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Substantial N₂O emissions from peat decomposition and N fertilization in an oil palm plantation exacerbated by hotspots

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Supplementary material for this article is available [online](#)

Abstract

It is unclear to what extent emissions of nitrous oxide (N₂O) from drained histosols in the tropics may contribute to the atmospheric burden of greenhouse gases. In particular, there is a critical need to elucidate their magnitude in oil palm plantations on these soils. We examined spatio-temporal variations of N₂O emissions from peat decomposition and nitrogen (N) fertilization in a plantation trial in Sumatra, which included three application rates: 0 (N0), 153 (N1) and 306 (N2) kg N ha⁻¹ y⁻¹. The spatially stratified sampling design distinguished the area around the palms which received fertilizer (9% of the surface) from the rest of the plot which was unfertilized. Annual emissions were substantial with rates of 22.1 ± 5.7, 12.8 ± 2.7 and 26.6 ± 5.7 kg N₂O-N ha⁻¹ in the N0, N1 and N2 treatments, respectively. These equal 9.3 ± 2.4, 5.4 ± 1.1 and 11.2 ± 2.4 Mg CO₂eq ha⁻¹ y⁻¹, or 5–10 times emission rates in natural peatland forest. The site exhibited two persistent hotspots located in the unfertilized zone, contributing 33 and 46% of annual emissions in N0 and N2 while representing only 10% of the area sampled. The response of emissions to fertilization was exponential but restricted to the small N application area. At the plot scale and over the year, the impact of fertilized-induced emissions was minimal due to the prevalence of emissions from peat decomposition. Annual rates among treatments were similar when discarding the contribution of hotspots to evaluate N addition effect. High N₂O emissions from peat decomposition in the tropics tend to be common within the restricted existing literature; which is in contrast with most recent IPCC emission factors. Our results emphasize the importance to integrate N₂O emissions in greenhouse gas budgets of plantations on peat, despite the predominance of CO₂ in total emissions.

1. Introduction

Agriculture contributes 10%–12% to worldwide greenhouse gas (GHG) emissions and 56% to global non-CO₂ GHG emissions (IPCC 2014, USEPA 2013). The emissions from this sector are mainly in the form of nitrous oxide (N₂O) (46%), followed by methane (CH₄) (45%) and CO₂ (9%). Nitrous oxide is classified as long-lived GHG and has a global warming potential 268 times higher than that of CO₂ over a 20 year time horizon and when including climate–carbon feedbacks (Myhre *et al* 2013). The atmospheric N₂O concentration in 2013 was 326 ppb, about 20% higher

than its pre-industrial value (IPCC 2014). N₂O emissions largely come from soil management including tillage and other cropping practices, such as fertilizer application (Baumert *et al* 2005). Emissions from synthetic fertilizers have increased more than nine-fold from 0.07 to 0.68 GtCO₂eq yr⁻¹ over the period between 1961 and 2010 (Tubiello *et al* 2013).

Oil palm is one of the most rapidly expanding crops in the tropics (Fitzherbert *et al* 2008). Malaysia and Indonesia began to dominate oil palm production in 1966 (Poku 2002) and Indonesia has been the largest producer of crude palm oil since 2005. In 2006 the country had 4.1 million ha of oil palm plantations

or 31% of the global plantation area, 7.2 million ha in 2010 and around 10.5 million ha in 2013 (Koh and Wilcove 2008, Bromokusumo and Jonn 2010, MoA 2014). This trend is likely to continue in the future as Indonesia aims at doubling palm oil production by 2020 (Koh and Ghazoul 2010). Plantations have been and are often developed on forestlands and conversion of primary forests into oil palm plantations accounted for more than 10% of the deforestation in Indonesia and Malaysia between 1990 and 2010 (Koh *et al* 2011) causing large biodiversity losses and contributing substantially to climate change (Hergoualc'h and Verchot 2011, Verchot *et al* 2012, Wijedasa *et al* 2017). At the same time, palm oil, is a key contributor to Indonesian economic growth, is an important source of edible oil for many countries, is used as a source of alternative fuel (Sheil *et al* 2009), and generates economic benefits for rural people (Sayer *et al* 2012). The Indonesian government allows the development of oil palm plantations on marginal lands such as peatlands; however, it forbids plantation on peat soils that are deeper than 3 m (RSPO 2012). Furthermore, oil palm is allowed to be grown only on sapric and hemic peat which have higher nutrient contents than fibric peat. A moratorium established in 2011 by the government of Indonesia and supported by Norway has put in place restrictions to halt the issuance of new licenses on primary forests and peatlands. Yet expansion in these areas is likely to continue, particularly for lands not included in the moratorium map and if economic incentives for environmental services such as carbon sequestration remains low while demand for palm oil continues to grow (Murdiyarso *et al* 2010, 2011, Koh *et al* 2011). In 2010 around 14.6% (1.2 million ha) of Indonesian oil palm plantations were established on peatlands, with the majority (85%) located in Sumatra (Miettinen *et al* 2012, MoA 2014).

Peat is considered to be a poor soil due to acidic conditions and limited nutrient availability (Murdiyarso *et al* 2010, Sabiham 2010), except for nitrogen which is high (Mutert *et al* 1999). Therefore N fertilizer for oil palm cultivated on peat is recommended to be applied at a lower rate than for cultivation on mineral soils (von Uexkull 2016). Notwithstanding, the fertilizer rate is high compared to rates applied to other major crops in Indonesia (Firmansyah 2010). Common nitrogen fertilizer doses for oil palm cultivated on peat in West Malaysia range from 50–100 N kg ha⁻¹ y⁻¹ for immature palms to 120–160 kg N ha⁻¹ y⁻¹ for mature ones (Mutert *et al* 1999) while in Indonesia application rates average 136, 170 and 102 kg N ha⁻¹ y⁻¹ for 3–8, 9–13 and 14–25 year old plantations, respectively (Darmosarkoro *et al* 2003). The addition of fertilizer to promote palm productivity is likely to foster peat mineralization and stimulate soil CO₂ and N₂O emissions (Hergoualc'h and Verchot 2014, Comeau *et al* 2016). Recent studies suggested an exponential increase in soil N₂O

emissions with increasing N fertilizer application rates especially when these exceed crop needs (Shcherbak *et al* 2014, van Lent *et al* 2015). On the other hand, the IPCC default emission factor is linear and amounts to 1% of the mineral fertilizer added (De Klein *et al* 2006). The direct emissions driven by peat mineralization were set by the IPCC at 1.2 kg N ha⁻¹ y⁻¹ for drained organic soils cultivated with oil palm (Drösler *et al* 2014).

The production and consumption of N₂O in soils is mainly the result of microbial nitrification and denitrification activity (Smith *et al* 1982). Nitrification is the aerobic oxidation of ammonium (NH₄⁺) to nitrate (NO₃⁻) and denitrification is the anaerobic reduction of nitrate (NO₃⁻) to dinitrogen (N₂). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately to the atmosphere (Bouwman 1998, Smith *et al* 2003). Among the main controlling factors of the flux are soil water content, temperature, and nitrogen availability (Verchot *et al* 2006). Soil water and more specifically the water-filled pore space (WFPS) is a key indicator of oxygen availability in soils and has an important effect on N₂O emissions because denitrification requires anaerobic conditions (Butterbach-Bahl *et al* 2013). The optimum WFPS for soil N₂O emissions under tropical climates was estimated to be around 60% but emissions can remain high at values of 80% (van Lent *et al* 2015). Denitrification is known to be extremely temperature sensitive as are N mineralization and nitrification, albeit to a lower extent than denitrification (Butterbach-Bahl *et al* 2013). The magnitude of *in situ* N₂O emissions variation associated with temperature changes may however remain low in the tropics wherever diurnal and seasonal fluctuations are limited.

Studies reporting soil N₂O emissions from oil palm plantations are few (Melling *et al* 2007, Aini *et al* 2015, Sakata *et al* 2015, Hassler *et al* 2017) and some are based on very short sampling periods (Ishizuka *et al* 2005, Banabas 2007, Fowler *et al* 2011). Aini *et al* (2015) observed highly elevated emission rates following N fertilization in a plantation cultivated on mineral soil in Jambi, Sumatra. The studies by Melling *et al* (2007) and Sakata *et al* (2015), both carried out in Sarawak, Malaysia, are the only ones that were conducted in oil palm plantations on peat. However none of them spatially stratified the emissions according to fertilizer application practices. Neither did they capture the magnitude and dynamics of emissions following fertilizer application. As a consequence these studies did not differentiate fertilizer-induced emissions from those stemming from peat decomposition.

