

## **Author's responses**

We thank Dr. Paul Stoy for the time he invested to give his feedbacks to our manuscript. For clarity, we have copied his comments and questions and placed our answers below each comment/question.

### *COMMENTS AND QUESTIONS:*

*1. Paul Stoy: How frequent are clay vs. loam Acrisol soils in Sumatra? Are both relatively common?*

Answer: Soil textural data are scarce, and so we cannot estimate the coverage of these two soil textural classes under this Acrisol soil group. However, this soil group (Acrisol soil; as the top level of soil classification in the FAO system), represents 50 % of land area in Sumatra (FAO et al., 2009). As Acrisol soil is dominant in area coverage (as the rest of 50 % is shared by many other soil groups), these two soil landscapes in our study area are indeed common in Sumatra.

*2. Paul Stoy: On page 9 (I emphasize that continuous line numbering is always strongly preferred) It is important to state how deep the chamber bases were installed. Too deep can damage belowground structures.*

Answer: We also see that it matters to specify how deep we inserted our chambers (~0.03 m) into the ground. To address this concern, we included this information on page 9, lines 13-14.

*3. Paul Stoy: On page 12, please use mathematical symbols for equations (the star means convolution and shouldn't be used as a surrogate for the multiplication symbol).*

Answer: We take this information and replaced the star symbol by the multiplication symbol ( $\times$ ; page 12, lines 3-5).

*4. Paul Stoy: On line 14, don't use marginal significance here or anywhere else in the manuscript. Decide what is unlikely to happen by chance and stick with it.*

Answer: As we explain on page 14, lines 2-5, we considered also marginal significance since our experimental design covers the inherently high spatial variability of soil N-oxide fluxes. This marginal significant level was also accepted in our previous publication on soil CO<sub>2</sub> and CH<sub>4</sub> fluxes measured in the same study area, which was published in Biogeosciences (Hassler et al., 2015). In the present manuscript the marginal significance level serves especially to illuminate the differences in soil NO fluxes between rubber and jungle rubber in the loam Acrisol ( $p = 0.07$ ). For these reasons we keep it in our manuscript.

*5. Paul Stoy: The paragraph on page 16 line 13 needs to be rewritten, it was difficult to follow.*

Answer: We re-structured this paragraph to improve clarity. We now state straightforwardly in the very beginning of the paragraph the main message and take out unnecessary information on fertilizer application times (page 16, lines 13-17).

6. *Paul Stoy*: What is SFB 990?

Answer: SFB stands for *Sonderforschungsbereich* or *Collaborative Research Center* (CRC) and this is financed by the German Research Foundation (DFG) within which we conducted our study. The description of CRC 990 is given in the acknowledgements. To improve clarity, we now replaced the German abbreviation with the English (CRC instead of SFB) (page 27, lines 19-20 and page 28, line 4). Also we referred to the acknowledgements on page 27, line 19, where the abbreviation is given the first time.

### **References:**

FAO, IIASA, ISRIC, ISSCAS, JRC: Harmonized World Soil Database (version 1.1), available at: <http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/> (last access: 05.04.2017), 2009.

Hassler, E., Corre, M. D., Tjoa, A., Damris, M., Utami, S. R., and Veldkamp, E.: Soil fertility controls soil–atmosphere carbon dioxide and methane fluxes in a tropical landscape converted from lowland forest to rubber and oil palm plantations, *Biogeosciences*, 12(19), 5831–5852, doi:10.5194/bg-12-5831-2015, 2015.

1 **Soil nitrogen oxide fluxes from lowland forests converted to**  
2 **smallholder rubber and oil palm plantations in Sumatra,**  
3 **Indonesia**

4

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1 **Abstract.** Oil palm and rubber plantations cover large areas of former rainforest in Sumatra,  
2 Indonesia, supplying the global demand for these crops. Although forest conversion is known  
3 to influence soil nitrous oxide (N<sub>2</sub>O) and nitric oxide (NO) fluxes, measurements from oil  
4 palm and rubber plantations are scarce (for N<sub>2</sub>O) or nonexistent (for NO). Our study aimed to  
5 (1) quantify changes in soil-atmosphere fluxes of N-oxides with forest conversion to rubber  
6 and oil palm plantations, and (2) determine their controlling factors. In Jambi, Sumatra, we  
7 selected two landscapes that mainly differed in texture but both on heavily weathered soils:  
8 loam and clay Acrisol soils. Within each landscape, we investigated lowland forest, rubber  
9 trees interspersed in secondary forest (termed as *jungle rubber*), both as reference land uses,  
10 and smallholder rubber and oil palm plantations, as converted land uses. In the loam Acrisol  
11 landscape, we conducted a follow-on study in a large-scale oil palm plantation for comparison  
12 of soil N<sub>2</sub>O fluxes with smallholder oil palm plantations. Land-use conversion to smallholder  
13 plantations had no effect on soil N-oxide fluxes ( $P = 0.58$  to  $0.76$ ) due to the generally low  
14 soil N availability in the reference land uses that further decreased with land-use conversion.  
15 Soil N<sub>2</sub>O fluxes from the large-scale oil palm plantation did not differ with those from  
16 smallholder plantations ( $P = 0.15$ ). Over one-year measurements, the temporal patterns of soil  
17 N-oxide fluxes were influenced by soil mineral N and water contents. Across landscapes,  
18 annual soil N<sub>2</sub>O emissions were controlled by gross nitrification and sand content, which also  
19 suggest the influence of soil N and water availability. Soil N<sub>2</sub>O fluxes ( $\mu\text{g N m}^{-2} \text{h}^{-1}$ ) were:  $7 \pm$   
20  $2$  to  $14 \pm 7$  (reference land uses),  $6 \pm 3$  to  $9 \pm 2$  (rubber),  $12 \pm 3$  to  $12 \pm 6$  (smallholder oil  
21 palm), and  $42 \pm 24$  (large-scale oil palm). Soil NO fluxes ( $\mu\text{g N m}^{-2} \text{h}^{-1}$ ) were:  $-0.6 \pm 0.7$  to  $5.7$   
22  $\pm 5.8$  (reference land uses),  $-1.2 \pm 0.5$  to  $-1.0 \pm 0.2$  (rubber) and  $-0.2 \pm 1.2$  to  $0.7 \pm 0.7$   
23 (smallholder oil palm). To improve estimate of soil N-oxide fluxes from oil palm plantations  
24 in this region, studies should focus on large-scale plantations (which usually have two to four

1 times higher N fertilization rates than smallholders) with frequent measurements following  
2 fertilizer application.

