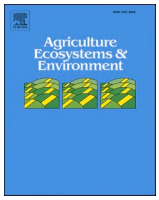
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Field-derived nitrous oxide emission factors for fertilised smallholder oil palm systems on mineral soils in South-East Asia

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ABSTRACT

Nitrous oxide (N_2O) emissions from fertilised oil palm (OP) systems remain poorly quantified despite their importance for regional greenhouse gas inventories and life-cycle assessments. This study measured N_2O emissions following 18 fertiliser application events across 12 smallholder OP farms in Indonesia and Malaysia between 2022 and 2025. Cumulative fertiliser-induced emissions were estimated over a 21-day measurement period and used to derive N_2O emission factors (EFs) for individual fertilisation events. Individual EFs ranged from 0.01% to 1.43% of applied nitrogen fertiliser (mineral and organic). To place these measurements in a regional context, results were combined with published EFs from OP systems on mineral soils in Southeast Asia (SEA). Using log-normal statistical treatment to account for the highly skewed distribution of EFs, a regional mean EF of 0.82% of applied nitrogen was derived (95% confidence interval: 0.44–1.78%). Sensitivity analyses indicated that regional EF estimates varied according to study inclusion and analytical approach, with mean values ranging from 0.51% to 1.12% of applied nitrogen. While uncertainties remain and the observational study design does not allow the independent effects of site, year, fertiliser type and management to be disentangled, the derived EF is broadly consistent with the IPCC Tier 1 default value of 1% and represents a regional estimate based on the currently available field evidence. These results contribute to a limited empirical dataset for OP systems in SEA and provide a transparent evidence base for greenhouse gas inventories, life-cycle assessments, and future evaluations of mitigation opportunities within the sector.

1. Introduction

Oil palm (OP) cultivation is an economically important agricultural industry in Southeast Asia (SEA), with Indonesia and Malaysia together accounting for more than 80% of global palm oil production (FAO 2025). Expansion of the sector over recent decades has been driven by increasing global demand for vegetable oils used in food, cosmetics, oleochemicals, and biofuels. As of 2022, palm oil (including palm kernel oil) accounted for over 40% of global vegetable oil production. This is despite OP crops occupying only about 5% of the land used for oil crop cultivation (Descals et al., 2024; Meijaard et al., 2024; FAO 2025). Alongside large commercial plantations which can cover thousands of ha of land, smallholder farmers (owning less than 50 ha of land each) also represent a substantial proportion of production, accounting for approximately 40% of palm oil across the SEA region (Reiss-Woolever et al., 2025). These smallholder systems vary considerably in management intensity, fertiliser use, planting density, palm age, and have varying access to agronomic support. While industrial plantations are often characterised by relatively standardised management practices and nutrient management strategies, smallholder production systems

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are typically more heterogeneous and influenced by local economic constraints and supply chain integration. This diversity creates significant challenges for evaluating both productivity and environmental performance across the sector (Cowan et al., 2026).

Agricultural production is a major source of anthropogenic greenhouse gas emissions, particularly nitrous oxide (N_2O), a potent greenhouse gas with a global warming potential 265 times greater than carbon dioxide over a 100-year timescale (IPCC, 2014). Nitrous oxide also contributes to stratospheric ozone depletion and represents one of the most important long-lived climate pollutants associated with agricultural land use (Ravishankara et al., 2009). The majority of agricultural N_2O emissions originate from microbial nitrification and denitrification processes in soils (Tang and Xia, 2025), which are strongly stimulated by nitrogen fertiliser inputs (Fowler et al., 2015). In OP systems, nitrogen fertiliser application is commonly required to maintain yields due to the high nutrient demand of the crop, particularly in highly weathered tropical soils (Kurniawan et al., 2018; Essono et al., 2023). However, fertiliser-derived N_2O emissions can vary substantially depending on fertiliser type, application rate, soil moisture, climatic conditions, and management practices (Davidson, 1991; Melling et al., 2007; Butterbach-Bahl et al., 2013; Shcherbak et al., 2014; Cowan et al., 2020). Fluxes are also highly episodic and spatially heterogeneous, often occurring in short-lived peaks following fertiliser application or rainfall events, which complicates their quantification and scaling (Levy et al., 2017).

Despite increasing interest in the environmental sustainability of palm oil production, relatively limited field data exist describing N_2O emissions from commercial-scale or smallholder OP systems in Southeast Asia (Skiba et al., 2020). Global understanding of N_2O emissions from OP remains constrained by a scarcity of long-term datasets and a lack of measurements across diverse management systems, particularly within smallholder contexts. Several studies have reported N_2O emissions from OP cropping in terms of annual emissions, where the longer-term impacts of conversion from forest or peatlands to OP monoculture have been investigated. Such studies provide annual N_2O emissions or budgets for the land use in general with the inclusion of nitrogen fertiliser application (Allen et al., 2018; Meijide et al., 2020; Swails et al., 2023; Chen et al., 2024). Emissions of N_2O from OP cultivation in peatlands has been reported to be particularly high, exceeding emissions from mineral soils by an order of magnitude in some cases (Melling et al., 2007; Sakata et al., 2014; Chaddy et al., 2019; Oktarita et al., 2017; Jovani-Sancho et al., 2023). Emissions of N_2O have also been modelled in the region in an attempt to estimate the impact of nitrogen fertiliser application to crops (Pardon et al., 2016). However, N_2O emissions as a direct result of fertiliser use are rarely quantified or reported in a way that would allow incorporation into a wider accounting system (e.g. fertiliser specific emission factors (EFs) that predict the fraction of nitrogen applied that is converted into N_2O). Where these studies do exist, they are split between commercial scale plantations (Sakata et al., 2014; Rahman et al., 2019) and smallholder farms (Aini et al., 2015; Hassler et al., 2017) with individual reported EFs (17 in total) ranging widely from near zero, to 2.7% of applied nitrogen fertiliser being released as N_2O (for mineral soils). To date, no comprehensive synthesis has been carried out on N_2O EFs for fertiliser application to OP cropping in the SEA region.

In life cycle assessments of OP production and in national greenhouse gas inventories across SEA, N_2O emissions from fertiliser use are typically estimated using standardized approaches rather than direct measurement. Both largely follow methodologies developed by the Intergovernmental Panel on Climate Change (IPCC), in which emissions are calculated as the product of nitrogen input (activity data) and an EF representing the proportion of applied nitrogen emitted as N_2O. In most cases, particularly where site-specific data are lacking, inventories apply the IPCC Tier 1 default EF, which assumes that approximately 1% of nitrogen applied to soils is directly emitted as N_2O-N (with associated uncertainty ranges of 0.03–3%) (IPCC, 2019). This EF is largely derived from data collated by Stehfest and Bouwman (2006), a global dataset of over 1000 reported EFs. However, this dataset is heavily biased by the number of studies carried out in northern hemisphere temperate regions and includes no experimental data from tropical OP cultivation. The 1% default IPCC EF used to estimate N_2O emissions after fertiliser application is widely used in national reporting under the United Nations Framework Convention on Climate Change (UNFCCC), where emissions are estimated at scale using aggregated fertiliser consumption statistics due to the impracticality of direct measurement. While some refinements (e.g. disaggregated EFs for synthetic versus organic inputs) have been introduced in updated IPCC guidance, most applications in practice still rely on simplified default values due to limited availability of region-specific datasets.