In this context, we set main objectives for this study to investigate N₂O emissions from peat decomposition and fertilizer application in an oil palm plantation and to assess how different doses of N

Table 1. Rate of fertilization applied in the N1 treatment of the oil palm plantation on peat, Jambi, Sumatra, Indonesia.

Age of palms (months)	Fertilization rate			kg N ha ⁻¹ y ⁻¹
	Year	Month	g urea palm ⁻¹	
3	2010	March	100	21
9		September	200	
15	2011	March	300	48
21		September	400	
27	2012	March	750	103
34		October ^a	750	
40	2013	April ^a	1500	103

^a Fertilizations during which intensive sampling was carried out.

fertilizer affect the emission rate. We evaluated the annual long-term response to N application and the short-term response immediately following the fertilization events. In order to get an understanding of the biochemical processes underlying the emissions the key environmental variables controlling N₂O emissions i.e. temperature, water table level, soil WFPS, mineral N content, and N mineralization and nitrification rates were monitored concomitantly with the fluxes.

2. Materials and methods

2.1. Site description

The study was conducted at an oil palm plantation located at Arang-Arang, Jambi district, Sumatra, Indonesia (1°38' S, 103°54' E). Long-term records from the Sultan Taha airport station in Jambi indicate an average annual air temperature of 26.5 °C during 1989–1997 and an average annual rainfall of 2466 mm y⁻¹ during 1951–1997. The driest months usually occur from June to August (Siderius 2004). The peat at the research site is deep (>8.5 m) and has been classified as Folic Hemic Histosol dystic drainic following the IUSS Working Group WRB (2006) classification (Comeau *et al* 2013). The site was cleared of native vegetation by fire in 2004 and planted in December 2009 at a density of 149 palms ha⁻¹ (8.8 m between palms in a triangular design). Additional land clearing fires may have taken place between first clearance and planting, but there are no records. The peat surface at the site is relatively flat as a result of compaction during land preparation. The water table depth is managed through a drainage system to be maintained at 60 cm below the soil surface; a level suitable for oil palm growth. Primary drainage canals are deep (>400 cm), secondary and tertiary canals are about 150 and 75 cm deep, respectively.

2.2. Experimental plots

The plots were located within a 11.7 ha long-term fertilization trial (see figure S1 in the supplementary material available at stacks.iop.org/ERL/12/104007/mmedia) using a 3³ × 2 factorial design that included three doses of urea (N0-N1-N2), three doses of rock

phosphate (P0-P1-P2), three doses of KCl (K0-K1-K2) as main treatments, plots were split with two doses of crushed limestone (Ca0-Ca1). In order to isolate the effect of N application, the three plots selected for this study all received the same applications of P (1 kg P palm⁻¹ y⁻¹ as rock phosphate), K (1.5 kg K palm⁻¹ y⁻¹ as KCl) and Ca (no application). These rates are consistent with current industry practices. Each plot corresponded to an N treatment as follows: The N0 plot received no N fertilizer and the N1 and N2 plots received an N application rate that gradually increased with the age of the palms until they reached maturity (table 1). The N2 dose was the double of the N1 dose; the latter treatment is representative of present industry practices. The palms received fertilizer for the first time 3 months after planting. They were fertilized twice a year in March/April and September/October until they reached full production at about 3 years. Afterwards, they were fertilized once a year in April.

2.3. Sampling design and soil flux measurement

The soil N₂O fluxes were measured monthly from October 2012 until September 2013. They were sampled more intensively following the 2 N fertilization events that took place on 23 October 2012 and 18 April 2013. Other nutrients were brought separately at different dates. During these events gas samples were collected 1 day before fertilization (d - 1), the day of the fertilization (d), daily during 1 week after fertilization (d + 1 - d + 7) and then every 2 d until d + 29. Thus in total, there were 19 measurement days over a 30 day fertilization period during both intensive sampling campaigns. Flux data were collected in the field between 9 am and 2 pm. Previous work on the site showed no diurnal variation in soil trace gas fluxes (Comeau *et al* 2014) however for precaution and with the objective to capture any potential diurnal variability the order of plot sampling was randomized.

During the fertilization applications, urea was homogeneously spread by hand within a 1 m radius around the trunk of the palms in the N1 and N2 treatments. In the first fertilization experiment the fertilizer was applied as granules, whereas in the second one the granules were dissolved in distilled water before being applied to the soil in order to

minimize N volatilization. We made a distinction in our sampling design between the area close to the palms (CP) which received fertilizer and the area further from the palms (FP) where fertilizer was not applied, as this application method is commonly practiced in oil palm plantations. The CP area consisted of a 1 m radius circle around a palm (on average 6.2 m² including the palm basal area) from which was subtracted the palm basal area (0.5 m² on average). Considering that the triangular planting design was perfectly equilateral, we estimated that the CP and FP areas represented, respectively, 9 and 91% of each plot area. The fertilization rate applied to the chambers located in the CP area of the N1 and N2 treatments was calculated as the surface ratio between the chamber and CP multiplied with the rate applied to the CP area. The same spatial stratification as in N1 and N2 was implemented in the N0 treatment although this plot did not receive N fertilizer; to account for root effects.

Soil fluxes were measured by the static chamber technique (Verchot *et al* 1999) using opaque white PVC chambers (diameter and height of 26 cm and 30 cm, respectively). Five replicate chambers were permanently installed at each position (CP and FP) in each N treatment plot. These were inserted into the soil to a 2–3 cm depth, 1 month before the first data collection. Chambers in the CP area were located at a 50 cm distance from the trunk of the palm while in the FP area chambers were located at mid-distance between two palms (following the design by Aini *et al* (2015)). The procedures for gas sampling, analysis and flux computation are presented in section S.1.1. of the supplementary material.

Cumulative emissions for each fertilization period (October 2012 and April 2013) were calculated using data from the day of fertilizer application until 29 d after fertilization, for a total of 29 d. For each spatial position in each N treatment cumulative annual and post-fertilization emissions were computed by linear interpolation between measurement dates. Cumulative emissions over the 344 day monitoring period were annualized by considering 365 days in a year. Cumulative emissions outside of fertilization periods were calculated by subtracting the two post-fertilization cumulative emissions from the annual emissions. The N₂O fluxes were further extrapolated to the plot scale using the proportion occupied by each area (9% CP and 91% FP) in the plot. Emissions of N₂O were converted to CO₂eq using the factor 268, which corresponds to a global warming potential over a 20 year time horizon including climate–carbon feedbacks from Myhre *et al* (2013). A 20 year time horizon was preferred over a 100 year time horizon given the 25 year rotational period of oil palm plantations.

2.4. Environmental parameters

Rainfall was monitored daily while air pressure, air temperature, soil temperature, soil moisture and water

table level data were collected concomitant with N₂O measurements. Root density and soil properties including pH, C and N content, available P, base saturation, CEC and bulk density were analyzed at the end of the experiment. Information on sampling methods, analytical methods and instruments used is available in section S.1.2. of the supplementary material.

2.5. Nitrogen availability

N availability was determined by measuring inorganic N pools and the rates of net mineralization and nitrification in February 2013—in the absence of fertilization and in April 2013—following the fertilization. Soil sampling and incubation methods are described in section S.1.3. of the supplementary material.

2.6. Statistics

Statistical analysis was performed with the SPSS software v.19, with a probability level of 5% to test the significance of treatments effects. Methods used for comparing treatments, spatial positions and periods and for establishing relationships between variables are described in section S.1.4. of the supplementary material.

Identification of emission hotspots was conducted using boxplot analysis (SPSS v.19 SPSS Inc. USA). A chamber was qualified as a hotspot whenever it displayed over the measurement period at least three extreme flux values (i.e. values > three times the interquartile range from the upper edge of the 50% percentile; van den Heuvel *et al* (2009)). The analysis was performed using emission rates measured outside of fertilization periods in order to not confound between spatial and temporal hotspots.