3

#### 4 **1 Introduction**

5 Expansion of industrial forestry and agriculture has caused rapid deforestation in Sumatra,  
6 Indonesia, resulting in a total primary forest loss of 36 % between 1990 and 2010 (Margono  
7 et al., 2012). Nowadays, most accessible lowland rainforests have been converted (Laumonier  
8 et al., 2010) into economically important crops, such as oil palm (*Elaeis guineensis*) and  
9 rubber (*Hevea brasiliensis*), with an area of 9.2 million hectare (Mha) (BPS, 2016a).  
10 Indonesia is currently the principal oil palm producer and second largest rubber producer  
11 worldwide (FAO, 2016), and Sumatra is the most important contributor to the Indonesian  
12 production (BPS, 2016b). Despite the extent of land-use change in Sumatra, it is still  
13 uncertain how forest conversion will affect soil emissions of climate-relevant N-oxide gases,  
14 nitrous oxide (N<sub>2</sub>O) and nitric oxide (NO). Only a few studies so far have reported soil N<sub>2</sub>O  
15 fluxes from forest conversion to these rapidly increasing and economically important land  
16 uses, oil palm and rubber, on lowland mineral soils in Southeast Asia (Aini et al., 2015;  
17 Ishizuka et al., 2002, 2005; Yashiro et al., 2008) and no study exists on soil NO fluxes.

18 Tropical forest soils are major sources of N<sub>2</sub>O and NO, emitting 1.3 Tg N<sub>2</sub>O-N yr<sup>-1</sup>  
19 (Werner et al., 2007) and 1.3 Tg NO-N yr<sup>-1</sup> (Davidson and Kinglerlee, 1997) to the  
20 atmosphere, whereby considerable amounts of NO are expected to get redirected in forest  
21 systems since NO is easily oxidized to NO<sub>2</sub> which, in turn, is absorbed by leaves (Jacob and  
22 Bakwin, 1991; Sparks et al., 2001). N<sub>2</sub>O is a potent greenhouse gas (IPCC, 2013) and is  
23 projected to be the single most important ozone-depleting substance throughout the 21<sup>st</sup>  
24 century (Ravishankara et al., 2009). NO plays an important role in the formation of

1 tropospheric ozone, which in itself is an important greenhouse gas (Lammel and Graßl, 1995).  
2 N<sub>2</sub>O and NO are produced in soil by the microbial processes of nitrification and  
3 denitrification. The conceptual model of “hole-in-the-pipe” (HIP), which had been validated  
4 by studies in the tropics (Davidson et al., 2000), suggests that production and consumption of  
5 these gases in soils are influenced by two levels of control: first, the amount of soil available  
6 N, and second, the soil water content. HIP suggests that the higher the soil N availability, the  
7 higher are the soil N-oxide fluxes, and that well-aerated soil conditions (low moisture  
8 contents) favor for nitrification with NO as the main gaseous product while with increasing  
9 water content denitrification with increasing proportion of N<sub>2</sub>O prevails (Davidson et al.,  
10 2000). Although there are other factors affecting soil N<sub>2</sub>O and NO fluxes through their  
11 influence on nitrification and denitrification (e.g., soil pH, temperature, bioavailable carbon;  
12 Firestone and Davidson, 1989; Heinen, 2006; Skiba and Smith, 2000), landscape-scale  
13 investigations in tropical areas show the dominant role of soil N availability and water content  
14 (Corre et al., 2014; Koehler et al., 2009; Müller et al., 2015).

15 Conversion of tropical forests to agricultural land uses generally alters soil N-oxide  
16 fluxes through their effects on soil N availability and aeration as a consequence of  
17 management practices (e.g., fertilization, harvest, cultivation), which can add and export  
18 nutrients as well as compact or loosen the soil (Keller and Reiners, 1994; Veldkamp et al.,  
19 2008). In particular, the application of N-containing fertilizers can increase N-oxide emissions  
20 (Matson et al., 1996; Veldkamp et al., 1998) whereas agricultural land uses without fertilizer  
21 application lead to long-term reductions of soil N-oxide fluxes or to comparably low-level  
22 fluxes as those from previous forests (Ishizuka et al., 2005; Keller and Reiners, 1994; Verchot  
23 et al., 1999). In tropical regions, it has been shown that soil NO and N<sub>2</sub>O emissions can be  
24 very high following fertilizer application, constituting 6.4–8.6 % of applied N fertilizer

1 especially at high fertilizer application rates (Veldkamp and Keller, 1997; Veldkamp et al.,  
2 1998).

3 For lowland forests on highly weathered soils in Sumatra, Indonesia, where our  
4 present study was conducted, it has been shown that soil N availability (with gross rates of  
5 ammonium ( $\text{NH}_4^+$ ) transformations as indices) is higher in the clay than loam Acrisol soils  
6 (Allen et al., 2015), suggesting that soil texture controls soil fertility which in turn affects  
7 plant productivity, soil water holding capacity, decomposition and ultimately soil-N cycling  
8 (Allen et al., 2015). Conversion of lowland forest and jungle rubber to oil palm and rubber on  
9 these Acrisol soils showed intermediate soil N availability in oil palm plantations, due to  
10 abatement of soil fertility decline by low to moderate applications of fertilizers and lime,  
11 whereas the unfertilized rubber plantations displayed the lowest soil N availability and  
12 fertility in general (Allen et al., 2015).

13 Our present study focuses on soil  $\text{N}_2\text{O}$  and  $\text{NO}$  fluxes from a region in Jambi, Sumatra  
14 where increased deforestation for rubber and oil palm production has occurred in the last two  
15 decades. We covered four land uses within two landscapes on highly weathered soils  
16 that mainly differed in soil texture (clay and loam Acrisols): forest, rubber trees interspersed  
17 in secondary forest (hereafter, termed as jungle rubber) as the reference land uses,  
18 and smallholder rubber and oil palm plantations as the converted land uses. In addition, we  
19 conducted a follow-on study to evaluate the effect of N input rate on soil  $\text{N}_2\text{O}$  fluxes by  
20 comparing a large-scale (with 2–4 times higher fertilization rate) and smallholder plantations  
21 within the same landscape of the loam Acrisol soil. Based on the above mentioned findings on  
22 soil N availability, we formulated two hypotheses: (H1) soil  $\text{N}_2\text{O}$  and  $\text{NO}$  fluxes from the  
23 reference land uses will be higher in the clay than the loam Acrisol landscapes; and (H2)  
24 forest and jungle rubber will have the highest soil  $\text{N}_2\text{O}$  and  $\text{NO}$  fluxes, followed by the  
25 smallholder oil palm plantations (fertilized at low to moderate rates), and with the lowest

1 fluxes from the unfertilized rubber plantations. Our study aimed to (1) quantify changes in  
2 soil-atmosphere fluxes of N-oxides with forest conversion to smallholder oil palm and rubber  
3 plantations, (2) determine the temporal controls of soil N-oxide fluxes measured within one  
4 year, and (3) assess landscape-scale controlling factors of annual soil N<sub>2</sub>O fluxes from  
5 converted lowland landscapes in Sumatra, Indonesia. Our study contributes to the much  
6 needed information on soil N-oxide fluxes from these economically and globally relevant  
7 tropical land uses.