Improved empirical datasets are needed to better characterise greenhouse gas emissions from these systems and to support the development of realistic mitigation strategies. As highlighted in recent syntheses (Skiba et al., 2020), advancing understanding in this area requires both an expansion of field measurements and improved approaches for integrating heterogeneous datasets into robust emission factors. Such information is needed to improve regional greenhouse gas inventories and refine emission factors for tropical perennial cropping systems.

To address these knowledge gaps, this study provides a multi-site, multi-year assessment of N_2O emissions from fertilised smallholder OP systems across Indonesia and Malaysia. Field measurements were conducted across 12 farms, spanning a range of fertiliser types, application rates, and management conditions representative of real-world smallholder practices. The aim of this study is to improve the empirical basis for quantifying N_2O emissions in OP systems and to develop a preliminary regional emission factor estimate for use in greenhouse gas inventories and life cycle assessments.

2. Method

2.1. Field sites

Four separate experiments were carried out from 2022 to 2025, each consisting of measurements taken from 3 smallholder farms (12 sites in total) (Table 1). In Indonesia, the three sites were part of a network of smallholders involved in the Plasma Programme (an Indonesian Government Initiative that promotes large scale plantation owners providing economic and social assistance to smallholder farmers). The Indonesian farms were located in the Kampar Regencies of the Riau Province, on the island of Sumatra. Field sites in Malaysia were situated in the Kampar District, Perak, in Peninsular Malaysia and were part of local partner WildAsia's smallholder network 'WAGS' (Wild Asia Group Scheme). The farms ranged in size from 0.6 to 4.0 ha, in planting density from 111 to 187 palms ha^{-1}, and in age from 12 to 20 years. All farms were on mineral soils. While we do not have detailed information of soil

Table 1
Details of smallholder oil palm farms where trials were carried out.

Year	Country	Region	Site ID	Farm Size (ha)	Planting Density (Trees ha^{-1})	Palm Age (Years)
2022	Indonesia	Riau	ID-A	2.0	136	15
2022	Indonesia	Riau	ID-B	2.0	136	15
2022	Indonesia	Riau	ID-C	2.0	136	15
2023	Malaysia	Perak	MY-A	1.2	137	19
2023	Malaysia	Perak	MY-B	0.6	132	20
2023	Malaysia	Perak	MY-C	4.0	123	12
2024	Malaysia	Perak	MY-D	1.3	131	13
2024	Malaysia	Perak	MY-E	4.0	111	18
2024	Malaysia	Perak	MY-F	1.1	175	12
2025	Malaysia	Perak	MY-G	1.0	141	16
2025	Malaysia	Perak	MY-H	0.9	141	15
2025	Malaysia	Perak	MY-I	1.3	187	15

properties for the farms reported in this study, we are confident these ranges span typical planting conditions in the area for which the 12 farms are representative.

2.2. Fertiliser application

A wide range of fertiliser products were used across the experimental sites to reflect the diversity of nutrient management practices observed in smallholder OP systems in SEA (Table 2). These included conventional mineral fertilisers (e.g. urea, compound NPK formulations), organo-mineral products (blends of mineral nutrients with organic substrates), and locally sourced organic amendments such as composts and biochar. Mineral fertilisers comprised both single-nutrient and compound formulations. Urea (46.0% N) was used at the Indonesian sites as a highly soluble and readily available nitrogen source, typical of smallholder input systems. Compound fertilisers (e.g. DuaDuan, MPOB, Eurotec, YaraMila) provided balanced inputs of nitrogen (N), phosphorus (P), and potassium (K), with additional secondary nutrients such as magnesium (Mg) and micronutrients (e.g. boron) in some formulations. These products are commonly used in mature OP systems to sustain fruit production.

Organo-mineral and organic fertilisers included Peladang and Bio-Kimia products, as well as locally produced compost (COMP). These materials typically contained lower concentrations of total nitrogen (approximately 1–2% nitrogen in compost-based amendments). Additional carbon-rich amendments, including OP-derived biochar (CHAR) and seaweed-derived charcoal (SeaChar), were applied at selected sites to explore their role in modifying soil conditions; however, these materials contained negligible nitrogen content and were therefore not considered direct sources of nitrogen.

Nitrogen application rates varied substantially across sites and treatments (Table 3), ranging from 0 kg N ha^{-1} in unfertilised plots (run in tandem with fertilisation experiments) to a maximum of 276 kg N ha^{-1} in high-input mineral fertiliser treatments. Intermediate application rates (e.g. 36–149 kg N ha^{-1}) reflected typical smallholder practices, where fertiliser inputs are often constrained by economic considerations and access to inputs. In Malaysia, compound fertilisers were generally applied at rates between 36 and 149 kg N ha^{-1}, while combined mineral–organic treatments reached up to 184 kg N ha^{-1}. At the Indonesian sites, urea was applied at two contrasting rates (138 and 276 kg N ha^{-1}) to explicitly examine the response of N_2O emissions to increasing nitrogen input.

Fertiliser applications were carried out manually by farmers or field technicians via even surface broadcasting within the weeded circle surrounding each palm (1.5–2.0 m radius around each palm). Application rates and subsequent emissions per area basis in this study refer to the areas in which fertiliser was applied akin to small plot experiments commonly used when determining EF experimentally In mixed treatments, mineral fertiliser and organic amendments were applied either simultaneously or in close succession, ensuring co-location within the palm nutrient uptake zone. The derived units represent hectares of fertilized land rather than actual OP cultivation area. While this still enables the calculation of an effective fertilizer application emission factor (i.e., the percentage of applied nitrogen emitted), it is less representative of the overall OP landscape, as it does not account for areas between palm circles. Biochar additions (where used) were applied in the weeded circle at a fixed rate (~30 t ha^{-1}) alongside fertiliser inputs. Across all experiments, application timing was aligned with local management practices and seasonal conditions, allowing assessment of emissions under realistic field scenarios.

Table 2
A summary of fertilisers applied to oil palm crops in the smallholder fertiliser trials.

Fertiliser ID	N content %	Origin	Description
Urea	~46	Indonesia	Mineral fertiliser pellets (a.k.a. Carbamide)
SeaChar	~0	Malaysia	Diluted seaweed charcoal (carbon-rich)
Peladang	~1.75	Malaysia	Peladang organic fertilizer pellets. P~3.34%, K~2.17%.
DuaDuan	~13	Malaysia	BAJA BUTIRAN BB88 mineral fertiliser with 2% MgO and added Boron and other trace elements. P_2O_5~5%, K_2O~21%.
MPOB	~10	Malaysia	Baja Sawit MPOB F1 Xtra K mineral fertiliser 2% MgO and 0.5% B_2O_3. P_2O_5~5%, K_2O~20%.
Eurotec	~13	Russia	Eurotec premium grade mineral fertiliser. P_2O_5~13%, K_2O~23% + MgO + TE.
BioKimia	~12	Malaysia	Baja Bio-Kimia biochemical organic fertilizer composed of up to 80% organic materials. P ~ 12%, K~17%.
YaraMila	~13	Europe	Prilled mineral fertiliser, with P_2O_5~11%, K_2O~21%, MgO~2% and B~0.2%.
COMP	~1.83	Malaysia	Locally produced compost. P ~ 0.52%, K~1.05%.
CHAR	No nutrients	Malaysia	Locally produced OP-derived biochar.