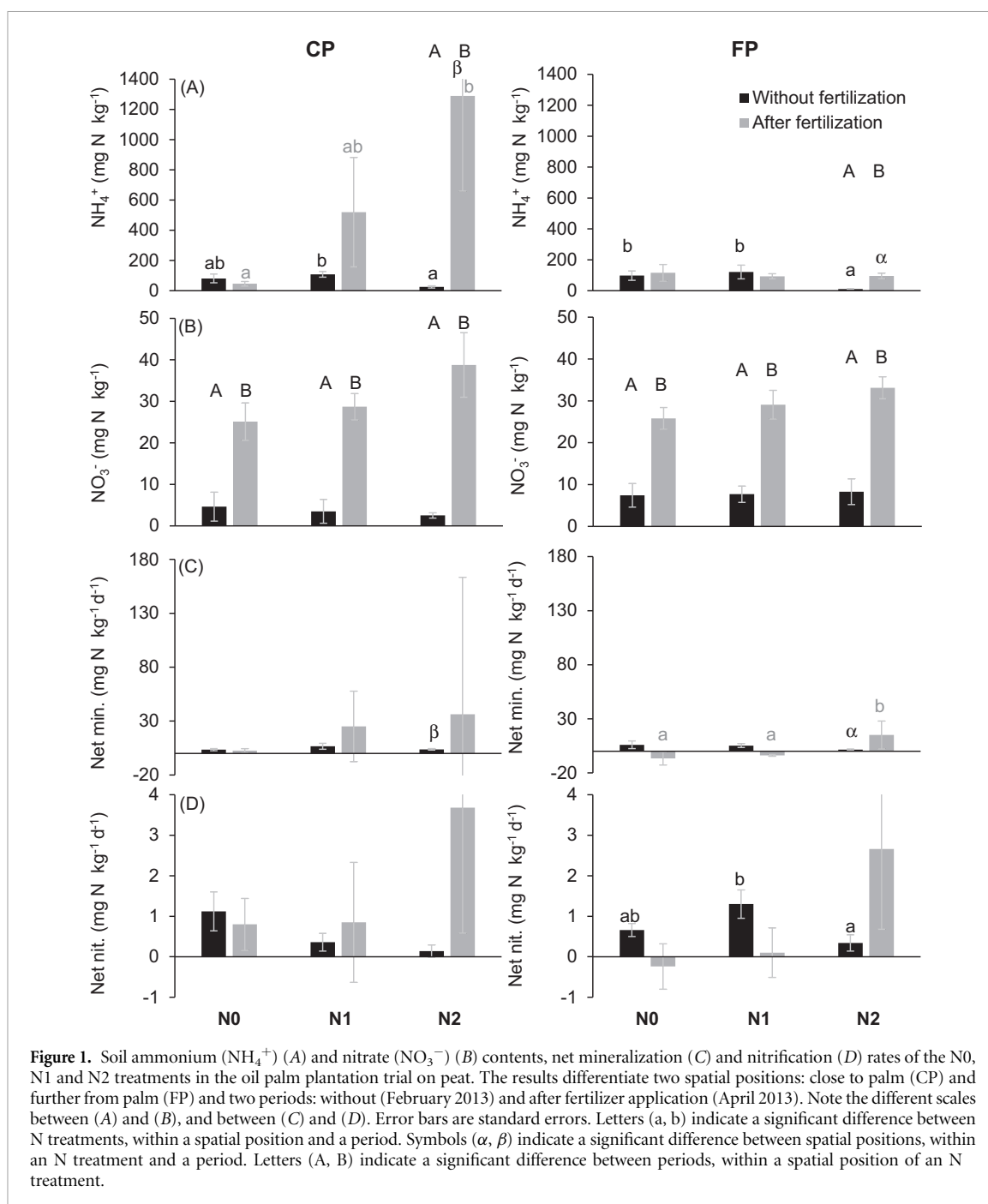
3. Results

Soil properties and climate results are available in section S.2. of the supplementary material.

3.1. Soil nitrogen concentrations, mineralization and nitrification rates

Inorganic-N pools were dominated by NH₄⁺ in all N treatments ($P < 0.007$), at both spatial positions ($P < 0.0001$) and during the 2 observation periods (February, absence of fertilization and April, after fertilization) ($P < 0.03$) (figures 1(A) and (B)). Net mineralization rates were higher than nitrification rates ($P = 0.03$) (figure 1(C) and (D)).

Soil NH₄⁺ content without fertilizer application was overall high (74 ± 19 mg N kg⁻¹ on average). It was significantly lower in the N2 than in the N1 treatment in the absence of fertilization at both spatial positions (figure 1(A)). Following the fertilization, the concentration was significantly higher in the N2 than in the N0 treatment at the close to palm (CP) position



whereas it was similar between treatments at the further from palm (FP) position. After fertilizing NH_4^+ content was significantly higher at the CP than at the FP position in the N2 treatment only. The comparison between the incubations of soils without and with fertilizer indicated that in N2 NH_4^+ content was significantly higher with than without fertilizer not only in the CP area where the fertilizer was applied but also in the FP area. This suggests urea leakage from the CP to the FP area in the N2 treatment.

Soil NO_3^- contents were systematically and significantly higher with fertilizer application than without it (figure 1(B)). The fact that this was true regardless of the spatial position or the N treatment likely indicates a seasonal rather than a fertilization effect.

The net mineralization rate was significantly higher close to palm than further from palm in the N2 treatment, in the absence of fertilizer application (figure 1(C)). Following fertilizer application the net mineralization rate was higher in N2 than in N0 and N1 in the FP area. Contrary to the observations from incubations without fertilizer, N was immobilized following fertilizer application in the FP area of the N0 and N1 treatments whereas the opposite happened for the N2 plot. The difference between the N2 and the other treatments arise from one single chamber displaying a net N mineralization rate 30 times higher than the average rate from the other chambers in the same area, albeit with an initial mineral N content similar to other chambers.

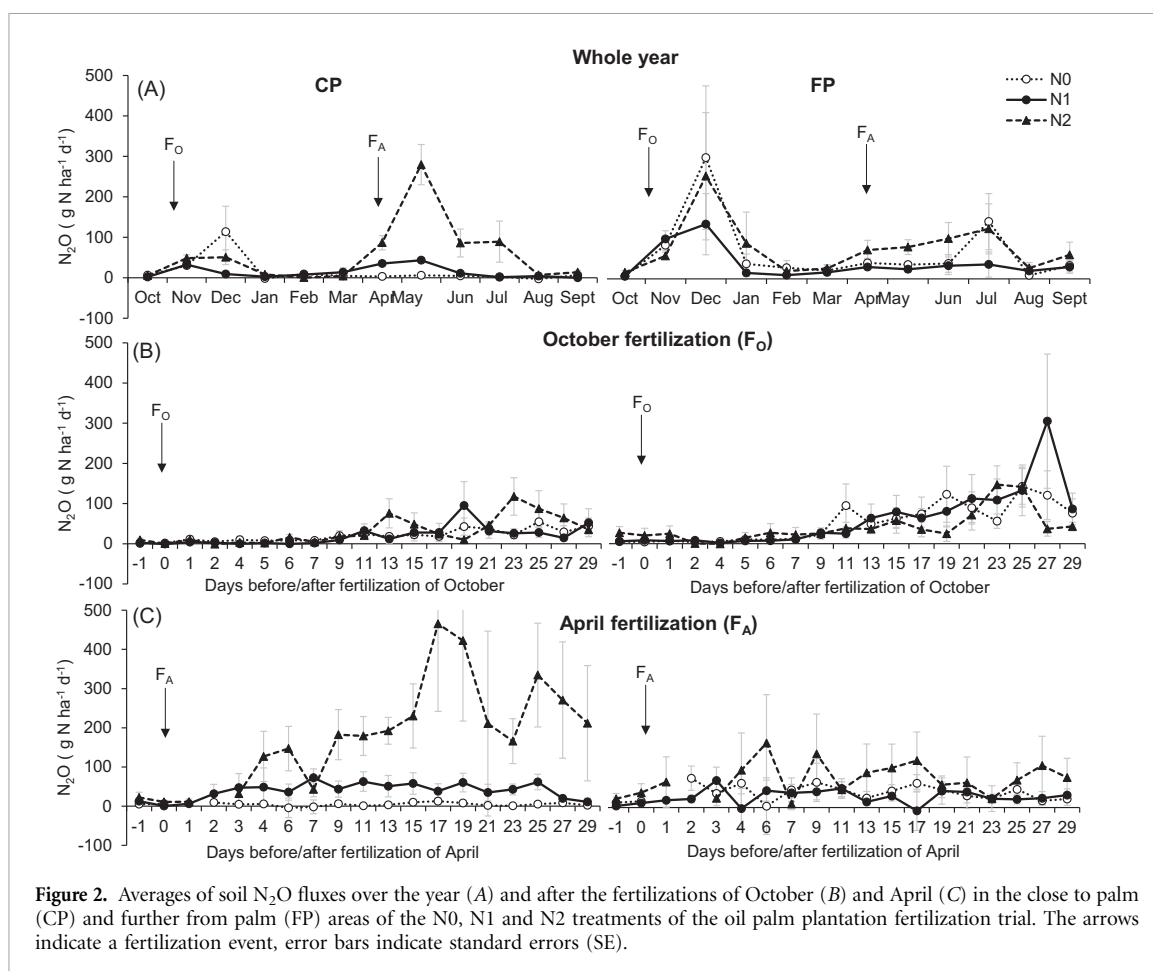


Figure 2. Averages of soil N_2O fluxes over the year (A) and after the fertilizations of October (B) and April (C) in the close to palm (CP) and further from palm (FP) areas of the N0, N1 and N2 treatments of the oil palm plantation fertilization trial. The arrows indicate a fertilization event, error bars indicate standard errors (SE).