8

## 9 **2 Material and methods**

### 10 **2.1 Study area, experimental design and management practices**

11 The study region is situated in Jambi province, Sumatra, Indonesia (2° 0' 57" S, 103° 15' 33"  
12 E, and elevation of 73 ± 3 m above sea level), where conversion of forest to rubber and oil  
13 palm plantations is widespread. The area has a mean annual temperature of 26.7 ± 0.1 °C and  
14 a mean annual precipitation of 2235 ± 381 mm (1991–2011; data from a climatological  
15 station at the Jambi Sultan Thaha Airport). During our study year (2013), annual rainfall in  
16 the study region was 3418–3475 mm (data from climatological stations at the Harapan Forest  
17 Reserve, Sarolangun and Lubuk Kepayang, approximately 10–20 km from our sites), which  
18 were higher than the long term average. Total dissolved N deposition via rainfall was between  
19 12.9 ± 0.1 and 16.4 ± 2.6 kg N ha<sup>-1</sup> yr<sup>-1</sup>, measured at two locations in the study region during  
20 2013 (Kurniawan, 2016).

21 We delineated the study region in two landscapes, which have the same highly  
22 weathered soil group but mainly differed in soil texture: clay and loam Acrisol soils. The clay  
23 Acrisol soil had larger pH (4.5 ± 0.0), base saturation (23 ± 6 %) and Bray-extractable P (1.4  
24 ± 0.1 g P m<sup>-2</sup>) and lower Al saturation (61 ± 3 %) in the top 10 cm depth compared to the  
25 loam Acrisol soil (4.3 ± 0.0 pH, 11 ± 1 % base saturation, 0.5 ± 0.1 g P m<sup>-2</sup> and 80 ± 1 % Al



1 saturation) (all  $P \leq 0.05$ ; Allen et al., 2015). In the first part of our study, we investigated four  
2 land-use types within each landscape: lowland forest, jungle rubber, both as the reference land  
3 uses, and smallholder monoculture plantations of rubber and oil palm, as the converted land  
4 uses. Each land use within each landscape had four sites as replicates, and we laid out a 50 m  
5  $\times$  50 m plot in each replicate site; in total we had 32 plots. Within each plot, a 10  $\times$  10 grid  
6 was established and we randomly selected four subplots (5 m  $\times$  5 m each) per plot, each with  
7 one permanently installed chamber base for measurements of soil N-oxide fluxes. All  
8 measurements (see Sect. 2.2) were conducted in 2013 (Appendix Table A1). A more detailed  
9 description of the study sites and plot design was reported earlier by Allen et al. (2015) and  
10 Hassler et al. (2015).

11 The second part was a follow-on study, wherein we conducted additional  
12 measurements in a large-scale oil palm plantation (called PTPN VI) in the loam Acrisol  
13 landscape from 2014 to 2015 in order to compare with the smallholder oil palm plantations  
14 within the same landscape (Appendix Table A1). In the PTPN VI site, we selected four  
15 replicates at a distance of 50 m apart. At each replicate, we installed three permanent chamber  
16 bases at 0.8 m, 2.8 m and 4.8 m from the tree base, in order to characterize possible spatial  
17 variation caused by management practices within each replicate.

18 Based on our interviews with the smallholders, the monoculture plantations were  
19 established after clearing and burning of either forest or jungle rubber and hence these land  
20 uses served as the reference land uses with which the converted plantations were compared.  
21 Additionally, the comparability of initial soil conditions between the reference and converted  
22 land uses was tested based on a land use-independent soil characteristic, i.e., clay content at  
23 0.5–2 m depth, which did not statistically differ among land uses within each landscape  
24 (Allen et al., 2015; Hassler et al., 2015). Thus, changes in soil N-oxide fluxes can be

1 attributed to land-use change with its associated management practices. The plantations' ages  
2 ranged between 7 and 17 years, and tree density, tree height, basal area and tree species  
3 abundance were higher in the reference land uses than the monoculture plantations (all  
4 reported by Allen et al., 2015; Hassler et al., 2015; Kotowska et al., 2015).

5 Management practices in the plantations included manual harvest, weeding and  
6 fertilizer application (details reported by Hassler et al., 2015). In 2013, fertilization in the  
7 smallholder oil palm plantations was conducted 1–2 times per year and fertilization rates  
8 ranged between 48–88 kg N ha<sup>-1</sup> yr<sup>-1</sup> (except two smallholders who applied 138 kg N ha<sup>-1</sup> yr<sup>-1</sup>  
9 <sup>1</sup>), 21–38 kg P ha<sup>-1</sup> yr<sup>-1</sup> and 40–157 kg K ha<sup>-1</sup> yr<sup>-1</sup>, with the lower range in the clay Acrisol and  
10 the upper range in the loam Acrisol. The fertilizer sources were NPK complete, urea and KCl.  
11 One of the smallholders in the loam Acrisol landscape applied 200 kg dolomite ha<sup>-1</sup> yr<sup>-1</sup>.  
12 Fertilizers were applied around each palm tree at about 0.8–1 m from the stem base (Hassler  
13 et al., 2015). Rubber plantations were not fertilized. In the large-scale oil palm plantation  
14 PTPN VI, fertilizer application rates were typically higher than those in smallholder  
15 plantations; fertilizers were applied once in 2014 at the rates of 196-36-206 kg N, P, K ha<sup>-1</sup> yr<sup>-1</sup>  
16 <sup>1</sup>, with also 602 kg dolomite ha<sup>-1</sup> yr<sup>-1</sup>, and once before the end of our measurements in July  
17 2015 at the rates of 96-23-96 kg N, P, K ha<sup>-1</sup> yr<sup>-1</sup>. The fertilizer forms were NPK complete,  
18 urea, triple superphosphate and KCl. Application in this large-scale plantation was done partly  
19 manually by applying the fertilizers at 1-m distance to the tree base, and partly mechanically  
20 by broadcasting the fertilizer within 1–3 m distance from the palm rows. In 2015, fertilizers  
21 were mainly mechanically broadcasted within these inter-rows.

