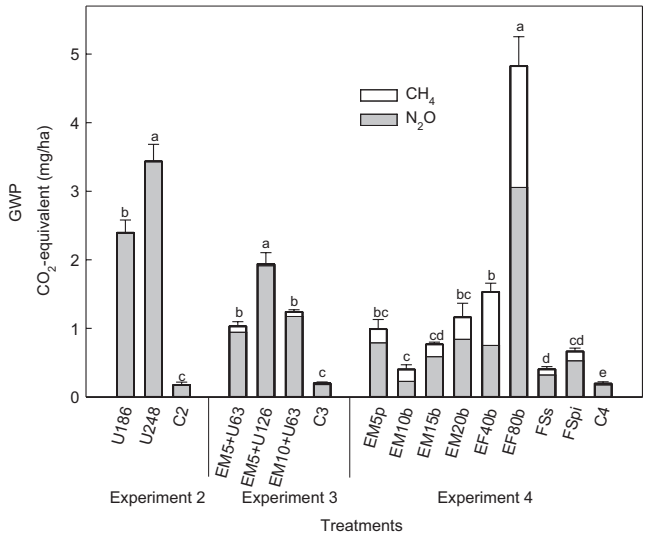


FIGURE 7 CO_2-eq GWP for experiments 2, 3 and 4. Exp. 2: Treatments (U186 = 186 kg N [urea] ha^{-1} $year^{-1}$, U248 = 248 kg N [urea] ha^{-1} $year^{-1}$ and C2 = controls). Exp. 3: Treatments—EM5 + U63 = (5 tonnes EMU + 63 kg N urea) ha^{-1} $year^{-1}$, EM5 + U126 = (5 tonnes EMU + 126 kg N urea) ha^{-1} $year^{-1}$, EM10 + U63 = (10 tonnes EMU + 63 kg N urea) ha^{-1} $year^{-1}$ and C3 = control. Exp. 4: Treatments—EM5p = 5 tonnes EMU ha^{-1} $year^{-1}$ in patch, EM10b = 10 tonnes EMU ha^{-1} $year^{-1}$, EM15b = 15 tonnes EMU ha^{-1} $year^{-1}$, EM20b = 20 tonnes EMU ha^{-1} $year^{-1}$, EF40b = 40 tonnes EFB ha^{-1} $year^{-1}$, EF80b = 80 tonnes EFB ha^{-1} $year^{-1}$, FSs = 7 tonnes FS ha^{-1} $year^{-1}$ in spread, FSpi = 7 tonnes FS ha^{-1} $year^{-1}$ in piles and C4 = control. Different letters reflect a significant difference ($p < 0.05$) between the treatments of the experiments separately. Error bars indicate 1 *SE* ($n = 4$) for GWP ($N_2O + CH_4$)

Similarly, in experiment 3, the highest net GWP was 1.9 Mg CO_2-eq/ha from treatment EM5 + U126, which was 37% and 48% greater than treatments EM10 + U63 and EM5 + U63 respectively.

Yield-scaled GHG emission was not calculated here because the treatment effect of nutrient additions was unlikely to be fully captured within the experimental period of this study.

4 | DISCUSSION

4.1 | Effects of rainfall/season and inorganic fertilizers on N_2O emissions from soil

The first experiment (simulated rainwater) confirmed that soil moisture (precipitation) was a major driver of N_2O emission ($R^2 = 0.84$) from oil palm plantations (Table S1). The moist condition of the soil in the first experiment (Figure 3) was totally dependent on artificially applied water which in association with the extra N added as urea prompted the processes of N_2O production. Other studies have also associated N_2O emission with the application of fertilizers under humid weather conditions and rain events (Buchkina, Balashov, Rizhiya, & Smith, 2010; Metay et al., 2007; Smith & Owens, 2010). The results from these 1 year experiments showed that the fluctuations in N_2O fluxes were influenced by seasonal changes and rain events (Figures 4 and 5). At the lower dose of urea fertilizer (186 kg N), the result showed twice the N_2O emission in the wet season than in the dry season. Similarly, Hergoualc'h, Skiba, Harmand, and Hénault (2008) observed 50% higher N_2O emission during the wet season than during the dry season in a monoculture coffee field in Costa Rica. However, the higher dose of urea application also generated N_2O emission in the dry season because the dry season was not completely dry: 0–30 mm rainfall was recorded after application of the N fertilizer.