The rate of nitrification also displayed a significant difference between treatments, but only at the FP position, with a lower value in the N2 plot as compared to the N1 one (figure 1(D)).

3.2. N_2O emissions

The emissions of N_2O are first presented outside of fertilization periods and correspond to emissions associated with peat decomposition. Second we present the emission rates during the 29 d following the October (23/10–21/11/2012) and April (18/4–15/5/2013) fertilizations; emissions which are from peat decomposition plus the fertilizer. Third, the cumulative emissions are detailed per spatial position including and excluding the contribution of hotspots.

3.2.1. Emissions outside of fertilization periods

Monthly averages of soil N_2O emissions in the CP and FP areas all together were in the range $-3 \pm 4 \text{ g N ha}^{-1} \text{ d}^{-1}$ (N0_{CP} in August) to $296 \pm 114 \text{ g N ha}^{-1} \text{ d}^{-1}$ (N0_{FP} in December) with very high spatial and temporal variability (figure 2(A)). December was the month displaying the highest average emission rate across treatments and areas followed by July, while October (before fertilizing) exhibited the lowest emission rate. The N2 treatment emitted N_2O at a significantly higher rate than the two other treatments in the CP area ($P=0.004$; table 2). It also emitted at a higher rate than the N1 treatment in the FP area

($P=0.049$). In all treatments the emissions were significantly ($P < 0.02$) higher FP than CP, by a factor of more than 2.

Through the boxplot analysis, two chambers were identified as being emission hotspots. Both of them were located FP, one was in the N0 treatment, the other was in the N2 treatment. These hotspots emitted at an average rate (135.3 ± 94.3 and $200.5 \pm 69.4 \text{ g N ha}^{-1} \text{ d}^{-1}$ in N0 and N2, respectively; figure 3) four and six times higher than the average rate from the other chambers in the FP area of their respective treatment (table 2). The common feature of the two hotspots was linked to an index of N availability. They displayed net mineralization rates much higher than that of all other chambers in the same area and treatment. The rate for the N0 hotspot in the absence of fertilization ($17.1 \text{ mg N kg}^{-1} \text{ d}^{-1}$) was five times higher than the average rate of the other chambers located FP ($3.2 \pm 2.8 \text{ mg N kg}^{-1} \text{ d}^{-1}$). The rate for the N2 hotspot following fertilizer application ($66.5 \pm 2.8 \text{ mg N kg}^{-1} \text{ d}^{-1}$) was, as already mentioned in section 3.1, 30 times higher than the other FP chambers average ($2.2 \pm 0.7 \text{ mg N kg}^{-1} \text{ d}^{-1}$).

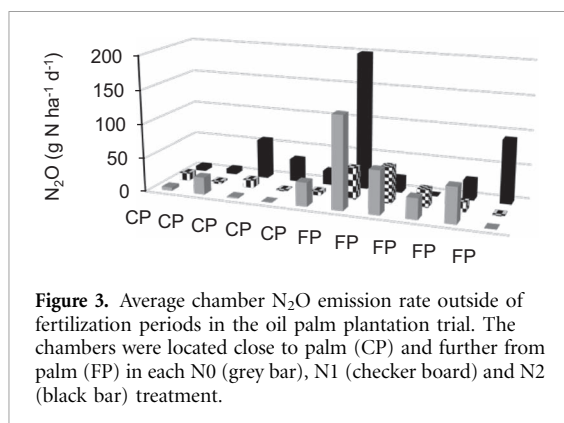
3.2.2. Post-fertilization emissions

During the post-fertilization period of October, soil N_2O emissions increased with time in both areas of all treatments ($P < 0.0001$) (figure 2(B)). This increase was associated with rainfall starting on day 3 after fertilizer application and intensifying towards the end of the

Table 2. Average and cumulative annual N_2O emissions \pm SE outside of fertilization periods (307 d) and during the two post fertilization periods (29 d each) in the N treatments of the oil palm plantation fertilization trial. Emission rates are presented for each spatial position (CP: close to palm; FP: further from palm) and at the plot scale (i.e. 91% N_2O_{FP} + 9% N_2O_{CP}). Emission rates without the contribution of the hotspots in N0 and N2 are displayed.

	Average emission rate ($g\ N\ ha^{-1}\ d^{-1}$)						Annual emission rate ($kg\ N\ ha^{-1}\ y^{-1}$)					
	Outside fert.		Post fert. October		Post fert. April		Per spatial position	Plot-scale	Plot-scale no hotspot			
N0 CP	13.2 \pm 6.9	a α	21.4 \pm 3.2	a α	4.6 \pm 2.0	a α	5.7 \pm 2.0	a α	22.1 \pm 5.7	b	14.7 \pm 3.3	a
FP	54.9 \pm 19.5	ab β	53.1 \pm 8.4	β	38.2 \pm 6.6	β	23.7 \pm 6.2	b β				
FP no hotspot	36.6 \pm 10.6	β	32.7 \pm 5.1	α	21.4 \pm 5.4	β	15.6 \pm 3.6	a β				
N1 CP	6.5 \pm 1.5	a α A	20.6 \pm 4.9	a α B	40.7 \pm 5.1	b C	4.8 \pm 0.9	a α	12.8 \pm 2.7	a		
FP	27.1 \pm 8.6	a β A	62.6 \pm 13.0	β B	27.5 \pm 5.2	A	13.6 \pm 2.9	a β				
N2 CP	25.2 \pm 6.9	b α A	31.1 \pm 5.5	b A	200.9 \pm 30.9	c β B	19.3 \pm 3.8	b α	26.6 \pm 5.7	b	14.5 \pm 3.8	a
FP	67.6 \pm 18.3	b β	40.1 \pm 6.2		78.0 \pm 15.4	α	27.3 \pm 6.3	b α				
FP no hotspot	34.4 \pm 10.9	α	25.7 \pm 4.7		24.2 \pm 5.1	α	14.0 \pm 4.1	a α				

Letters (a, b, c) indicate a significant difference between N treatments, within a spatial position and a period. Symbols (α , β) indicate a significant difference between spatial positions, within an N treatment and a period. Letters (A, B, C) indicate a significant difference between periods, within a spatial position of an N treatment. In the absence of a significant difference no letters are displayed. n is about 55 outside of fertilization periods, 90 during post-fertilization periods. Cumulative emission rates are based on 47 sampling days.



monitoring period (figure S3 in the supplementary material). The water table level also significantly increased as the result of rainfall ($P=0.0005$). The emissions peaked once 19 d after fertilization in the CP area of the N1 treatment; they peaked twice 13 and 23 d after fertilization in the CP area of the N2 treatment. At this spatial position the average emission rate in the N2 treatment was significantly higher than in the two other treatments (table 2). The punctually high emission rates observed in the FP area of the N0 treatment were essentially due to the hotspot chamber emitting at rates $> 250\ g\ N\ ha^{-1}\ d^{-1}$ on d + 11, + 19, + 25 and + 27. Over the post fertilization period this hotspot emitted at a rate ($134.8 \pm 30.2\ g\ N\ ha^{-1}\ d^{-1}$) four times higher than the average rate of other chambers in the same area and treatment (table 2). The same occurred in the FP area of the N2 treatment where the hotspot mainly was at the origin of the large emissions and emitted at a rate ($96.2 \pm 18.9\ g\ N\ ha^{-1}\ d^{-1}$) four times that of the average rate of other chambers in the same area and treatment (table 2). The peak observed on d + 27 in the FP area of the N1 treatment may come from fertilizer leakage from a chamber located

CP to its neighbor located FP. The emission rate in the FP area was not significantly different between treatments. Following the trend observed outside of fertilization periods soil emissions of N_2O were significantly higher FP than CP in the N0 ($P=0.009$) and N1 treatments ($P=0.0002$) whereas this wasn't the case in the N2 treatment ($P=0.24$).