22

## 23 **2.2 Soil N-oxide fluxes and supporting soil factors**

1 In the first part of our study, soil N<sub>2</sub>O fluxes were measured in all land uses (32 plots) at  
2 monthly interval from December 2012 to December 2013, whereas soil NO fluxes were  
3 measured four times between March and September 2013 (Appendix Table A1). Two forest  
4 sites and one jungle rubber site in the clay Acrisol landscape were not measured for soil NO  
5 fluxes due to difficulty in accessing these sites that did not allow us to stabilize the NO  
6 detector during transport in the field (i.e., using motorcycle on very rugged trails). Soil NO  
7 fluxes were not measured as frequently as N<sub>2</sub>O fluxes because these fluxes were always very  
8 low at all sites and we decided to stop this measurement in September 2013. In the follow-on  
9 study, soil N<sub>2</sub>O fluxes were measured more frequently (biweekly from July 2014 to July  
10 2015; Appendix Table A1) in a large-scale oil palm plantation PTPN VI (in congruent with its  
11 high fertilizer application rate) to compare with the smallholder oil palm plantations within  
12 the same landscape of the loam Acrisol soil.

13 For the first part of our study, we used randomly installed chamber bases (inserted to  
14 ~0.03-m depth with distances to the tree base between 1.8 and 5 m; see Sect. 2.1) with  
15 monthly measurements, which may have missed the N fertilizer-induced pulse of soil N-oxide  
16 emissions in the smallholder oil palm plantations (Veldkamp and Keller, 1997; Veldkamp et  
17 al., 1998). Therefore, we conducted more intensive measurements of soil N<sub>2</sub>O fluxes during 3  
18 to 8.5 weeks (with 6 to 11 sampling days) following fertilizer application at three of the  
19 smallholder oil palm plantations within each landscape. These measurements served to  
20 characterize the short-term, N fertilizer-induced contribution (e.g., Koehler et al., 2009) to  
21 total N<sub>2</sub>O fluxes. Soil NO fluxes were also measured during 6 to 8.5 weeks (with 9 to 10  
22 sampling days) following fertilizer application at one of the smallholder oil palm plantations  
23 within each landscape. Measurements in the three smallholder oil palm plantations at each  
24 landscape were conducted during October–December 2013, January–March 2014, and  
25 February–April 2014 (Appendix Table A1). We applied the same fertilizer forms, rates and

1 methods as used by the smallholders. Three oil palm trees were selected in each of the six  
2 sites. In the clay Acrisol landscape, each tree was applied with 2 kg complete NPK fertilizer  
3 (equivalent to 0.32 kg N tree<sup>-1</sup>), whereas in the loam Acrisol, each tree was applied with 2 kg  
4 of combined complete NPK, ammonium sulfate and KCl fertilizers (equivalent to 0.26 kg N  
5 tree<sup>-1</sup>). The fertilizer was applied within 0.8–1 m distance from the tree base. We installed  
6 three permanent chamber bases at various distances from the tree base: 0.3 m from the tree  
7 base (F1 = chamber location with incidental fertilization), 0.8 m from the tree base that was  
8 on the fertilized area (F2 = fertilized chamber location), and 4–4.5 m from the tree base that  
9 was in the middle of the inter-rows and served as the reference chamber without fertilizer  
10 application (NF = non-fertilized chamber location).

11 Soil N<sub>2</sub>O fluxes were measured using the same methods employed in our earlier  
12 studies (e.g., Corre et al., 2014; Koehler et al., 2009). During gas sampling, the permanently  
13 installed chamber bases were covered with vented static, polyethylene hoods (chamber area of  
14 0.05 m<sup>2</sup> and total volume of 12 L), and four gas samples (30 mL each) were taken at 1, 11, 21  
15 and 31 min after chamber closure by connecting a syringe with a Luer-lock to the chamber  
16 sampling port. Gas samples were immediately injected into pre-evacuated 12 mL Labco  
17 Exetainers sealed with rubber septa (Labco Limited, Lampeter, UK), maintaining an  
18 overpressure; these exetainers have been tested by our group to be leak proof during extended  
19 period of storage (e.g., up to 6 months) (Hassler et al., 2015). Within 3–4 months the gas  
20 samples were transported by airfreight to Germany and were analyzed upon arrival using a  
21 gas chromatograph with an electron capture detector (GC 6000 Vega Series 2, Carlo Erba  
22 Instruments, Milan, Italy). For the measurements from March–July 2015 in the large-scale oil  
23 palm plantation PTPN VI, the gas samples were analyzed with another gas chromatograph  
24 (SRI 8610C, SRI Instruments Europe GmbH, Bad Honnef, Germany), which had been  
25 previously cross-calibrated using the same standards. For calibration, three standard gases

1 were used with concentrations of 360, 1000 and 1600 ppb N<sub>2</sub>O (Deuste Steininger GmbH,  
2 Mühlhausen, Germany).

3 Soil NO fluxes were measured (described in detail in our earlier works, e.g., Corre et  
4 al., 2014; Koehler et al., 2009) using the same chamber bases described above. During  
5 measurements, the chamber bases were covered with dynamic vented, polyethylene hoods  
6 (total volume of 12 L), and NO concentrations were measured in situ during 5–7 min  
7 following chamber closure using a Scintrex LMA-3 chemiluminescence detector (Scintrex,  
8 Ontario, Canada), in which NO is oxidized to NO<sub>2</sub> by a CrO<sub>3</sub> catalyst after which it reacts  
9 with a luminol solution. Calibration of the NO detector was carried out at each site prior to  
10 and after measurements using a two-point calibration of a standard gas with 3000 ppb NO  
11 (Deuste Steininger GmbH, Mühlhausen, Germany) which was diluted using dried ambient air.  
12 NO measurements were recorded every 5 seconds using a data logger (CR510, Campbell  
13 Scientific, Logan, USA).