Table 3
Details of nitrogen fertiliser application events across all trials. Each event is provided with a unique Event ID.

Year	Country	Event ID	Fertiliser	Application (kg N ha^{-1})	N Type
2022	Indonesia	ID-A	None	0	None
2022	Indonesia	ID-B	Urea	138	Mineral
2022	Indonesia	ID-C	Urea	276	Mineral
2023	Malaysia	MY-A	SeaChar	0	None
2023	Malaysia	MY-B	Peladang	41	Mineral/ Organic
2023	Malaysia	MY-C	DuaDuan	149	Mineral
2024	Malaysia	MY-D	MPOB	36	Mineral
2024	Malaysia	MY-E	Eurotec	53	Mineral
2024	Malaysia	MY-F	BioKimia	55	Mineral/ Organic
2025	Malaysia	MY-GA, MY-HA, MY-IA	YaraMila	147, 147, 195	Mineral
2025	Malaysia	MY-GB, MY-HB, MY-IB	YaraMila(50%), COMP(50%)	149, 149, 198	Mineral/ Organic
2025	Malaysia	MY-GC, MY-HC, MY-IC	YaraMila(50%), COMP(50%), CHAR(20 kg)	149, 149, 198	Mineral/ Organic

2.3. Flux chamber measurements

Soil–atmosphere fluxes of nitrous oxide (N_2O) and methane (CH_4) were quantified using the static chamber technique (Drewer et al., 2021; Drewer et al., 2024). At each site, permanent chamber bases (collars) were installed in the soil prior to measurements to minimise disturbance effects during sampling (4–8 chambers per treatment). Chambers were treated as spatial subsamples rather than independent experimental replicates, and the fertiliser application event was considered the experimental unit. Chambers were positioned within the fertilised area around selected palms and were used to characterise spatial variability in soil N_2O fluxes. Chamber lids (diameter = 40 cm, height = 30 cm) consisting of opaque polypropylene cylinders with an aluminium flat sheet at the end were used during measurement duration only. Collars were distributed to capture spatial heterogeneity within the OP system, with sampling locations positioned within fertilised palm circles. The depth to the surface in each collar was measured at 5 points on the sides of the collar base using a ruler, from which the average was used to calculate the volume of air during closure with the lids attached. Chambers were deployed during discrete measurement campaigns centred around fertiliser application events.

During measurement periods, lids were fastened onto the bases using four strong clips; a strip of draft excluder glued onto the lid provided a gas tight seal between chamber and lid. A three-way tap was used for gas sample removal using a 100 ml syringe. 20 ml glass vials were filled with a double needle system to flush the vials with five times their volume. Headspace gas samples were collected at multiple time points over the enclosure period (four samples over approximately 60 min). Samples were subsequently analysed by gas chromatography (Agilent GC7890B with headspace autosampler 7697 A; Agilent, Santa Clara, California with a micro-electron capture detector (μECD)) for N_2O, and flame ionisation detection for CH_4 concentrations, calibrated with certified standard gases spanning the expected concentration range.

Fluxes were calculated from the linear rate of change in gas concentration within the chamber headspace over time (dC/dt) (Eq. 1):

$$F = \frac{dC}{dt} \times \rho \times \frac{V}{A} \quad (1)$$

Where F is gas flux from the soil (nmol m^{-2} s^{-1}), p is the density of air in mol m^{-3}, V is the volume of the chamber in m^3 and A is the ground area enclosed by the chamber in m^2. Only regressions meeting quality control criteria (e.g. linearity and minimum number of valid sampling points) were retained. Sampling typically included measurements before fertilisation to establish background fluxes (e.g. 1–10 days prior), followed by an intensive post-application sampling period extending over approximately 10–21 days to capture emission peaks and subsequent decline.

For each flux chamber measurement, soil temperature and soil volumetric water content (VWC) were also measured next to the chamber (<0.5 m distance) at the time of the flux measurement. Soil temperature was measured at 10 cm depth using a handheld probe (ETI Ltd., Worthing, UK), and soil VWC was measured at 7 cm depth using an ML3 ThetaProbe Soil Moisture Sensor (Delta-T Devices, Cambridge UK), with 4 replicates for each chamber.

2.4. Cumulative flux estimation and statistical analysis

Cumulative N_2O emissions were estimated over a 21-day period following each application event. Measurements roughly took place on days −3, −1, 0, 1, 2, 4, 7, 10, 14, and 21 after fertiliser application (with zero being the day of fertiliser application). The days of −3 and −1 provided the background. Due to logistical constraints associated with repeated field measurements across dispersed smallholder sites, sampling frequency and timing varied slightly between experiments, preventing the consistent application of interpolation-based approaches across all sites and experiments. Instead, a simplified approach was adopted to derive cumulative emissions from observed flux measurements.

For each experimental site, mean background fluxes were calculated from measurements obtained prior to fertiliser application. Post-application fluxes were then averaged over the full 21-day monitoring period (or all measurements available) (Eq. 2). Fertiliser-induced emissions were estimated by subtracting the mean background flux from the mean post-application flux, then multiplying by the duration of the measurement period (21 days) to derive cumulative emissions on an area basis (kg N ha^{-1}). This approach assumes that the observed mean post-application flux is representative of the average emission rate over the monitoring period and provides a consistent basis for comparison across sites with differing sampling schedules.

$$E_{21} = \left(\overline{F}_{post} - \overline{F}_{pre}\right) \times 0.508 \quad (2)$$

Where E_{21} is the cumulative emission of N_2O-N over a 21-day period (in kg N ha^{-1}), $\overline{F}_{post}$ is the mean flux measured during the 21 days after fertilisation and $\overline{F}_{pre}$ is the mean background flux measured before fertilisation (nmol m^{-2} s^{-1}). Conversion of units from nmol m^{-2} s^{-1} to kg N ha^{-1} over a 21-day period uses the constant value of 0.508.

Given that chamber-based N_2O flux data are non-normally distributed and often exhibit log-normal characteristics, statistical summaries (means) and uncertainty estimates (95% confidence intervals (95% C.I.s)) were calculated using approaches appropriate for log-transformed data. Specifically, we applied Zou's method (Zou and Donner, 2007), also known as the Method of Variance Estimates Recovery (MOVER), to derive 95% C.I.s for cumulative emissions. This method enables the calculation of confidence intervals for functions of log-normally distributed variables (e.g. differences between means) using closed-form expressions. To incorporate negative flux data into the analysis, data was shifted into positive space adding a constant of 0.34, then after means were calculated, this difference was subtracted again. In the absence of a suitable mechanistic or empirical model to describe temporal emission dynamics across all sites, this method offers a transparent and defensible means of estimating cumulative N_2O emissions under conditions of constrained and irregular sampling.