During the post-fertilization period of April the rainfall pattern was erratic as was the pattern in soil WFPS and water table level, especially in the first 15 d following the fertilization for this last variable (figure S3 in the supplementary material). Soil emissions of N_2O remained steady in the CP area of the N0 treatment while in the same area of the N1 and N2 treatments the emissions started increasing as of d + 2 following fertilizer application reaching extremely high average rates in the N2 treatment (figure 2(C)). The average emission rate in the CP area was significantly different between each treatment, following the order $N2 > N1 > N0$ ($P < 0.0001$; table 2). In the FP area the average emission rate was similar across treatments. The hotspots emitted at rates (100.5 ± 16.7 and $276.1 \pm 42.3\ g\ N\ ha^{-1}\ d^{-1}$ in N0 and N2, respectively) 5 and 11 times higher than the rate from other chambers in the same area (table 2). Soil emissions of N_2O were significantly higher in FP than in CP in the N0 treatment; while the opposite was observed in the N2 treatment ($P < 0.0001$). There was no difference in emission rate between the two spatial positions in the N1 treatment ($P=0.19$).

The fertilization rates applied to the N1 and N2 treatments during the fertilization of April 2013 were twice the rates applied during the fertilization of October 2012 (table 1). As a consequence soil average N_2O emission rates in the CP area were significantly higher during the second than during the first fertilization in both treatments ($P < 0.0001$) (table 2).

Table 3. Relationships between soil fluxes of N₂O and soil and environmental variables either across N treatments, or within N treatments (N0, N1, N2) or spatial position (CP: close to palm; FP: further from palm). The models are presented with slope (SE) and intercept (SE) with their level of significance.

Dataset	Model	R ²	n	Equation
Cumulative emissions over post fertilization periods	$N_2O_{CP} = 0.3268^{**} (0.0687) \times \exp [0.0131^{***} (0.001) \times N_{\text{applied}}]$	0.99	6	(1)
Average per spatial position, daily time step except during the April fertilization ^a	$N_2O = 13.81^* (5.77) \times \text{Nit} + 40.49^* (12.5) \times \text{SoilT} + 0.12^{***} (0.02) \times \text{NH}_4^+ - 1138^* (352)$	0.95	12	(2)
Average per spatial position, annual time step	$N_2O = -6.8^* (1.5) \times \text{C:N} - 282.5^* (51.7)$	0.84	6 6	(3)
	$N_2O = 110.5^* (29.6) \times N_{\text{content}} - 151.0^* (53.2)$	0.78		(4)
All chambers, daily time step except during the April fertilization ^a	$N_2O_{FP} = 2.37^{***} (0.56) \times \text{Min} + 25.83^{**} (8.05)$	0.39	30	(5)
	$N_2O_{FP} = 11.88^* (4.43) \times \text{Nit} + 23.08^* (9.67)$	0.20	30	(6)
	$N_2O = 0.06^{***} (0.02) \times \text{NH}_4^+ + 25.46^{**} (9.00)$	0.22	59	(7)
	$N_2O = 10.14^{**} (3.38) \times \text{Nit} + 28.65^{**} (9.39)$	0.14	59	(8)
Average per spatial position, daily time step	$\text{Ln}(N_2O + 9)_{N2} = 0.04^{***} (0.01) \times \text{WT} + 6.15^{***} (0.50)$	0.23	66	(9)
	$\text{Ln}(N_2O + 9)_{N1} = 0.02^{**} (0.01) \times \text{WT} + 4.56^{***} (0.37)$	0.11	68	(10)

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. Soil N₂O fluxes are expressed in g N ha⁻¹ d⁻¹ except for the relationship for cumulative emissions over the post-fertilization periods for which the unit is kg N ha⁻¹ 29 d⁻¹. N_{applied} is the amount of fertilizer applied i.e. 0, 52, 105 kg N ha⁻¹ in N0, N1 and N2 in October; 0, 100, 223 kg N ha⁻¹ in the same treatments in April.

^a Since soil mineral N content, mineralization and nitrification rates were measured once during the post fertilization of April, the other variables were averaged over the 29 d following fertilizer application for the purpose of relationship testing. Soil NH₄⁺ contents are in mg N kg⁻¹ d.m., net nitrification (Nit) and mineralization (Min) rates in mg N kg⁻¹ d.m. d⁻¹, soil temperature (SoilT) in °C, water table level in cm with a negative value indicating that the water is below ground.

The average N₂O emission rates in the FP area were, on the other hand, similar during both fertilization periods in the N0 and N2 treatments.

3.2.3. Annual emissions

Plot-scale soil annual N₂O emissions were remarkably high in all treatments (table 2). They were similar in the N0 and N2 treatments and lower in the N1 treatment. This difference arose essentially from the greater cumulative emissions in the FP area of the N0 and N2 treatments which were about the double of that in the N1 treatment. Annual emissions in the N0 and N2 treatments, excluding the hotspots, resulted in rates within the same magnitude of the rate in the N1 treatment. The hotspots which represent 10% of the area sampled contributed 33 and 46% of annual emissions at the plot scale in the N0 and N2 treatments.

The contribution of post-fertilization emissions to annual emissions was significant in the CP area of the fertilized treatments (41 and 37% in N1 and N2), especially during the second fertilization (27 and 31% in N1 and N2). The contribution of post-fertilization emissions to annual emissions in the CP area of the unfertilized N0 treatment (16%) was less than half that of the N1 and N2 treatments. Notwithstanding, at the plot scale post-fertilization emissions represented 13, 22 and 15% of annual emissions in the N0, N1 and N2 treatments, respectively, which is similar to the contribution of the duration of the two post-fertilization periods (58 d) to one year. Therefore even though fertilization increased significantly soil fluxes of N₂O over prolonged periods in the CP area of

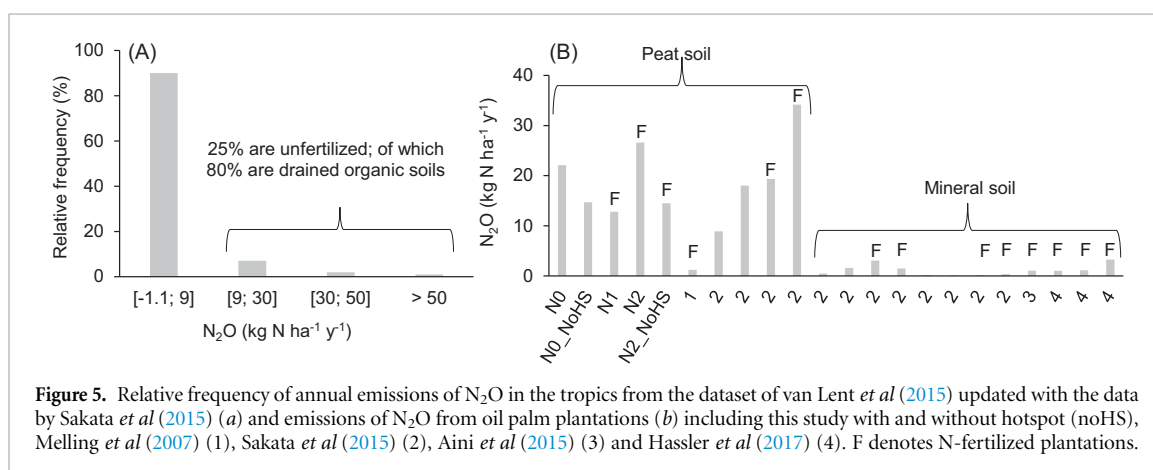
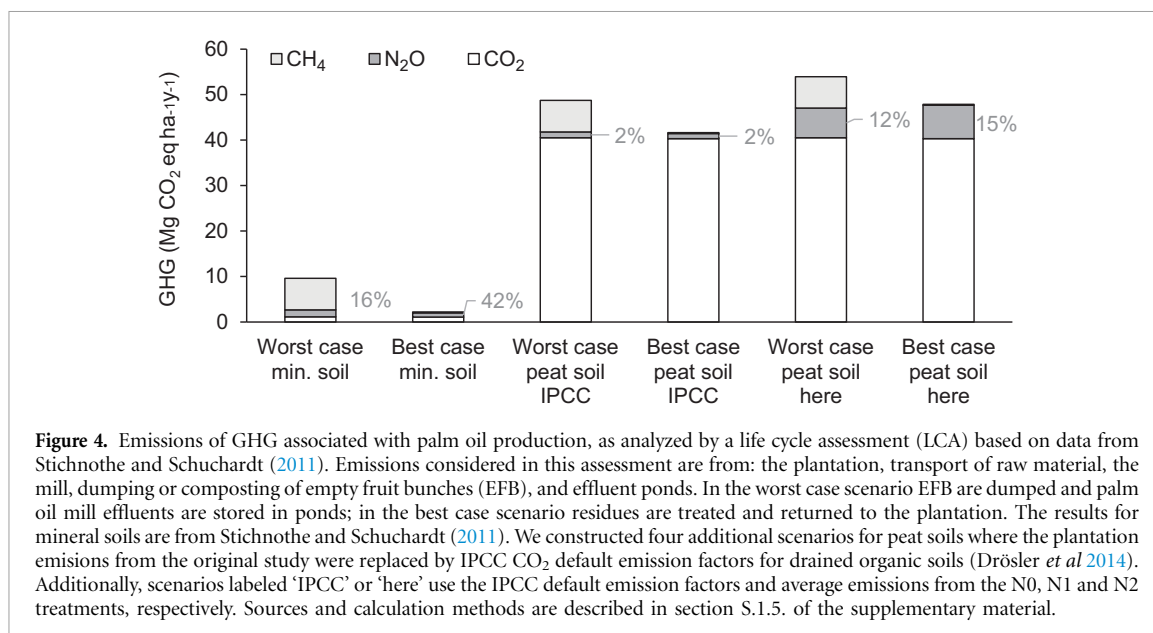
the N1 and N2 treatments, the effect at the plot-scale and over the year was minimal due to very high background emissions from peat decomposition.