14 Soil N<sub>2</sub>O and NO fluxes were calculated from the linear increase of concentration  
15 over time of chamber closure and adjusted for air temperature and atmospheric pressure,  
16 measured at each site on each sampling day. Annual soil N<sub>2</sub>O fluxes from the monthly  
17 sampling at each site were estimated using the trapezoidal rule, which is an interpolation  
18 between measured fluxes and the interval between sampling days. Interpolated fluxes were  
19 summed for the entire year (e.g., Hassler et al., 2015). Annual NO fluxes were not calculated,  
20 since we only conducted four measurement periods for each plot as explained above. To  
21 calculate the N fertilizer-induced pulse of soil N-oxide fluxes, we also used the trapezoidal  
22 rule on day intervals between measured flux rates to estimate the total flux during the entire  
23 period following fertilizer application, covering pre-fertilizer level, the peak, and the return to

1 background levels of soil N-oxide fluxes. We calculated the percentage of combined soil NO  
2 and N<sub>2</sub>O emissions from the applied N-fertilizer rate at each site as follows:

$$\begin{aligned} & \% \text{ NO-N} + \text{N}_2\text{O-N of N applied yr}^{-1} = (\text{NO-N} + \text{N}_2\text{O-N fluxes from F1 and F2 chambers} - \\ & \text{NO-N} + \text{N}_2\text{O-N fluxes from NF chamber}) \times \text{frequency of fertilization yr}^{-1} \times \text{fertilized area} \\ & (\text{m}^2 \text{ ha}^{-1}) \div \text{N fertilization rate (kg N ha}^{-1} \text{ yr}^{-1} \times 10^9 \text{ } \mu\text{g/kg}) \times 100 \end{aligned}$$

6 where NO-N + N<sub>2</sub>O-N is expressed in  $\mu\text{g N m}^{-2}$  for the entire period of fertilizer effect. In this  
7 calculation, we included fluxes from chamber location F1 in order to include any incidental  
8 fertilizer application to this area (possibly from previous applications by the smallholders and  
9 possible redistribution of applied nutrients within the soil), since N-oxide fluxes from  
10 chamber location F1 were often higher than those from NF chambers (see Sect. 3.2).

11 Soil factors known to control soil N-oxide fluxes (i.e., temperature, water-filled pore  
12 space (WFPS), and extractable NH<sub>4</sub><sup>+</sup> and nitrate (NO<sub>3</sub><sup>-</sup>) were measured within the top 0.05 m  
13 depth during each soil N-oxide flux measurement at all 32 sites and at the six sites of  
14 smallholder oil palm plantations following fertilization. Soil temperature was measured close  
15 to each chamber base using a digital thermometer. Soil samples were taken at 1 m distance  
16 from the four chambers, pooled, mixed thoroughly, and subsampled for immediate extraction  
17 of mineral N in the field, using prepared extraction bottles containing 150 mL 0.5 M K<sub>2</sub>SO<sub>4</sub>.  
18 Upon arrival at the field station, extraction bottles were shaken for 1 h, filtered and extracts  
19 were frozen immediately. The remaining soil sample was used to determine the gravimetric  
20 moisture content (by oven-drying for at least 1 day at 105 °C), whereby WFPS was calculated  
21 using a particle density of 2.65 g cm<sup>-3</sup> for mineral soil and the measured soil bulk density at  
22 our study sites (Allen et al., 2015). Concurrent to the measurements following the fertilizer  
23 applications, soil was sampled close to each of the chamber locations F1, F2 and NF  
24 (described above) and was processed separately for mineral N extraction and WFPS

1 determination. Frozen extracts were transported by airfreight to Germany and analyzed for  
2  $\text{NH}_4^+$  and  $\text{NO}_3^-$  concentrations using continuous flow injection colorimetry (SEAL Analytical  
3 AA3, SEAL Analytical GmbH, Norderstedt, Germany), as described in detail by Hassler et al.  
4 (2015).

5 In addition, soil physical and biochemical parameters within the top 0.1 m were  
6 measured once in 2013 at all 32 plots (i.e. soil-N cycling processes, including gross  
7 nitrification as one of the indices of N availability in the soil, microbial biomass, total organic  
8 C, total N, exchangeable cations, pH, soil texture and soil bulk density), reported by Allen et  
9 al. (2015). We used these soil parameters to analyze their relationships (see Sect. 2.3) with  
10 annual soil  $\text{N}_2\text{O}$  fluxes and reported the parameters that showed significant relationships with  
11 annual soil  $\text{N}_2\text{O}$  fluxes in Appendix Table A2.

12

### 13 **2.3 Statistical analysis**

14 We first tested each parameter for normal distribution (Shapiro-Wilk's test) and equality of  
15 variance (Levene's test), and a logarithmic transformation was applied when these  
16 assumptions were not met. Linear mixed-effect (LME) models (Crawley, 2007) were used to  
17 assess differences in N-oxide fluxes between landscapes for the reference land uses (testing  
18 H1) or to assess differences in N-oxide fluxes among land uses within each landscape (testing  
19 H2). Furthermore, a LME model was applied to assess differences in soil  $\text{N}_2\text{O}$  fluxes between  
20 the smallholder and large-scale (PTPN VI) oil palm plantations (as a follow-on study) within  
21 the loam Acrisol landscape. The LME models were also used to assess fertilization effects (i.e.,  
22 as represented by the chamber locations F1, F2 and NF) on soil N-oxide fluxes from  
23 smallholder oil palm plantations and to test differences in N-oxide fluxes between landscapes  
24 following fertilization for chamber locations F1 and F2. The detailed descriptions of the LME

1 models are provided in Appendix A. Significant differences were based on the analysis of  
2 variance with Fisher's least significant difference test for multiple comparisons. We set the  
3 statistical significance at  $P \leq 0.05$  and, only for a few specified parameters, we also  
4 considered marginal significance at  $P \leq 0.09$  because our experimental design encompassed  
5 the inherently high spatial variability in our study area (e.g., Hassler et al., 2015).

6 To assess the temporal relationships between soil N-oxide fluxes and soil factors  
7 (temperature, WFPS,  $\text{NO}_3^-$  and  $\text{NH}_4^+$ ), we used the means of the replicate plots per land use  
8 on each of the 12 monthly measurements and conducted Pearson's correlation test separately  
9 for the reference land uses (forest and jungle rubber,  $n = 48$  ( $\text{N}_2\text{O}$ ),  $n = 16$  ( $\text{NO}$ )) and the  
10 converted land uses (rubber and oil palm,  $n = 48$ , ( $\text{N}_2\text{O}$ ),  $n = 16$  ( $\text{NO}$ )) across landscapes for  
11 the whole year. Similarly, for soil  $\text{N}_2\text{O}$  and  $\text{NO}$  fluxes following fertilizer application from  
12 smallholder oil palm plantations, we used the means of the three replicate trees per chamber  
13 location on each sampling day and conducted Pearson's correlation test for each site across  
14 the entire measurement period of fertilization effects ( $n = 6-11$ ). To assess the spatial controls  
15 of soil biochemical characteristics (Appendix Table A2) on annual soil  $\text{N}_2\text{O}$  fluxes, we used  
16 the annual flux of each replicate plot and conducted Spearman's rank correlation test  
17 separately for the reference land uses and converted land uses across landscapes ( $n = 16$ ) and  
18 within each landscape ( $n = 8$ ). We did not assess the spatial control of soil biochemical  
19 characteristics on annual soil  $\text{NO}$  fluxes since we did not calculate annual flux from the four  
20 measurement periods (as explained in Sect. 2.2). Correlations were considered statistically  
21 significant at  $P \leq 0.05$  and marginally significant at  $P \leq 0.09$ . All statistical analyses were  
22 conducted using R 3.2.2 (R Development Core Team, 2015).