3. Results

3.1. Chamber flux and soil measurements

Individual flux measurements ranged from −5.1–3.6 nmol m^{-2} s^{-1} for CH_4, and −1.6–47.1 nmol m^{-2} s^{-1} for N_2O. The analytical uncertainties for gas fluxes were calculated to be 0.53 and 0.066 nmol m^{-2} s^{-1} for CH_4 and N_2O, respectively, using the method of Cowan et al. (2025a) (GC analyser detection limit of 40 parts per billion (ppb) for CH_4 and 5 ppb for N_2O). A total of 83% of measured CH_4 and 25% of measured N_2O fluxes fell below the analytical uncertainty (Fig. 1a & 1b). No further data analysis of CH_4 fluxes was carried out as measured fluxes were largely in the magnitude of statistical noise, with an overall median flux of −0.014 nmol m^{-2} s^{-1} (essentially zero flux) across all field sites.

Fluxes of N_2O were log-normally distributed, with fluxes ranging over three orders of magnitude (Fig. 1b). Despite the large overall range, 81% of measured N_2O fluxes were below 1 nmol m^{-2} s^{-1}. Neither emission of CH_4 or N_2O correlated with soil moisture or soil temperature measurements, despite the large range of conditions over which field trials took place (Figs. 1c -1f). However, interpretation of the soil moisture measurements should be treated with caution because site-specific calibration was not possible and some extreme values were recorded during the field campaigns.

Prior to fertiliser application fluxes of N_2O ranged from −0.6–4.2 nmol m^{-2} s^{-1} with mean fluxes at the different sites ranging from 0.02 to 0.61 nmol m^{-2} s^{-1} (Fig. 2 & Table 4). With the exception of the two events where negligible quantities of nitrogen were applied (ID-A and MY-A), emissions of N_2O were on average, higher after application than before (Table 4). The temporal response to nitrogen application and the magnitude of N_2O fluxes varied considerably between field sites. During some of the events (for example MY-C, MY-GB, MY-IC) an immediate peak in N_2O emissions is observed during the first 1–2 days after application, while during other events a delayed peak is observed 4–6 days after application (MY-B, MY-GA, MY-HB), or no peak response it observed at all and fluxes remain relatively low throughout (ID-B, MY-D, MY-F) (Fig. 2). There is no observable difference in temporal emission behaviour between application of the mineral or organo-mineral fertiliser types. Where data is available, peaks in emissions have all subsided near to background flux magnitude (< 0.6 nmol m^{-2} s^{-1}) by the 21-day mark.

3.2. Cumulative flux and emission factors

Cumulative fluxes were estimated over a 21-day period to estimate the impact of nitrogen application on N_2O emissions, which is used to establish the emission factor (EF, the % of N applied lost as N_2O-N) (Table 4). The cumulative emissions of N_2O after each fertiliser event ranged from 0.00 to 3.54 kg N_2O-N ha^{-1}, with considerable variability across the events (Fig. 3). For the two events where zero nitrogen was

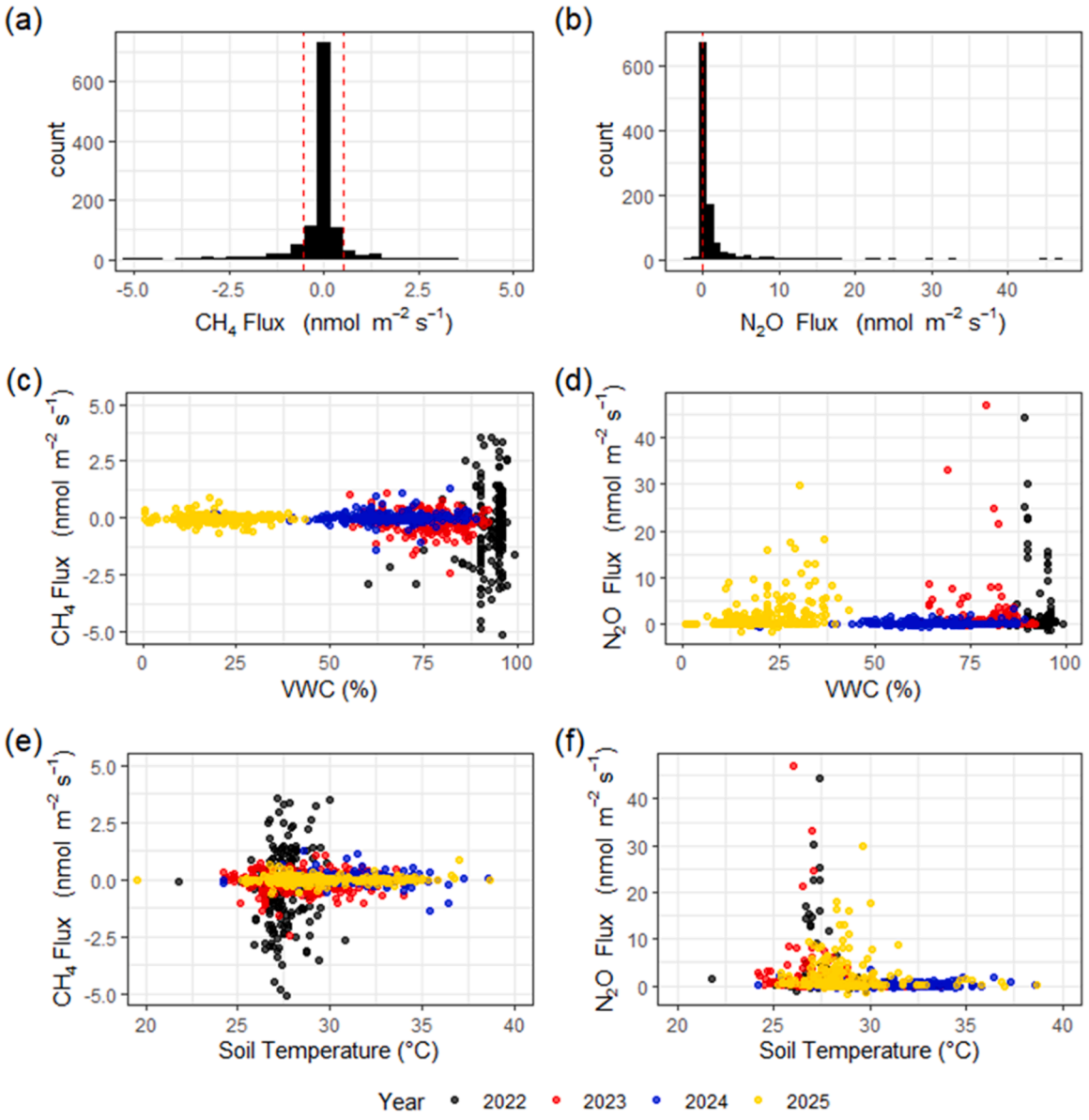


Fig. 1. Distributions of (a) all CH_4 chamber flux data and (b) all N_2O chamber flux data measured over all experiments. Red vertical lines indicate analytical uncertainty of the flux measurement methods. VWC measured using soil probes (7 cm depth) at the time of chamber flux measurements is plot against (c) CH_4 flux and (d) N_2O flux. Soil temperature measured using soil probes (10 cm) at the time of chamber flux measurements is plot against (e) CH_4 flux and (f) N_2O flux.

applied, cumulative emissions are reported as negative as emissions were lower after the associated application dates than before. However, confidence intervals cross the zero-flux threshold, indicating that these results are not significantly different from zero-flux conditions.