3.3. Controlling factors of soil N₂O fluxes

The relationship explaining most of the variation in N₂O emissions was developed from cumulative emissions during each post-fertilization period in the CP area of each treatment (table 3, equation (1)). It indicates an exponential response of soil N₂O emissions to the amount of N applied. The second best model relates to average daily N₂O fluxes within both spatial positions (equation (2)) which denotes increasing emission rates with increasing nitrification rate, soil temperature and NH₄⁺ content. Average annual N₂O emission rates within spatial positions were found to be enhanced as soil C:N ratios were lower (equation (3)) and as soil N contents were higher (equation (4)). Soil NH₄⁺ content, nitrification and mineralization rate alone were also significantly and positively correlated to daily N₂O emission rate in each individual chamber (equations (5)–(8)). Average daily soil emissions of N₂O within each spatial position were partially and exponentially controlled by the water table level only in the N1 and N2 treatments (equations (9)–(10)).

4. Discussion

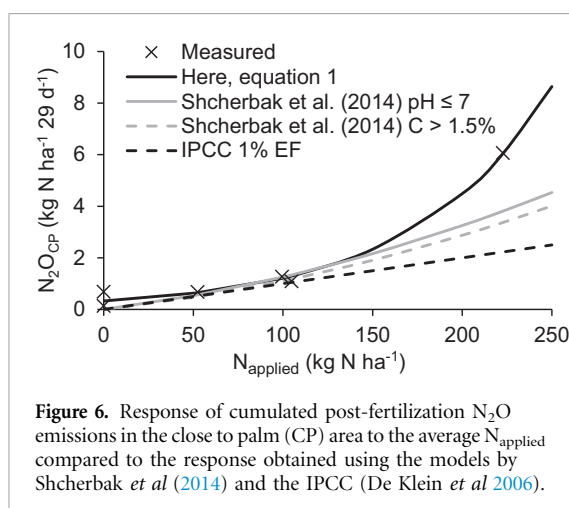
Despite having a global warming potential about 270 times that of CO₂ and being known as highly responsive to mineral N application, N₂O remains a



forgotten gas in many studies from the tropics, notably in oil palm plantations. The results by Stichnothe and Schuchardt (2011) for plantations on mineral soil denote a share of N₂O emissions in palm oil production that varies considerably (16%–42%) according to plantation management (figure 4). Estimates based on current IPCC CO₂ and N₂O emission factors for peat soil suggest that N₂O makes only a small contribution to total emissions. When we substitute the average N₂O emission rate from the N0, N1, and N2 plots for the IPCC N₂O emission factors, the role played by N₂O is significant (12%–15%) and cannot be neglected. In a land-use change perspective, which is disconsidered in the results from figure 4, it is worthwhile noting that average N₂O emissions from natural peat forests of 2.7 kg N ha⁻¹ y⁻¹ or 1.1 Mg CO₂eq ha⁻¹ y⁻¹ (Hergoualc'h and Verchot 2014) are 5 to 10 times lower than the emission rates measured in this study.

Current mechanistic understanding of soil N₂O emissions in tropical peatlands remains limited and their magnitude is poorly characterized (van Lent *et al* 2015). To evaluate the representativeness of the

emissions from this oil palm plantation we examined the most recent synthesis on soil emissions of N₂O in the tropics (van Lent *et al* 2015). The analysis points out that among the 9% of studies (40 cases) reporting high annual emission rates (>9 kg N ha⁻¹ y⁻¹); 25% were from unfertilized sites of which 80% were from drained peat soils (figure 5(A)). Thus, the present and limited literature suggests that N₂O emissions from peat decomposition in the tropics can be substantial and that our results are no exception. With respect to emissions in oil palm plantations, studies encompassing monthly sampling over a year are very few (four studies). The emissions tends to be much higher in peat than in mineral soils in both fertilized and unfertilized plantations (figure 5(B)). It seems therefore that the IPCC emission factors for peat decomposition in the tropics which are < 5 kg N ha⁻¹ y⁻¹ (Drösler *et al* 2014) and more specifically the one for oil palm plantation (1.2 kg N ha⁻¹ y⁻¹) may be underestimated and would need to be revised following collection of additional data. Higher N₂O emissions in drained peat soils compared to mineral soils is consistent with higher emissions from lower pH soils



where N_2O reductase inhibition during denitrification results in an increase of the $N_2O:N_2$ ratio (Knowles 1982). Furthermore high concentrations of electron donors (soil organic C) such as in peat soils may result in rapid oxygen depletion favoring denitrification (van den Heuvel *et al* 2009) even though the dominant product of denitrification (N_2O or N_2) will depend upon the relative availability of electron donors versus electron acceptors (NO_3^-) (Firestone *et al* 1980).

Capturing hot moments induced by fertilization in oil palm plantations requires a sampling design that integrates management practices. The local application of fertilizer around palm trunks requires differentiating the fertilized area from the non-fertilized area between the palms. This spatial stratification is also needed to appropriately scale-up the emissions estimates. In addition, given the erratic nature of fertilizer-induced pulses in emissions for prolonged periods (Hergoualc'h *et al* 2008), sampling needs to be intensive for at least a month after fertilizer application. Our results obtained from such a design confirmed the exponential nature of the response of N_2O emissions to N fertilizer application with a magnitude of the effect more pronounced than that evaluated by Shcherbak *et al* (2014) or the IPCC (De Klein *et al* 2006) (figure 6). Notwithstanding this effect was significant only in the fertilized area (CP) which represents 9% of the plot and only during the two post-fertilization periods of 29 d which account for 16% of the year. On a plot and annual scale there was no difference in annual N_2O emissions between treatments (table 2, excluding the contribution of hotspots) because high emissions from peat decomposition were prevalent. Similarly, Takakai *et al* (2006) did not find a significant relationship between annual N applied and N_2O emissions in croplands and a grassland on drained peat of Central Kalimantan; where emissions from peat decomposition were substantial. The high emission factors proposed by Sakata *et al* (2015) in an oil palm plantation on peat were derived from measurements taken in the

fertilized area exclusively and likely overestimate actual plot scale emissions induced by fertilization.