23

## 24 **3 Results**

### 25 **3.1 Soil N-oxide fluxes**



1 In the reference land uses (forest and jungle rubber), N<sub>2</sub>O was the dominant N-oxide emitted  
2 from soils. In the clay Acrisol landscape, there was a net NO consumption in the soil of the  
3 jungle rubber (Table 1). Soil N<sub>2</sub>O and NO fluxes from reference land uses were comparable  
4 between the two landscapes ( $P = 0.54\text{--}0.74$ ; Table 1; Fig. 1a, b). These fluxes also  
5 exemplified high inherent spatial and temporal variations as indicated by their large standard  
6 errors.

7 In the converted land uses (smallholder rubber and oil palm plantations), soil N<sub>2</sub>O  
8 fluxes were similar to the fluxes of reference land uses ( $P = 0.58\text{--}0.76$ ; Table 1; Fig. 1a, b)  
9 within each landscape. However, in the loam Acrisol landscape, the large-scale oil palm  
10 plantation PTPN VI had on average 3.5 times higher soil N<sub>2</sub>O fluxes than those from the  
11 smallholder plantations (Table 1), although this trend was not statistically different ( $P = 0.15$ )  
12 because of the large variation among replicate plots (as indicated by the large standard error)  
13 in this large-scale plantation. Soil NO fluxes, were not different either among land uses in the  
14 clay Acrisol landscape ( $P = 0.73$ ; Table 1). However, in the loam Acrisol landscape, soil NO  
15 fluxes were marginally lower ( $P = 0.07$ ) in rubber plantations (with net NO consumption in  
16 the soil) than in jungle rubber (with net NO emission), whereas they were intermediary in  
17 forests and oil palm plantations (Table 1).

18

### 19 **3.2 Fertilization effects on soil N-oxide fluxes from smallholder oil palm plantations**

20 In comparison to the unfertilized area (chamber location NF at 4–4.5 m from the tree base),  
21 soil N<sub>2</sub>O fluxes were on average 442 times (clay Acrisol) and 22 times (loam Acrisol) higher  
22 within the small fertilized areas around the oil palms (chamber location F2 at 0.8–1 m from  
23 the tree base that received 0.32 and 0.26 kg N tree<sup>-1</sup> in the clay and loam Acrisols,  
24 respectively) during the 3 to 8.5 weeks following fertilizer applications (all  $P < 0.01\text{--}0.03$ ;  
25 Table 2; Fig. 2c, d). In the chamber location closest to the tree (chamber location F1 at 0.3 m

1 from the tree base), soil N<sub>2</sub>O emissions were also 25 times higher compared to the reference  
2 chamber location NF in the clay Acrisol landscape (all  $P < 0.01$ ; Table 2; Fig. 2a). In the loam  
3 Acrisol landscape, we only detected such an effect in site 2 which displayed 16 times higher  
4 soil N<sub>2</sub>O emissions in chamber location F1 compared to the reference chamber location NF ( $P$   
5 = 0.03; Table 2; Fig. 2b).

6 In the clay Acrisol landscape, soil N<sub>2</sub>O emissions in chamber location F2 increased  
7 immediately after fertilizer application, reached a peak within 9 days following fertilizer  
8 application and stayed elevated for at most 2 months (Fig. 2c). In the loam Acrisol landscape,  
9 N<sub>2</sub>O fluxes in chamber location F2 increased within the first 5 days, reached maximum fluxes  
10 within 5–21 days and remained elevated for at most 6.5 weeks (Fig. 2d). Soil N<sub>2</sub>O fluxes in  
11 chamber location F1 displayed a similar but less pronounced pattern as those of chamber  
12 location F2 in both landscapes (Fig. 2a, b).

13 The average contributions of the fertilizer-induced N<sub>2</sub>O emissions to the annual fluxes  
14 were 21 % in the clay Acrisol landscape, and only 6 % in the loam Acrisol landscape (Table  
15 1). To calculate this contribution (see Sect. 2.2), we considered the area coverage (4 % of a  
16 hectare, based on the number of palms ha<sup>-1</sup>) and time span of fertilizer-induced N<sub>2</sub>O  
17 emissions.

18 Compared to the unfertilized area (chamber location NF), soil NO fluxes from the  
19 fertilized area (chamber location F2) had on average 357 times (clay Acrisol) and 238 times  
20 (loam Acrisol) higher fluxes (both  $P < 0.01$ ) during 6 to 8.5 weeks of measurements  
21 following fertilizer application (Table 2; Fig. 3c, d). No differences in soil NO fluxes were  
22 detected between chamber locations F1 and NF ( $P = 0.10$ – $0.12$ ; Table 2; Fig. 3a, b). Soil NO  
23 fluxes in chamber location F2 peaked after 10 days in the loam Acrisol and after 3 weeks in  
24 the clay Acrisol landscape (Fig. 3c, d), and returned to the background fluxes after 6–8.5

1 weeks with a drastic drop after 3–5 weeks (Fig. 3c, d). In chamber location F1, soil NO fluxes  
2 increased quickly and decreased to the background fluxes within at most 16 days following  
3 fertilizer application (Fig. 3a, b). As was the case for the monthly sampling, soil N<sub>2</sub>O fluxes  
4 from chamber locations F1 and F2 were larger than soil NO fluxes for both landscapes, (Table  
5 2; Fig. 2a–d and 3a–d). Comparing between landscapes, soil N<sub>2</sub>O fluxes from chamber  
6 location F2 were higher in the clay than loam Acrisol soils ( $P = 0.09$ ; Table 2; Fig. 2c, d) but  
7 were comparable for chamber location F1 ( $P = 0.41$ ; Table 2; Fig. 2a, b) and for soil NO  
8 fluxes of both chamber locations ( $P = 0.45$ – $0.78$ ; Table 2; Fig. 3a–d).