In general, the highest N_2O fluxes occurred in the first or second week after urea application which is in agreement with other studies (Liu, Mosier, Halvorson, & Zhang, 2005; Schils, Groenigen, Velthof, & Kuikman, 2008). However, the effect of urea started to decrease after 2 weeks and reached the control level approximately 2 months after application of urea in the wet season. This occurred due to the presence of rainwater (Figures 4 and 5; Table S1) and organic amendments (Figure 5), which contributed to maintaining the soil moisture, thus allowing anaerobic conditions in some microsites and therefore allowing N_2O emissions for more than 2 weeks. Zhang and Han (2008) reported a similar trend in which the fertilization effect of urea and ammonium nitrate application started decreasing after 20 days and disappeared after approximately 2 months.

To verify the impact of rainfall on emissions, the emission of simulated rainwater was compared with actual wet season emissions and the absence of simulated rainwater with actual dry season emissions. N_2O emissions from simulated rainwater were close (13% difference) to the actual wet season, with the difference not being significant. However, compared to the actual dry season emission, actual emissions were found to be greater, since the actual dry season was not completely dry, as in the treatments without simulation. These results indicate that a change in soil moisture through rainfall is a major environmental factor affecting N_2O emissions. Therefore, the timing of fertilizer application is an important management implication to significantly reduce N_2O emissions from oil palm plantations by avoiding periods of heavy rainfall.

4.2 | GHG emission influenced by inorganic fertilizers

Urea fertilizer applied alone or in combination with organic amendments confirmed that an increasing application dose of urea led to a higher N_2O emission (Figures 4 and 5 and Table 3). This finding is supported by Signor, Cerri, and Conant (2013) who also observed higher emissions from

a higher dose of urea and ammonium nitrate fertilizer on a sugarcane field in Brazil. The stimulatory effect of N-application on N_2O emissions was probably due to the increased mineral N levels, that is, nitrate and ammonium which were supplied as a substrate for denitrification (Castaldi & Smith, 1998; Luo, Ledgard, & Lindsey, 2007; Ruser et al., 2006; Strong & Fillery, 2002). In the present experiment, the result also showed that average N_2O flux from oil palm plantation ranged from 1.96 to 2.81 mg N_2O-N m^{-2} day^{-1} for urea fertilizer, depending on the dose applied (Table 3). Aini et al. (2015) reported the average N_2O emission from urea fertilizer on smallholder oil palm plantations to be 0.002–1.25 mg N_2O-N m^{-2} day^{-1}. In the present study, the average emission factor for urea fertilizer from the commercial oil palm plantation was 2.6%. Aini et al. (2015) reported an emission factor 3.1% when applying 33 kg N (urea) ha^{-1} $year^{-1}$ on smallholder oil palm plantations, which is surprisingly high given the relatively small N dose applied. This higher emission factor might be linked to the age of the palms (Ishizuka et al., 2005) and lower nutrient use efficiency on smallholder plantations. With best management practice that involves the efficient management of nutrients, nutrient use efficiency on commercial plantations is generally considered high, resulting in smaller losses in the form of GHG emissions, which might explain the lower emission factor compared to smallholder systems. Both the present results and those of Aini et al. (2015) are substantially greater than the 1% emission factor proposed by the IPCC guidelines (IPCC, 2006).

The present findings indicate that the current IPCC emission factor underestimates emissions from oil palm plantations, which urgently needs validating in future trials and updating.