In the 2022 field trials in Indonesia, the high application of urea (276 kg N ha^{-1}) resulted in a significant emission of N_2O (3.53 kg N_2O-N ha^{-1}), however cumulative emissions from the event where 138 kg N ha^{-1} was applied were near the same magnitude as the zero nitrogen applied plots (0.06 (-0.09—0.23) and −0.09 (-0.27—0.12) kg N_2O-N ha^{-1}, respectively). Similarly in the 2023 trials in Malaysia, the largest application of N (149 kg N ha^{-1}) resulted in the highest cumulative N_2O emissions 2.13 kg N_2O-N ha^{-1}, and the application of 41 kg N ha^{-1} emitted only 0.25 kg N_2O-N ha^{-1} (Table 4 & Fig. 3). During the 2024 trials, a relatively small quantity of N was applied to the fields (36–55 kg N ha^{-1}) and cumulative emissions of N_2O observed were also low (ranging from 0.00 to 0.06 kg N_2O-N ha^{-1}). During the 2025 trials, a more consistent N application rate (147–198 kg N ha^{-1}) resulted in a wide range of observed cumulative fluxes, ranging from 0.09 to 2.06 kg N_2O-N ha^{-1}, with no particular fertiliser type consistently emitting more or less N_2O than the others (Table 4 & Fig. 3a).

During the 21-day period, EFs ranged from 0.01% to 1.43% of applied N, following a log-normal distribution. EFs from each event did not correlate significantly with mean soil moisture ($r = -0.012$, $R^2 = 0.0001$, $p = 0.96$) or soil temperature ($r = -0.228$, $R^2 = 0.05$, $p = 0.40$) during the trials. A positive relationship was observed between the quantity of N applied and EF ($R^2 = 0.39$, $p = 0.0096$), where EF increased as N quantity increased (Fig. 3b). The fitted relationship suggests an increase in EF with increasing N application rate, although the limited number of observations and confounding among experiments mean this relationship should be interpreted cautiously.

By compiling the currently available datasets of individual emission events from literature and reported values in this study, it is possible to derive a regional EF estimate for OP systems including both commercial and smallholder OP (Table 5 & Fig. 4). Using EFs reported for fertilisation events on OP grown in mineral soils in SEA (Table 5, as reported in Sakata et al. 2014, Aini et al. 2015, Hassler et al. 2017 and Rahman

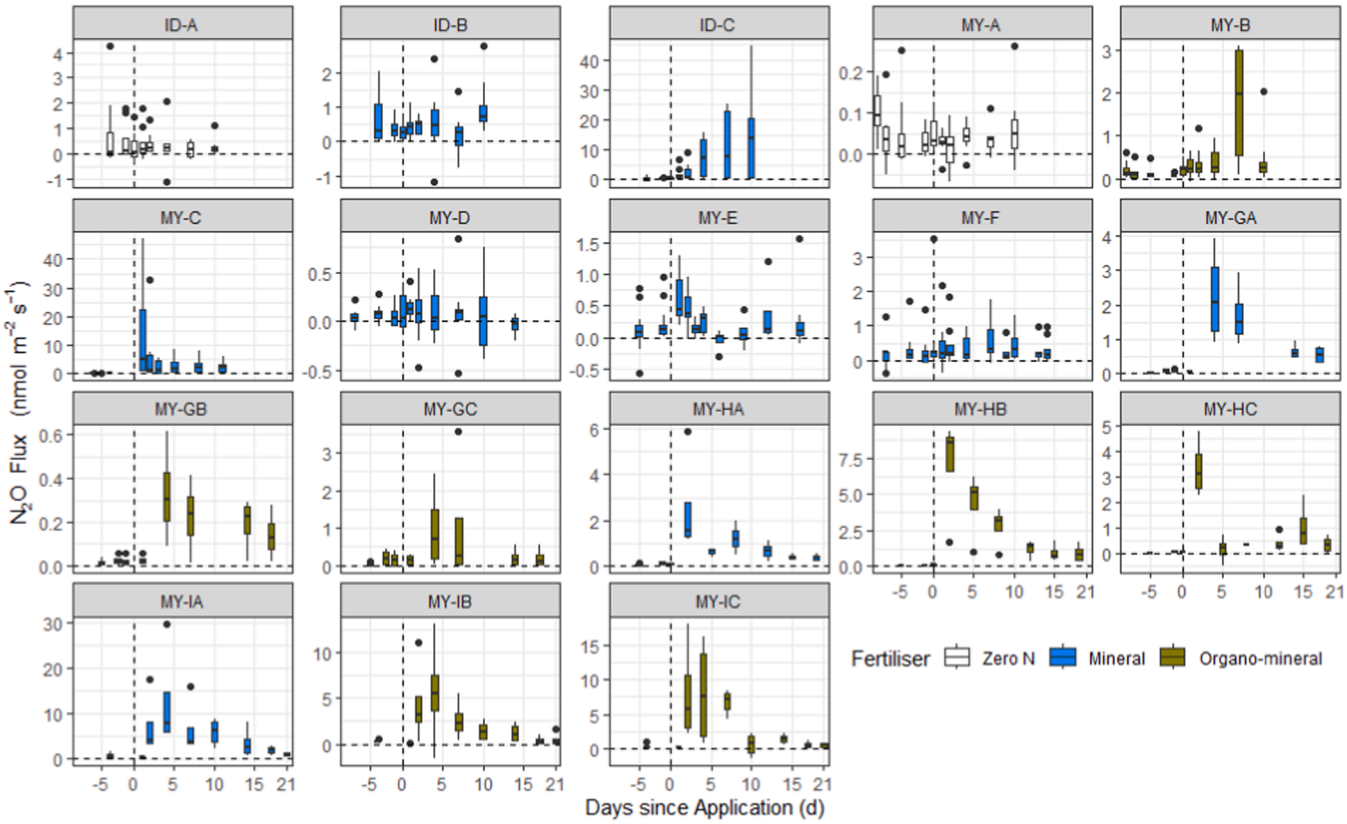


Fig. 2. N_2O flux measurements were carried out prior to and for up to 21 days after fertiliser application (vertical dashed line) during 18 different trial events). Boxplots and whiskers represent the median, 25th and 75 %iles of data on a daily basis.

et al. 2019) we can combine a total of 33 measured EFs over a variety of OP cropping conditions in SEA. Similarly to our own measurements, some EFs appear negative, essentially due to relatively high analytical noise in the comparisons between control (background) fluxes and the effect of fertiliser application. This data follows a log-normal distribution (Fig. 4a); thus, data should be treated using an appropriate analytical method (in this study, Zou's method).

To carry out this analysis, where negative data exists, all data was shifted into positive space by adding the minimum flux to all values (0.34), which was then subtracted from the calculated mean. It should be noted that while this method accounts for the log-normal distribution of the data, inclusion of negative values increases the sensitivity of analysis. To evaluate the robustness of the regional EF estimate, a sensitivity analysis was conducted using alternative data inclusion criteria and averaging approaches (Table 6). Calculated mean EFs ranged from 0.51% to 1.12% of applied nitrogen, highlighting the uncertainty associated with the limited number of available studies and the treatment of highly variable N_2O flux datasets. Nevertheless, the estimates remained broadly centred around the overall regional mean, suggesting that the derived EF is relatively stable despite differences in study inclusion and analytical approach. This range of calculated emission factors is consistent with, but typically lower than, the IPCC Tier 1 default value of 1% (IPCC 2019). Where the number of data points is small, the upper uncertainty in the mean of the log-normal distribution is poorly constrained by Zou's method, exceeding realistic constraints (e.g. > 100%).