9 Fertilizer-induced soil NO fluxes in the loam Acrisol landscape were  $0.07 \pm 0.02$  kg  
10 NO-N ha<sup>-1</sup> yr<sup>-1</sup>, which was roughly the same as our extrapolated annual value of  $0.06 \pm 0.06$   
11 kg NO-N ha<sup>-1</sup> yr<sup>-1</sup> from the four measurement periods (Table 1). In the clay Acrisol  
12 landscape, fertilizer-induced soil NO fluxes were  $0.12 \pm 0.04$  kg NO-N ha<sup>-1</sup> yr<sup>-1</sup>, which was a  
13 net emission compared to our extrapolated annual value with a net sink of  $-0.02 \pm 0.11$  kg  
14 NO-N ha<sup>-1</sup> yr<sup>-1</sup>, based on the four measurement periods (Table 1). The percentages of  
15 combined soil N<sub>2</sub>O and NO fluxes to the applied N fertilizer rate were on average  $0.73 \% \text{ yr}^{-1}$   
16 in the clay Acrisol landscape and  $0.20 \% \text{ yr}^{-1}$  in the loam Acrisol landscape.

17

### 18 **3.3 Temporal controls of soil N-oxide fluxes**

19 In the reference land uses, soil N<sub>2</sub>O and NO fluxes were both positively correlated with soil  
20 NO<sub>3</sub><sup>-</sup> contents, while soil NO fluxes were also negatively correlated with WFPS and soil NH<sub>4</sub><sup>+</sup>  
21 contents (Table 3). In the converted land uses, soil N<sub>2</sub>O fluxes were positively correlated with  
22 soil NO<sub>3</sub><sup>-</sup> contents (Table 3). There were no significant correlations observed between soil NO  
23 fluxes and soil factors in the converted land uses due to the very low NO emissions and even  
24 net NO uptake.

1 From the fertilizer application experiment in the smallholder oil palm plantations, the  
2 location directly receiving fertilizer (chamber location F2) showed positive correlations of  
3 soil N<sub>2</sub>O fluxes with soil NH<sub>4</sub><sup>+</sup> and/or NO<sub>3</sub><sup>-</sup> contents in three of the six sites (Table 4). Here,  
4 also soil NO fluxes correlated positively with soil NO<sub>3</sub><sup>-</sup> contents in the loam Acrisol but not in  
5 the clay Acrisol (Table 4). In chamber location F1, positive correlations of soil N<sub>2</sub>O fluxes  
6 with soil NH<sub>4</sub><sup>+</sup> and/or NO<sub>3</sub><sup>-</sup> contents were observed in four of the six sites (Table 4). The  
7 correlations of soil N<sub>2</sub>O fluxes with mineral N for chamber location F1 in site 2 of the clay  
8 Acrisol landscape were caused by one measurement period with very high flux, and exclusion  
9 of this observation resulted in a none significant correlation. For soil NO fluxes from chamber  
10 location F1, we did not detect any significant correlation with soil factors (Table 4). A  
11 positive correlation of soil N<sub>2</sub>O fluxes with WFPS was observed for chamber locations F1 and  
12 F2 in site 1 of the loam Acrisol landscape, whereas this correlation was negative for chamber  
13 location F1 in site 3 of the same landscape (Table 4). We also detected a negative correlation  
14 between soil NO fluxes and WFPS for chamber location F2 in site 3 of the clay Acrisol,  
15 whereas in the same site soil NO fluxes and WFPS were positively correlated for the  
16 unfertilized chamber location NF (Table 4); however this latter correlation was caused by  
17 only one sampling time with a high flux and high WFPS.

18

### 19 **3.4 Spatial controls of annual soil N<sub>2</sub>O fluxes**

20 The soil physical and biochemical characteristics (reported earlier by Allen et al., 2015) that  
21 showed significant correlations with annual soil N<sub>2</sub>O fluxes are reported in Appendix Table  
22 A2. For the reference land uses, annual N<sub>2</sub>O fluxes were positively correlated with gross  
23 nitrification rates across landscapes (*Spearman's*  $\rho = 0.57$ ,  $P = 0.02$ ,  $n = 16$ ). Within each  
24 landscape, annual soil N<sub>2</sub>O fluxes from the reference land uses correlated negatively with soil  
25 C:N ratio ( $\rho = -0.69$ ,  $P = 0.07$ ,  $n = 8$ ) in the clay Acrisol, whereas in the loam Acrisol annual

1 soil N<sub>2</sub>O fluxes correlated positively with microbial C ( $\rho = 0.69$ ,  $P = 0.07$ ,  $n = 8$ ). For the  
2 converted land uses, annual N<sub>2</sub>O fluxes correlated negatively with sand content across  
3 landscapes ( $\rho = -0.57$ ,  $P = 0.06$ ,  $n = 12$ ). There were no other correlations detected with any  
4 other soil biochemical parameters.

5

## 6 **4 Discussion**

### 7 **4.1 Soil N<sub>2</sub>O and NO fluxes from the reference land uses**

8 The N<sub>2</sub>O fluxes from our forest soils (Table 1) fell at the lower end of those reported for  
9 humid tropical forests (10–85  $\mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ ; summarized by Castaldi et al., 2013).  
10 Compared to soil N<sub>2</sub>O fluxes measured in Indonesia, our values were comparable to those  
11 reported for montane forests on Cambisol soil with similar sampling frequency and spatial  
12 replication (13  $\mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ ; Purbopuspito et al., 2006) and to five lowland forest stands  
13 on Acrisol soil measured once (12  $\mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ ; Ishizuka et al., 2005). However, soil  
14 N<sub>2</sub>O fluxes from our forests were lower than those reported for montane forests on Cambisol  
15 soils with six monthly measurements and comparable replication (25  $\mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ ;  
16 Veldkamp et al., 2008) and from a lowland forest on Ferralsol soil with 13 measurements at  
17 monthly interval (20  $\mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ ; Aini et al., 2015). In contrast, our values were higher  
18 than those reported for two lowland forests on Ferralsol soil with nine measurements at  
19 monthly interval (3  $\mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ ; Ishizuka et al., 2002). Since the studies from the  
20 montane forests were conducted on fertile, less-weathered Cambisol soils and the studies  
21 within the same region (Jambi province) by Ishizuka et al. (2002, 2005) and Aini et al. (2015)  
22 have less sampling frequency or spatial replication, their values should be carefully related to  
23 our measured fluxes.