The high spatial variability of soil N_2O emissions has been observed from the microscale to the regional one but appears to be more substantial at smallest scales and to be linked to denitrifying microsites (Hénault *et al* 2012). The presence of hotspots is common but not consistently evaluated (Groffman *et al* 2009). Hotspots are attributed to a series of plant and soil factors such as rooting patterns, soil structure (aggregates), topography and hydrological flows that govern oxygen diffusion and the fate of mineral N. In artificially drained agricultural fields, variation in drainage paths and lack of plant cover can result in significant variation in soil moisture and N dynamics. The hotspots encountered in this study did not display an air temperature, soil temperature, bulk density or porosity significantly different from the average of other chambers in the respective area and treatment. The hotspot in N0 exhibited a lower live root density than the average of other chambers in the same area but the opposite was true for the hotspot in N2. Both hotspots were located further from palm, where roots are potentially less active in taking up nutrients; as demonstrated by Nelson *et al* (2006). Both hotspots exhibited, during *in vitro* incubation, a net mineralization rate much larger than the rate from other chambers in the same area despite similar initial mineral-N contents. This suggests that the hotspots were also governed by microbial or fungal community composition. The hotspots contributed substantially to annual emissions (33%–46%) while representing a very small sampled area (10%). Such a disproportional contribution was also observed by van den Heuvel *et al* (2009) in riparian buffer zones. Given the potential high contribution of hotspots to annual emissions, investigation in a particular ecosystem needs to consider the type and scale of hotspots that might occur before starting a study and to establish an experimental design allowing heterogeneity quantification from the outset (Groffman *et al* 2009).

The conceptual hole-in-the-pipe model (Firestone and Davidson 1989) proposes that the variation in N-oxide emissions from the soil is mainly controlled by N availability and soil water content. Common indexes of N availability include net mineralization and nitrification rates while the WFPS controls the $N_2O:NO$ flux. Soil fluxes of NO were not measured in the present study but variations in N_2O were positively related to different indices of N availability (NH_4^+ content, net mineralization and net nitrification rates) individually or in combination with soil temperature (table 3). A positive correlation between N_2O emissions and net mineralization and net nitrification rates is consistent with observations by Davidson *et al* (2000) and Ishizuka *et al* (2005) across different land uses in the tropics and Sumatra, Indonesia, respectively. Whereas NH_4^+ is generally found to be negatively correlated to N-oxide emissions (Davidson

et al 2000, Hadi *et al* 2005, Hergoualc'h and Verchot 2014) the positive correlation found here arise from the increase in N₂O emissions following urea application. The predominance of NH₄⁺ in mineral N pools together with the robust correlation between annual N₂O emissions and C:N supports the assumption that N is the main limiting factor for N₂O emissions in drained histosols (Klemedtsson *et al* 2005). The relative proportion of NO:N₂O:N₂ is usually determined by the WFPS; but the N₂O flux alone is also controlled by WFPS levels, especially in non-fertilized land uses (van Lent *et al* 2015). One reason why we did not find a significant relationship linking N₂O emission to WFPS may come from a shortcoming in the experimental design with measurements of WFPS taken without considering the spatial stratification (CP, FP) put in place for N₂O monitoring. As observed by Aini *et al* (2015) and Hergoualc'h *et al* (2008) in, respectively, oil palm and coffee plantations, the WFPS is generally higher further than closer to plants due to differences in bulk density and water uptake by root plants. The high emissions from peat decomposition observed at our site is likely a combination of optimal soil moisture conditions for N₂O production (60% WFPS) (van Lent *et al* 2015) together with high net N mineralization and intermediate net N nitrification rates (4.5 and 0.7 mg N kg⁻¹ d⁻¹ on average, respectively, outside of fertilization periods) as compared to rates in the tropics (Davidson *et al* 2000). The site is also subject to intense precipitation events likely promoting nitrate leaching to deeper soil layers and subsequently enhancing denitrification.

5. Conclusion

Given the high global warming potential of N₂O, the expanses of drained peatlands in Southeast Asia and the increasing development of oil palm plantations on peat, it is critical to put more effort in quantifying N₂O emissions in these systems, in evaluating their spatio-temporal variability and in investigating the mechanisms at their origin. Appropriate experimental designs that incorporate plantation management practices and allow heterogeneity quantification need to be put in place. Ideally soil emissions of N₂O should be monitored together with other main components of the soil N budget such as nitrate leaching. Strategies to mitigate N₂O emissions from soils exist but their success depend upon an appropriate knowledge of N pathways within the ecosystem.

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References

- Aini F K, Hergoualc'h K, Smith J U and Verchot L V 2015 Nitrous oxide emissions along a gradient of tropical forest disturbance on mineral soils in Sumatra *Agric. Ecosyst. Environ.* **214** 107–17
- Banabas M 2007 Study of nitrogen loss pathways in oil palm (*Elaeis guineensis* Jacq.) growing agro-ecosystems on volcanic ash soils in Papua New Guinea *PhD thesis* Massey University, Palmerston North
- Baumert K, Herzog T and Pershing J 2005 *Navigating the Numbers: Greenhouse Gas Data and International Climate Policy* (Washington, DC: World Resources Institute (WRI))
- Bouwman A F 1998 Nitrogen oxides and tropical agriculture *Nature* **392** 866–7
- Bromokusumo A K and Jonn S 2010 Indonesia Oilseeds and Products Annual (USDA Foreign Agriculture Services)
- Butterbach-Bahl K, Baggs E M, Dannenmann M, Kiese R and Zechmeister-Boltenstern S 2013 Nitrous oxide emissions from soils: how well do we understand the processes and their controls? *Phil. Trans. R. Soc. B* **368** 20130122
- Comeau L-P, Hergoualc'h K, Smith J U and Verchot L V 2013 *Conversion of Intact Peat Swamp Forest to Oil Palm Plantation: Effects on Soil CO₂ Fluxes in Jambi, Sumatra* Working paper 110 (Bogor: CIFOR)
- Comeau L P, Hergoualc'h K, Hartill J, Smith J, Verchot L V, Peak D and Salim M A 2016 How do the heterotrophic and the total soil respiration of an oil palm plantation on peat respond to nitrogen fertilizer application? *Geoderma* **268** 41–51
- Comeau L P, Hergoualc'h K, Smith J, Verchot L V and Hartill J 2014 Carbon dioxide emissions and soil properties in intact and disturbed tropical peatlands of Indonesia *20th World Congress of Soil Science* (Jeju, Korea, June 2014) pp 8–13
- Darmosarkoro W, Sutarta E S and Winarna 2003 Teknologi pemupukan tanaman kelapa sawit *Dalam Lahan dan Pemupukan Kelapa Sawit* (Medan: Pusat Penelitian Kelapa Sawit) pp 113–34
- Davidson E A, Keller M, Erickson H E, Verchot L V and Veldkamp E 2000 Testing a conceptual model of soil emissions of nitrous and nitric oxides *BioScience* **50** 667–80