4. Discussion

4.1. N_2O emissions and fertiliser-induced emission factors

The variability in EFs observed across the sites in this study is consistent with the broader literature on N_2O emissions from agricultural soils, where EFs are known to span orders of magnitude depending on environmental conditions and management practices (Stehfest and Bouwman, 2006; Shcherbak et al., 2014; Cowan et al., 2020; O'Neill et al., 2020). Although no statistically significant relationships were observed between EFs and soil moisture or temperature in this study, this does not imply that these variables are unimportant controls. Possible calibration issues may have prevented accurate soil moisture measurements in this present study. However, in humid tropical systems such as those studied here, soil moisture and temperature may often remain within ranges that are favourable for microbial activity for much of the year and will not be limiting factors as experienced in temperate climates (Flechard et al., 2007; Liengaard et al., 2013).

The positive relationship observed between EF and nitrogen application rate is consistent with previous studies demonstrating non-linear responses of N_2O emissions to nitrogen inputs. Meta-analyses have shown that N_2O emissions increase disproportionately at higher nitrogen application rates, reflecting saturation of plant nitrogen uptake capacity and increased availability of mineral nitrogen for microbial processes (Shcherbak et al., 2014; Hoben et al., 2011). The higher emission factors observed in some of the high-input treatments in this study (e.g. >1%) are potentially indicative of such non-linear behaviour. However, the limited number of observations constrains the ability to robustly quantify this relationship for OP systems specifically. The relationship between nitrogen applied and N_2O emission factor reported in this study suggests that there is a linear relationship between N applied and EF, such that EF $\approx$ 0.0046 multiplied by the N application rate (kg N ha^{-1}), minus an intercept of approximately −0.115 (effectively zero emissions until a threshold of 24 kg N ha^{-1} is applied). The observed relationship is consistent with the hypothesis that smaller, more frequent fertiliser applications could reduce N_2O emissions, although dedicated experiments would be required to test this directly.

Table 4
A summary of all mean N_2O fluxes pre- and post-fertiliser application and the associated effect on cumulative N_2O fluxes for the subsequent 21 days afterwards (21 Days Effect). All means and 95% C.I.s are estimated using Zou's method to account for log-normal data distributions. Emission factors are estimated as the % of nitrogen applied released as N_2O-N over the 21 days after nitrogen application.

Event	Nitrogen Applied (kg N ha^{-1})	N_2O Flux Background (nmol m^{-2} s^{-1})	N_2O Flux Post App (nmol m^{-2} s^{-1})	N_2O Flux 21 Days Effect (kg N_2O-N ha^{-1})	EF (%)
ID-A	0	0.52 (0.22–0.90)	0.33 (0.17–0.53)	-0.09 (-0.27–0.12)	NA
ID–B	138	0.45 (0.28–0.65)	0.57 (0.34–0.85)	0.06 (-0.09–0.23)	0.04
ID–C	276	0.35 (0.16–0.57)	7.31 (4.68–13.0)	3.54 (2.19–6.47)	1.28
MY–A	0	0.06 (0.04–0.08)	0.05 (0.03–0.06)	-0.01 (-0.02–0.00)	NA
MY–B	41	0.15 (0.11–0.20)	0.65 (0.44–0.90)	0.25 (0.14–0.38)	0.61
MY–C	149	0.09 (0.05–0.12)	4.27 (3.01–6.37)	2.13 (1.48–3.19)	1.43
MY–D	36	0.07 (0.03–0.12)	0.09 (0.01–0.17)	0.00 (-0.04–0.05)	0.01
MY–E	53	0.16 (0.07–0.27)	0.28 (0.20–0.38)	0.06 (-0.00–0.13)	0.12
MY–F	55	0.36 (0.18–0.56)	0.38 (0.28–0.49)	0.01 (-0.09–0.12)	0.02
MY–GA	146.6	0.08 (0.05–0.10)	1.15 (0.80–1.60)	0.55 (0.36–0.77)	0.37
MY–GB	149.3	0.02 (0.01–0.03)	0.19 (0.13–0.26)	0.09 (0.05–0.12)	0.06
MY–GC	149.3	0.13 (0.04–0.23)	0.57 (0.28–0.94)	0.22 (0.06–0.41)	0.15
MY–HA	146.6	0.09 (0.05–0.13)	0.96 (0.66–1.35)	0.44 (0.28–0.63)	0.30
MY–HB	149.3	0.05 (0.03–0.07)	2.82 (1.93–4.25)	1.41 (0.95–2.13)	0.94
MY–HC	149.3	0.05 (0.03–0.07)	1.01 (0.57–1.64)	0.49 (0.26–0.80)	0.33
MY–IA	194.5	0.61 (0.04–2.97)	4.67 (3.22–7.21)	2.06 (1.26–3.82)	1.06
MY–IB	198.0	0.27 (0.11–0.48)	3.31 (1.54–8.39)	1.55 (0.64–4.13)	0.78
MY–IC	198.0	0.08 (0.05–0.10)	1.15 (0.80–1.60)	1.90 (0.92–4.41)	0.96

However, with limited field data to provide further evidence of mitigation impact, it would be premature to attempt to scale EFs in the region based on this relationship. Further trials should be caried out to investigate if split applications are a valid greenhouse gas (GHG) mitigation strategy in the region.

The EF reported by the combination of results in this study with a pooled synthesis of literature values provides an EF of 0.82% of applied nitrogen (95% C.I.s 0.44–1.78%, n = 33) and is broadly consistent with, but slightly lower than, the IPCC Tier 1 default value of 1% (IPCC 2019). Our sensitivity analysis (Table 6) suggests that the mean EF of the available data is likely under 1%, though large uncertainty persists, especially in the upper bounds of these estimates. Notably, the study-weighted mean (0.87%) was similar to the event-weighted estimate (0.82%), suggesting that the regional EF estimate is not dominated by the large number of events contributed by any single study. Importantly, the IPCC default EF is derived largely from datasets dominated by temperate agricultural systems, particularly in Europe and North America, with limited representation of tropical cropping systems and no inclusion of OP cultivation (Stehfest and Bouwman, 2006).

While the dataset reported in this study enables improved estimation of a regional EF, it remains insufficient to resolve differences between fertiliser types, soil conditions, or management practices. Even after 33 events, the uncertainty in the mean of the log-normally distributed data set spans an order of magnitude. We have deliberately excluded EFs reported for OP grown on peatland soils due to the extreme nature of some of the data collected, with EFs occasionally exceeding 30% of applied N (Sakata et al., 2014; Chaddy et al., 2019; Oktarita et al., 2017). In the case of agricultural peatlands, it has been observed in long-term N_2O flux studies that the application of N occasionally has no immediate effect on emissions as mineralised N content in the soil is not a limiting factor in denitrification rates, and instead fluxes are controlled by environmental conditions (Cowan et al., 2025b), which may complicate the interpretation of conventional fertiliser EF experiments on peat soils.