4.3 | GHG emission influenced by organic amendments

4.3.1 | Timing hotspot of higher emissions from organic amendments

Application of organic amendments in this study resulted in high N_2O emissions in the first 10 days after application. During this period, the share of N_2O emissions from the different organic amendments accounted for 34%–51% of annual total cumulative N_2O emissions (Figure 6). Lou and Nair (2009) reviewed that N_2O emissions were higher at the starting of the decomposition process (He et al., 2000) due to the availability of labile organic C and higher microbial metabolism activity which serves as an energy and electron source for denitrifiers (Zhou et al., 2016).

In the present experiment, most of the CH_4 emissions were recorded during the first week after application which is in line with others studies (Beck-Friis, Pell, Sonesson, Jönsson, & Kirchmann, 2000; Sánchez et al., 2015; Sánchez-Monedero, Serramiá, Civantos, Fernández-Hernández, & Roig, 2010). For the EMU and FS treatments, 31%–60% of the annual cumulative CH_4 emissions were found during the first 21 days of the experiment. However, for the EFB treatments, 49%–70% of the annual total cumulative CH_4 emissions were found between day 21 and day 60 of the experiment with a peak around 40 days after application. This could be due to the difference in the degrees of degradability of EFB compared to EMU, which might be coupled with the anaerobic conditions created by rainfall that ultimately favour the methanogenic archaea activity needed for CH_4 production (De Nobili, Contin, Mondini, & Brookes, 2001). The low emission from the EMU treatments maybe because it was already decomposed and available C was already stabilized/lost from the system (Sánchez et al., 2015). Thus, when monitoring CH_4 emissions from applied organic amendments, high intensity flux measurements should focus on the period up to 60 days after application, and less so on the period afterwards.

4.3.2 | Characteristics of the materials and availability of C and N

Organic amendments significantly affected both N_2O and CH_4 emissions in this study. The emission factors depended on the specific characteristics, the amount and placement, and the size of the pile of the organic materials added in the soil. These determine the environmental conditions as well as the process performance for the mineralization process (Beck-Friis et al., 2000; Sánchez-Monedero et al., 2010). By the decomposition of crop residues, C is made available gradually which may influence nitrification and denitrification processes (Kalbitz, Schmerwitz, Schwesig, & Matzner, 2003; Senbayram et al., 2014). It stimulates the microbial metabolic activity by providing available C to denitrifiers, which increase O_2 consumption and consequently enhance N_2O production through denitrification (Miller et al., 2008; Morley & Baggs, 2010).

In general, the C:N ratio of crop residues affects the availability of soil N, and thus, the nitrification–denitrification and immobilization processes (Chen, Li, Hu, & Shi, 2013). Application of crop residues with C:N ratios (below 30) leads to a release of NH_4^+-N and NO_3-N, may affect nitrification–denitrification process and results in higher N_2O emission. However, a C:N ratio > 30 often results in N immobilization and thus reduces soil N availability, and therefore, the production of N_2O (Huang, Zou, Zheng, Wang, & Xu, 2004; Signor & Cerri, 2013).

In this study, the C:N ratios of EFB, EMU and FS were 54:1, 25:1 and 38:1 respectively. However, the cumulative N_2O emissions from the EF40b and EM5p treatments were

comparable but significantly higher than those from the FSs treatment (Table 3). A greater emission from the EFB treatment, despite its higher C:N ratio (54:1), suggests that N_2O production were controlled by chemical properties, for example, lignin content in crop residues, available C and N, as well as by environmental factors other than C:N ratios (Table S1) which is also supported by Velthof, Kuikman, and Oenema (2003) and Begum, Guppy, Herridge, and Schwenke (2014). Among the different organic materials in the present study, EFB had three to five times greater NH_4^+-N (292 mg/kg) content, which might have been released to the soil and increased the substrate needed for N_2O production. However, if this is compared to emissions from urea, N_2O emissions were found to be 66%–86% lower from the generally applied dose of organic amendments (EFB40, EMU5 and FSsp). This might be linked to the higher C:N ratio of organic amendments, which provokes microbial immobilization by N released during the residue degradation in the soil, thus leading to lower N_2O emissions. This is the cause of the comparatively lower emission from crop residues that were returned to the plantation in this study than from inorganic fertilizers.