- De Klein C *et al* 2006 N₂O emissions from managed soils, and CO₂ emissions from lime and urea application V4 *Agriculture, Forestry and Other Land Use, 2006 IPCC Guidelines for National Greenhouse Gas Inventories* ed S Eggleston *et al* (Kanagawa: Institute for Global Environmental Strategies) ch 11 pp 11.11–11.54
- Drösler M *et al* 2014 Drained inland organic soils 2013 *Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands* ed T Hiraishi, T Krug, K Tanabe, N Srivastava, B Jamsranjav, M Fukuda and T Troxler (Geneva: IPCC) ch 2
- Firestone M K, Firestone R B and Tiedje J M 1980 Nitrous oxide from soil denitrification: factors controlling its biological production *Science* **208** 749–51
- Firestone M K and Davidson E A 1989 Microbial basis of NO and N₂O production and consumption in soil *Exchange of Trace Gases Between Terrestrial Ecosystems and the Atmosphere* ed M O Andrea and D S Schimel (Toronto: Wiley) pp 7–21
- Firmansyah M A 2010 Rekomendasi pemupukan umum karet, kelapa sawit, kopi dan kakao, Balai Pengkajian Teknologi Pertanian Kalimantan Tengah
- Fitzherbert E B, Struebig M J, Morel A, Danielsen F, Bru C A, Donald P F and Phalan B 2008 How will oil palm expansion affect biodiversity? *Trends Ecol. Evol.* **23** 538–45
- Fowler D *et al* 2011 Effects of land use on surface–atmosphere exchanges of trace gases and energy in Borneo: comparing fluxes over oil palm plantations and a rainforest *Phil. Trans. R. Soc. B* **366** 3196–209
- Groffman P M, Butterbach-Bahl K, Fulweiler R W, Gold A J, Morse J L, Stander E K, Tague C, Tonitto C and Vidon P 2009 Challenges to incorporating spatially and temporally explicit phenomena (hotspots and hot moments) in denitrification models *Biogeochemistry* **93** 49–77
- Hadi A, Inubushi K, Furukawa Y, Purnomo E, Rasmadi M and Tsuruta H 2005 Greenhouse gas emissions from tropical peatlands of Kalimantan, Indonesia *Nutr. Cycles Agroecosys.* **71** 73–80
- Hassler E, Corre M D, Kurniawan S and Veldkamp E 2017 Soil nitrogen oxide fluxes from lowland forests converted to smallholder rubber and oil palm plantations in Sumatra, Indonesia *Biogeosciences* **14** 2781–98
- Hergoualc’h K, Skiba U, Harmand J-M and Hénault C 2008 Fluxes of greenhouse gases from andosols under coffee in monoculture or shaded by *Inga densiflora* in Costa Rica *Biogeochemistry* **89** 329–45
- Hergoualc’h K and Verchot L V 2011 Stocks and fluxes of carbon associated with land-use change in Southeast Asian tropical peatlands: a review *Glob. Biochem. Cycles* **25** GB2001
- Hergoualc’h K and Verchot L V 2014 Greenhouse gas emission factors for land use and land-use change in Southeast Asian peatlands *Mitig. Adapt. Strat. Glob. Change* **19** 789–807
- Hénault C, Grossel A, Mary B, Roussel M and Léonard J 2012 Nitrous oxide emission by agricultural soils: a review of spatial and temporal variability for mitigation *Pedosphere* **22** 426–33
- IPCC 2014 Climate change 2014: mitigation of climate change *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed R P M Ottmar Edenhofer *et al* (New York: IPCC)
- IUSS Working Group 2006 *World Reference Base for Soil Resources 2006* World Soil Resources Report No. 103 (Rome: FAO)
- Ishizuka S, Iswandi A, Nakajima Y, Yonemura S, Sudo S, Tsuruta H and Murdiyarso D 2005 The variation of greenhouse gas emissions from soils of various land-use/cover types in Jambi province, Indonesia *Nutr. Cycles Agroecosys.* **71** 17–32
- Klemedtsson L, von Arnold K, Weslien P and Gundersen P 2005 Soil CN ratio as a scalar parameter to predict nitrous oxide emissions *Glob. Change Biol.* **11** 1142–7
- Koh L P and Ghazoul J 2010 Spatially explicit scenario analysis for reconciling agricultural expansion, forest protection, and carbon conservation in Indonesia *Proc. Natl Acad. Sci.* **107** 11140–4
- Koh L P, Miettinen J, Liew S C and Ghazoul J 2011 Remotely sensed evidence of tropical peatland conversion to oil palm *Proc. Natl Acad. Sci.* **108** 5127–32
- Koh L P and Wilcove D S 2008 Is oil palm agriculture really destroying tropical biodiversity? *Conserv. Lett.* **1** 60–64
- Knowles R 1982 Denitrification *Microbiol. Rev.* **46** 43–70
- Melling L, Hatano R and Goh K J 2007 Nitrous oxide emissions from three ecosystems in tropical peatland of Sarawak, Malaysia *Soil Sci. Plant Nutr.* **53** 792–805
- Miettinen J, Hooijer A, Shi C, Tollenaar D, Vernimmen R, Liew S C, Malins C and Page S 2012 Extent of industrial plantations on Southeast Asian peatlands in 2010 with analysis of historical expansion and future projections *GCB Bioenergy* **4** 908–18
- MoA 2014 Tree crop estate statistics of Indonesia *Oil Palm 2013–5* (Ministry of Agriculture Indonesia)
- Murdiyarso D, Dewi S, Lawrence D and Seymour F 2011 *Indonesia’s Forest Moratorium: A Stepping Stone to Better Forest Governance?* Working paper 76 (Bogor: CIFOR)
- Murdiyarso D, Hergoualc’h K and Verchot L V 2010 Opportunities for reducing greenhouse gas emissions in tropical peatlands *Proc. Natl Acad. Sci.* **107** 19655–60
- Mutert E, Fairhurst T H and von Uexküll H R 1999 Agronomic management of oil palms on deep peat *Better Crops Int.* **13** 22–7
- Myhre G *et al* 2013 Anthropogenic and natural radiative forcing *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker, D Qin, G K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley (Cambridge: Cambridge University Press)
- Nelson P N, Banabas M, Scotter D R and Webb M J 2006 Using soil water depletion to measure spatial distribution of root activity in oil palm (*Elaeis guineensis* Jacq.) plantations *Plant Soil* **286** 109–21
- Poku K 2002 *Small-scale Palm Oil Processing in Africa* FAO Agriculture Service Bulletin 148 (Rome: FAO)
- RSPO 2012 RSPO Manual on best Management Practices for Existing Oil Palm Cultivation on Peat
- Sabiham S 2010 Properties of Indonesian peat in relation to the chemistry of carbon emission *Int. Workshop on Evaluation and Sustainable Management of Soil Carbon Sequestration in Asian Countries* (Bogor)
- Sakata R, Shimada S, Arai H, Yoshioka N, Yoshioka R, Aoki H and Inubushi K 2015 Effect of soil types and nitrogen fertilizer on nitrous oxide and carbon dioxide emissions in oil palm plantations *Soil Sci. Plant Nutr.* **61** 48–60
- Sayer J, Ghazoul J, Nelson P and Boedhihartono A K 2012 Oil palm expansion transforms tropical landscapes and livelihoods *Glob. Food Secur.* **1** 114–9
- Shcherbak I, Millara N and Robertson G P 2014 Global metaanalysis of the nonlinear response of soil nitrous oxide (N₂O) emissions to fertilizer nitrogen *Proc. Natl Acad. Sci.* **111** 9199–204
- Sheil D, Casson A, Meijaard E, van Noordwijk M, Gaskell J, Sunderland-Groves J, Wertz K and Kanninen K 2009 *The Impacts and Opportunities of Oil Palm in Southeast Asia: What Do We Know and What Do We Need to Know?* Occasional paper no. 51 (Bogor: CIFOR)
- Siderius C 2004 *A Hydrological Model of the Air Hitam Laut Watershed and the Impact of Various Land Use Scenarios* Wageningen University Report
- Smith C J, Brandon M and Patrick W H Jr 1982 Nitrous oxide emission following urea-N fertilization of wetland rice *Soil Sci. Plant Nutr.* **28** 161–71
- Smith K A, Ball T, Conen F, Dobbie K E, Massheder J and Rey A 2003 Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes *Eur. J. Soil. Sci.* **54** 779–91
- Stichnothe H and Schuchardt F 2011 Life cycle assessment of two palm oil production systems *Biomass Bioenergy* **35** 3976–84

- Takakai F *et al* 2006 Effects of agricultural land-use change and forest fire on N₂O emission from tropical peatlands, Central Kalimantan, Indonesia *Soil Sci. Plant Nutr.* **52** 662–74
- Tubiello F N, Salvatore M, Rossi S, Ferrara A, Fitton N and Smith P 2013 The FAOSTAT database of greenhouse gas emissions from agriculture *Environ. Res. Lett.* **8** 015009
- USEPA 2013 *Global Mitigation of Non-CO₂ Greenhouse Gases: 2010–2030* (Washington DC: Executive and Technical Summary)
- van den Heuvel R N, Heftinga M M, Tanb N C G, Jettenb M S M and Verhoevena J T A 2009 N₂O emission hotspots at different spatial scales and governing factors for small scale hotspots *Sci. Total Environ.* **407** 2325–32
- van Lent J, Hergoualc'h K and Verchot L V 2015 Reviews and syntheses: soil N₂O and NO emissions from land use and land-use change in the tropics and subtropics: a meta-analysis *Biogeosciences* **12** 7299–313
- Verchot L V, Kamalakumari A, Romijn E, Herold M and Hergoualc'h K 2012 Emissions factors: converting land use change to CO₂ estimates *Analysing REDD+: Challenges and Choices* ed A Angelsen, M Brockhaus, W D Sunderlin and L V Verchot (Bogor: CIFOR)
- Verchot L, Hutabarat L, Hairiah K and van Noordwijk M 2006 Nitrogen availability and soil N₂O emissions following conversion of forests to coffee in southern Sumatra *Glob. Biogeochem. Cycles* **20** GB4008
- Verchot L V, Davidson E A, Cattânio J H, Ackerman I L, Erickson H E and Keller M 1999 Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia *Glob. Biogeochem. Cycles* **13** 31–46
- von Uexkull H R 2016 Oil palm *World Fertilizer Use Manual* (International Fertilizer Industry Association)
- Wijedasa L S *et al* 2017 Denial of long-term issues with agriculture on tropical peatlands will have devastating consequences *Glob. Change Biol.* **23** 977–82