4.2. *Uncertainty and limitations of N_2O flux estimates*

This study provides one of the more extensive field-based datasets of N_2O fluxes from smallholder OP systems in SEA; however, important methodological and data limitations remain. Measurements of fertiliser-induced N_2O emissions from smallholder OP systems in SEA remain scarce despite the regional importance of palm oil production. Collecting repeated chamber measurements using consistent methodology and timing across operational smallholder farms is logistically challenging because sites are geographically dispersed, management practices are determined by and enacted by farmers, and access to sites and technical resources are often more limited than in highly instrumented experimental research stations commonly used in similar types of experiments. Consequently, studies in these systems frequently involve trade-offs between measurement intensity, spatial coverage, and the practical realities of working within commercial smallholder farms. The approach adopted in this study sought to maximise the number of fertiliser application events and farms represented while maintaining a feasible monitoring programme across multiple countries and years.

A limitation of this study is that measurements were conducted within operational smallholder farms and did not include unfertilised control plots for comparison for each fertiliser application event. Fertiliser-induced emissions were therefore estimated relative to background fluxes measured before fertiliser application. While this approach enabled measurements to be collected across a larger number of farms and fertiliser events than would otherwise have been feasible, it increases uncertainty because changes in environmental conditions occurring during the monitoring period cannot be completely separated from fertiliser effects. Consequently, the resulting EFs are not derived from a typical controlled experimental design. Another limitation of the analysis is that cumulative emissions were estimated from mean fluxes rather than by trapezoidal integration between individual sampling dates (essentially a before and after for up to 21 days after fertiliser application). While trapezoidal integration can account somewhat for unequal sampling intervals, estimates from chamber-based N_2O measurements can also be strongly influenced by the treatment of highly skewed flux distributions (Levy et al., 2017). Additionally, cumulative measurements of N_2O flux from soils over the span of a year is highly sensitive to the relatively large measurement uncertainty of the measurement technique. Statistical noise from temporal integration of flux measurements can obscure the actual impact of nitrogen application, which is relatively short term (typically less than 1 month). Consequently, different analytical approaches may yield somewhat different event-scale emission factors, particularly when measurements are sparse and spatial variability is high.

Despite four years of coordinated field campaigns across multiple sites, the number of fertiliser application events captured remains relatively modest in comparison to the inherent spatial and temporal variability of N_2O flux. Nitrous oxide emissions from soils are highly episodic and driven by short-term interactions between nitrogen availability, soil moisture, oxygen status, and microbial activity, leading to large spatial and temporal variability even under relatively stable climatic conditions (Davidson et al., 2000; Butterbach-Bahl et al., 2013; Levy et al., 2017). Static chamber measurements, particularly when

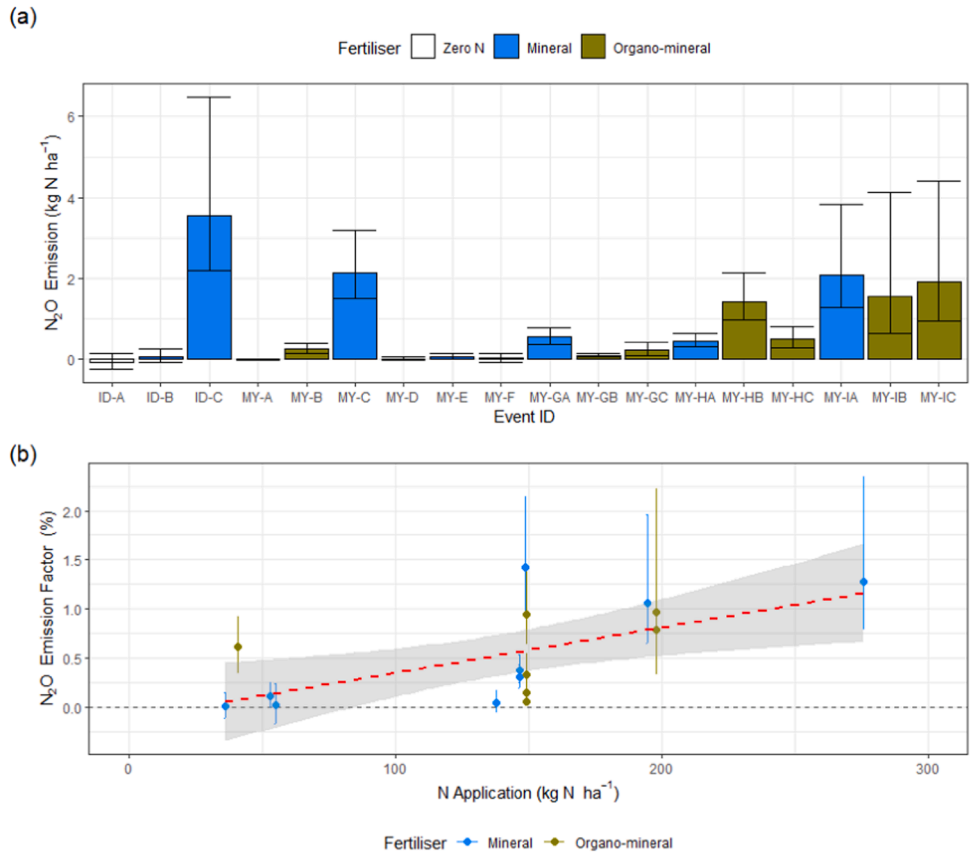


Fig. 3. Cumulative emission of N_2O (kg N ha^{-1}) were calculated over a 21-day period after fertiliser application for each of the 18 events where chamber measurements took place.

Table 5
A combination of all N_2O emission factors (EFs) reported in literature for nitrogen application to oil palm in the Southeast Asian region and the results from this study.

Publication	Reported N_2O EFs	Location	Duration
Sakata et al. (2014)	-0.33, −0.26, 0.49, 2.29	Riau Province, Indonesia Sarawak, Malaysia	Seasonal
Aini et al. (2015)	3.1	Jambi Province, Indonesia	Annual
Hassler et al. (2017)	0.2, 0.73	Jambi Province, Indonesia	Annual
Rahman et al. (2019)	0.02, 0.05, 0.10, 0.11, 0.14, 0.2, 0.28, 0.58, 2.44, 2.69	North Sumatra, Indonesia	Annual
This study	0.01, 0.02, 0.04, 0.06, 0.12, 0.15, 0.3, 0.33, 0.37, 0.61, 0.78, 0.94, 0.96, 1.06, 1.28, 1.43	Riau Province, Indonesia Perak, Malaysia	3 weeks

deployed during discrete campaigns, are unlikely to fully capture all short-lived emission peaks (sometimes lasting less than 24 h), which may contribute disproportionately to cumulative fluxes (Dorich et al., 2020; Levy et al., 2017; Zhang et al., 2024). As a result, even intensive chamber-based measurement strategies are unlikely to fully capture peak emission events, particularly under the logistical constraints associated with smallholder systems.