4.3.3 | Doses of organic amendments

The increase in N_2O and CH_4 emissions followed the increased dose of organic amendments in the present study. In agreement with these results, Velthof et al. (2003) and Kirchmann and Lundvall (1993) reported that a high content of available C in organic amendments would increase the N_2O and CH_4 emissions. By doubling the application dose of EMU from 10 tonnes/ha to 20 tonnes/ha, N_2O emissions increased by 262%, whereas the increase in CH_4 emission was only 86%. A high dose of EFB (80 tonnes/ha) produced 304% more N_2O emissions and 127% more CH_4 emissions than the 40 tonnes/ha EFB treatment. The large increase in emissions due to the increase in application dose might be linked to the loading effect and anoxic conditions created by an increase in microbial respiration (Bernal, 1998). EMU applied in a patch (5 tonnes/ha covering only 1.3% of the area) produced 69% and 54% more N_2O and CH_4 emissions than 10 tonnes EMU/ha applied in the 2 m band (covering 12% of the area) in terms of the emission factor due to a high dose of C and N being applied in a specific area. Similarly, due to a higher loading rate, application of the same rate of FSs in a pile resulted in 63% and 71% more N_2O and CH_4 emissions, respectively, compared to their application in a spreading technique. However, the differences were not significant.

These findings indicate that careful consideration needs to be given to the loading rate of organic amendments, which greatly affects the intensity of GHG emissions. It is recommended that organic amendments be applied as evenly spread out as possible, avoiding application in large piles.

4.4 | Effect of a combination of inorganic fertilizers and organic amendments on GHG emissions

The combined application of urea and EMU resulted in low N_2O emissions despite the high N content (579–1,095 kg N ha^{-1} $year^{-1}$). Being partially decomposed, EMU has less influence on N_2O emission as it has less readily available carbon that is needed as an energy source for microorganisms. Moreover, the early incorporation of EMU (30 days before urea application) may have caused N immobilization, which might explain the reduced N_2O emissions. This is supported by an experiment conducted by Htun, Tong, Gao, and Xiaotang (2017), which showed that early incorporation of straw reduced N_2O emissions by 35% compared to the application of straw and N fertilizer at the same time. The N_2O emission factor of combination treatments (EM5 + U126) was only 0.58, which was 87% lower than the urea-only treatments applied in experiment 2. Overall, the CH_4 emission was also low, with an average emission factor of just 0.005. The low CH_4 emission from EMU could be due to the fact that reactive C was stabilized during the co-composting stage; hence, the labile carbon needed to initiate methanogenesis was low (Bernal, 1998; Htun et al., 2017). However, in any organic amendments, the N is organically bound and only partly and slowly becomes available to plant may lead to an unrealized production potential (De Ponti, Rijk, & Ittersum, 2012). To prevent this, farmers should add some inorganic fertilizers, as in the combination treatments in the present study. Comparing the present treatments, EM5 + U63 (about 100 kg N/ha applied) and EM10 + U63 (136 kg N/ha applied) were found to result in a similar GWP. Since the general advice is to apply 135 kg N/ha, the EM10 + U63 treatment comes closest to this advice. Therefore, a combination of urea with EMU could be an effective way of applying sufficient nitrogen to oil palm plantations with lower N_2O and CH_4 emissions.