The use of log-normal statistical treatment and uncertainty propagation via Zou's method (Zou and Donner, 2007) provides a transparent method for extracting estimates from heterogeneous datasets; however, uncertainty arising from sampling frequency and spatial variability remains unavoidable in field-based studies of this nature. There also remains uncertainty regarding how to handle negative flux and emission factors when analysis is carried out using methods suited for log-normal datasets (which prevents the inclusion of negative data). In this study, data was "shifted" into positive space by adding a constant value to each data point (the smallest value in the dataset), then subtracting from the final mean estimated by Zou's method. In the case of EFs, small changes to the data distribution can alter estimated EFs significantly.

4.3. *Implications for greenhouse gas inventories and future research*

The absence of consistent differences in EFs between mineral and organic or organo-mineral fertilisers observed in this study is notable but should be interpreted cautiously. The lack of differences in direct field emissions does not imply equivalence in overall environmental impact. Organic amendments, particularly those derived from local waste streams, generally have lower upstream GHG emissions than synthetic fertilisers, which are energy-intensive to produce and transport (Brentrup et al., 2004; Hasler et al., 2015). Therefore, fertiliser management strategies should be evaluated within a full life-cycle framework to assess their mitigation potential. The results of this study also only measure direct N_2O emission from soils and does not account for secondary emissions such as those from ammonia volatilisation and dispersion or emissions from unfertilised areas between palm circles and nitrogen leaching into water streams, which are still poorly quantified (Sham et al., 2024; Silverthorn et al., 2025; Chang et al., 2026).

Additional measurements across a broader range of environmental and management conditions would be required to further constrain regional EF estimates. Detecting statistically significant differences in N_2O EFs between fertiliser types, or across soil types (e.g. textures, pH,

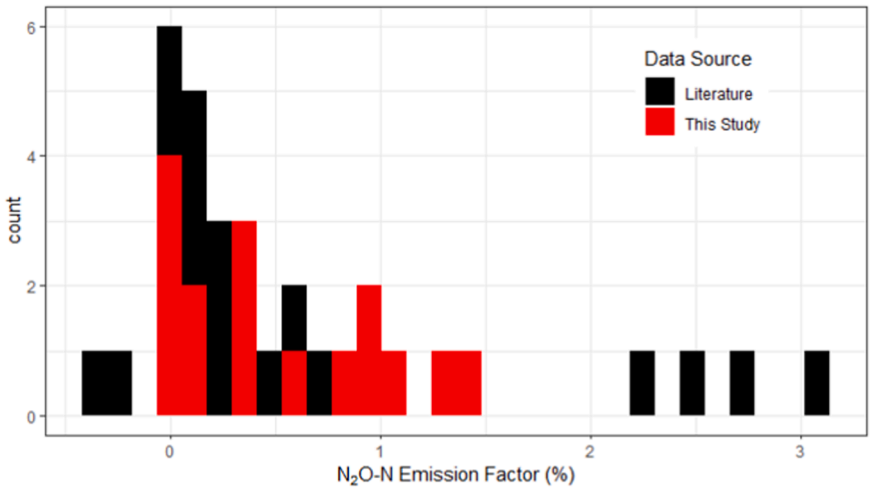


Fig. 4. A histogram of all EF data reported for nitrogen application in OP cropping in both reported literature and from the results of this study.

Table 6
Comparison of regional N_2O emission factor estimates obtained using different datasets and analytical approaches. Studies were excluded individually as a simple sensitivity analysis to explore the influence of individual datasets on the regional EF estimate.

Analysis	n	Mean EF % Arithmetic Mean	Mean EF % Zou's Mean
Mineral N (this study)	9	0.51 (0.32 – 0.71)	0.70 (0.22 – 121.22)
Organo-mineral (this study)	7	0.55 (0.41 – 0.69)	0.61 (0.29 – 7.11)
All Events	33	0.65 (-0.22–1.51)	0.82 (0.44–1.78)
Excluding this study	17	0.75 (0.48–1.02)	1.12 (0.38–6.85)
Excluding Aini et al.	29	0.57 (0.44–0.7)	0.73 (0.38–1.61)
Excluding Sakata et al.	29	0.66 (0.5–0.81)	0.82 (0.44–2.77)
Study Weighted Mean	4	0.66	0.87

carbon content), management practices and climatic conditions, would require a substantially larger number of independent fertiliser application events, possibly in the order of hundreds of replicated observations. Such an experimental effort would be extremely challenging to achieve in practice due to the high financial and logistical costs associated with chamber-based flux measurements, particularly across geographically dispersed smallholder landscapes. As a result, further refinement of EF values using traditional field chamber methods is likely to encounter diminishing returns. Future progress in this area will therefore likely depend on the adoption of alternative measurement approaches capable of capturing emissions at larger spatial and temporal scales. Techniques such as eddy covariance, long-term automated chamber systems, or emerging atmospheric monitoring approaches (e.g. tall tower networks or satellite observations, e.g. Haszpra et al., 2018) may provide opportunities to better constrain N_2O emissions and reduce uncertainty in EF estimates in the region. One study has been published to date using eddy covariance to measure N_2O emissions from OP crops (Stiegler et al., 2023). These approaches could complement, rather than replace, plot-scale measurements by providing continuous data streams and improved integration across heterogeneous landscapes.

One consideration when interpreting the EF derived in this study is that fertiliser inputs in these systems are overwhelmingly urea-based, whereas the datasets underpinning the IPCC default EF of 1% are dominated by temperate studies including the use of ammonium nitrate (AN) and calcium ammonium nitrate (CAN) fertilisers. Large syntheses of fertiliser EFs have demonstrated that application of ammonium nitrate typically produces higher N_2O emissions than urea, with mean EFs of approximately 1.0% compared to around 0.6% for urea-based fertilisers under temperate conditions (Cowan et al., 2020). The emission factor of 0.82% reported in this study therefore lies between these two estimates (with large overlap of uncertainties). This suggests that while OP systems may reflect the lower-emitting characteristics of urea-based fertilisation, emissions are enhanced relative to temperate systems where urea is applied, possibly due to the climatic and biogeochemical conditions of humid tropical soils that favour denitrification (warm, damp, carbon rich conditions) and thus emission of N_2O.

5. Conclusions

This study provides one of the largest field-based datasets currently available for quantifying fertiliser-induced N_2O emissions from OP systems in SEA, spanning twelve farms and eighteen fertiliser application events between 2022 and 2025. While the dataset captures a broad range of conditions representative of smallholder systems, the observational study design does not allow the independent effects of site, year, fertiliser type, and management practices on N_2O emissions to be disentangled. By combining these measurements with the limited body of published data from OP systems on mineral soils in SEA, we derived a regional emission factor estimate of 0.82% of applied nitrogen (95% C.I. 0.44–1.78%). Sensitivity analyses indicated that the estimated regional EF varies largely depending on the individual studies included and the analytical approach adopted, highlighting the continued uncertainty associated with quantifying fertiliser-induced N_2O emissions in the region. Nevertheless, the estimated EF lies broadly in line with the IPCC default value of 1% and provides a preliminary regional estimate based on the currently available field evidence. Additional measurements across a wider range of sites, years, soils and management conditions are required to further constrain this estimate and improve understanding of the factors controlling N_2O emissions from these systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Research Link Provided

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