4.5 | GLOBAL WARMING POTENTIAL

The GWP (Mg CO_2-eq/ha) of N_2O and CH_4 emissions was estimated in order to assess the effect of the separate application of inorganic fertilizers, organic amendments and their combinations. Overall GWP was higher for a high dose of fresh EFB treatments followed by a high dose of urea application, where the contribution of N_2O to GWP was significantly higher than that of CH_4 (Table 3 and Figure 7). A rise in GWP with an increased N fertilization dose (Figure 7) may be associated with higher N_2O emissions, which play a considerable role in net GWP. This has been supported by other studies (Archer & Halvorson, 2010; Halvorson, Grosso, & Reule, 2008;

Mosier et al., 2006), as well as a review undertaken by Sainju (2016) who found that applying 246 kg N/ha to an irrigated soybean field in Fort Collins produced a GWP of 1.2 Mg CO_2-eq. ha^{-1} $year^{-1}$ (Archer & Halvorson, 2010), which is less than the present result with the same dose of applied N on an oil palm plantation in Indonesia. Organic amendments contributed significantly more to GWP by CH_4 emission compared to mineral N fertilizer application on oil palm plantations. The lowest GWP was calculated from 10 tonnes EMU ha^{-1} $year^{-1}$, which could be the recommended organic amendment dose for oil palm plantations from the perspective of reducing GHG emissions. However, it may affect production because of the lower supply of nutrients. The management practice currently adopted by the BLRS in Sumatra involves applying 186 kg urea by broadcasting (U186) and FS applied in piles on the oil palm plantation. The total net GWP calculated from the whole field based on their relative areas of the input applied under this practice is 2.75 Mg CO_2-eq/ha. However, an improved combined management practice, which involves replacing some of the urea with recycled organic materials, such as treatment EM10 + U63 along with FS applied in a pile, would reduce net GWP (1.40 Mg CO_2-eq/ha) by 50%. Therefore, by combining inorganic fertilizers and organic amendments, N_2O and CH_4 emissions could be decreased by a greater extent than by applying the N fertilizer or organic amendments individually and could therefore be an effective fertilization strategy for oil palm plantations.

5 | MANAGEMENT IMPLICATIONS AND FUTURE RESEARCH DIRECTIONS

This study showed that the timing and magnitude of both inorganic and organic fertilization have an impact on N_2O and CH_4 emissions, which depend on many concomitant factors whose relationship is complex. N fertilization by inorganic fertilizers increased N_2O emissions without significantly influencing CH_4 emissions. Organic amendments contributed to GHG emissions and although the emission factors were found to be less than those of inorganic fertilizers, they need to be taken into consideration when evaluating GHG emissions from oil palm plantations. Among the various organic amendments available, application of EMU could be the best options due to its greater GHG mitigation potential. It is recommended that EMU to be applied as a nutrient source as well as mulching material, with the addition of a low dose of inorganic fertilizers applied after one month of EMU application, as in treatment EM10 + U63, which could prevent a large negative yield effect and reduce the risk of high CH_4 and N_2O emissions from the soil while maintaining productivity. Although FS application by spreading or in pile did not show any significant difference in GHG emission, it is recommended that FS be evenly spread, which may improve soil fertility by reducing heterogeneity in the field. The rainfall experiment showed that increased precipitation dramatically increased N_2O emission, suggesting that time of fertilization is a critical management option for reducing emissions. Careful timing of the application of inorganic fertilizers/organic amendments to avoid heavy rainfall periods would also result in lower GHG emissions. However organic amendments such as EMU and EFB require more research to improve their efficiency as a fertilizer. This study could serve as a baseline for better understanding GHG emissions and their dynamics in mineral soils to reduce environmental losses, which can increase the economic benefits and agroecological efficiency of oil palm management systems. New emission factors could be used in an environmental impact assessment since current emission factors in the IPCC guidelines, rely on datasets that underestimate the emission factors of urea and overestimate emission factors of organic amendments. Moreover, in terms of sustainability, these results could be useful for developing an agroecological indicator for management or certification systems and improving life cycle assessments. However, long-term experiments are needed to fully capture the emission dynamics and the effects on oil palm productivity of different organic amendments. Finally, a network of long-term experimental trials with proper monitoring and technical contexts is needed to fully evaluate the multidimensional variability of these fluxes.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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