1           Soil NO fluxes from Southeast Asian lowland forests are not reported so far. Our  
2 measured NO fluxes from the forest soils (Table 1) tended to be lower than those reported for  
3 lowland forests in Latin America with soils ranging from less weathered Cambisols to highly  
4 weathered Acrisols and Ferralsols (from 3–90  $\mu\text{g NO-N m}^{-2} \text{ h}^{-1}$ ; Corre et al., 2014; Davidson  
5 et al., 2004; Keller et al., 2005; Verchot et al., 1999). There are only two studies conducted in  
6 Indonesia that reported soil NO fluxes from montane forests on Cambisol soils (Purbopuspito  
7 et al., 2006, Veldkamp et al., 2008). Our measured soil NO fluxes were comparable with the  
8 values reported for montane forests at  $\geq 1800$  m elevation ( $2 \mu\text{g NO-N m}^{-2} \text{ h}^{-1}$ ; Purbopuspito  
9 et al., 2006) but lower than those reported for (pre)montane forests ( $6\text{--}12 \mu\text{g NO-N m}^{-2} \text{ h}^{-1}$ ;  
10 Purbopuspito et al., 2006; Veldkamp et al., 2008). Although it is known that tropical forest  
11 soils are the largest natural source of  $\text{N}_2\text{O}$  and produce considerable amounts of NO, our  
12 measurements from these lowland forests in Jambi, Indonesia on highly weathered Acrisol  
13 soils showed generally low soil N-oxide fluxes.

14           In contrast to our first hypothesis (H1), soil N-oxide fluxes from the reference land  
15 uses were comparable between loam and clay Acrisol landscapes. This is possibly due to the  
16 generally low soil N availability in these sites, as indicated by their lower gross N  
17 mineralization rates (Allen et al., 2015) compared, for example, to the less weathered  
18 Cambisol and Nitisol soils in a lowland forest of Panama (Corre et al., 2010). Soil N-oxide  
19 fluxes are largely controlled, first, by the magnitude of soil N availability, as depicted in the  
20 HIP conceptual model (Davidson et al., 2000). This influence of soil N availability on N-  
21 oxide fluxes was illustrated by the positive correlations of soil N-oxide fluxes with soil  $\text{NO}_3^-$   
22 contents (Table 3). Across landscapes, this first level of control was also corroborated by the  
23 positive correlations of annual soil  $\text{N}_2\text{O}$  fluxes with gross nitrification rates, and within each  
24 landscape by the negative correlation with the soil C:N ratio (clay Acrisol landscape) and by  
25 the positive correlation with microbial C (loam Acrisol landscape) (see Sect. 3.4). Our

1 findings were consistent with those from other tropical soils, illustrating that soil N-oxide  
2 fluxes across or within sites are controlled by soil N availability as expressed in various  
3 indexes such as soil  $\text{NO}_3^-$  contents (Keller and Reiners, 1994; Müller et al., 2015),  
4 nitrification rates (Davidson et al., 2000) and soil C:N ratio (Breuer et al., 2000).

5         Moreover, we attributed the low soil NO fluxes and the dominance of  $\text{N}_2\text{O}$  (Table 1)  
6 in our sites to the second level of control of N-oxide fluxes - soil aeration status (HIP model;  
7 Davidson et al., 2000). The ratio of  $\text{N}_2\text{O}$  to NO is expected to increase when WFPS exceeds  
8 60 % as low soil aeration favors  $\text{N}_2\text{O}$  production by denitrification and nitrification processes  
9 (Davidson et al., 2000). WFPS in the reference land uses were  $\geq 60$  % (Appendix Table A3,  
10 except in jungle rubber of the loam Acrisol with 54 % WFPS). Hence, it was not surprising  
11 that our measured soil NO fluxes were close to zero or showed net consumption (Table 1); the  
12 high WFPS may have led to NO reduction to  $\text{N}_2\text{O}$  (Conrad, 1996; Pilegaard, 2013). This was  
13 supported by the negative correlation between soil NO fluxes and WFPS (Table 3).  
14 Furthermore, increased concentrations of NO in the atmosphere due to biomass burning in  
15 this region (Field et al., 2009; Levine, 1999), which also occurred in 2013 (Gaveau et al.,  
16 2014), may have resulted in a net NO consumption (not only in the reference land uses but  
17 also in the converted land uses; Table 1) since increased ambient NO concentration could  
18 enhanced soil NO uptake (Conrad, 1994). In summary, soil NO fluxes from the reference land  
19 uses were of minor importance compared to soil  $\text{N}_2\text{O}$  fluxes. However, if droughts will occur  
20 more frequently or extremely in this region (Lestari et al., 2014), soil NO fluxes might  
21 become important.

22

#### 23 **4.2 Land-use change effects on soil $\text{N}_2\text{O}$ and NO fluxes**

24         Soil  $\text{N}_2\text{O}$  fluxes from our unfertilized rubber plantations (Table 1) were comparable to  
25 a rubber plantation on Ferralsol soil in Malaysia with eight measurements during 1.5-year

1 period ( $8 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ , fertilized with  $9 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ; Yashiro et al., 2008) and slightly  
2 higher than fluxes reported from a rubber plantation on a lateritic soil in China with only two  
3 months of measurement ( $4 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ , fertilized with  $55 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ; Werner et al.,  
4 2006). Studies from the same region (Jambi, Indonesia) report either lower soil  $\text{N}_2\text{O}$  fluxes  
5 from a rubber plantation on Ferralsol soil with nine sampling days at monthly interval ( $1 \mu\text{g}$   
6  $\text{N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ ; Ishizuka et al., 2002) or higher fluxes from five rubber plantations on Acrisol  
7 soils with only one-time measurement ( $21 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ ; Ishizuka et al., 2005) and from  
8 one rubber plantation on Ferralsol soil with 13 sampling days at monthly interval ( $12 \mu\text{g N}_2\text{O-}$   
9  $\text{N m}^{-2} \text{ h}^{-1}$ ; Aini et al., 2015). The rubber plantations in these latter three studies were all not  
10 fertilized. Soil  $\text{N}_2\text{O}$  fluxes from our oil palm plantations (Table 1), which had fertilization of  
11  $48\text{--}88 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , were in the same order of magnitude as those reported from three  
12 fertilized oil palm plantations on Acrisol soils in Jambi, Indonesia with only one-time  
13 measurement ( $15 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ ; Ishizuka et al., 2005) and from one unfertilized oil palm  
14 plantation on Cambisol soil in Jambi, Indonesia with 13 monthly measurements ( $12 \mu\text{g N}_2\text{O-}$   
15  $\text{N m}^{-2} \text{ h}^{-1}$ ; Aini et al., 2015). However, soil  $\text{N}_2\text{O}$  fluxes from our oil palm sites were higher  
16 compared to one oil palm plantation on Ferralsol soil in Malaysia with eight measurements  
17 during 1.5-year period ( $-0.1 \mu\text{g N}_2\text{O-N m}^{-2} \text{ h}^{-1}$ , fertilized with  $25 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ; Yashiro et al.,  
18 2008). Soil  $\text{NO}$  fluxes have never been reported from rubber or oil palm plantations.

19 In contrast to our second hypothesis (H2), soil N-oxide fluxes were comparable among  
20 land uses (except for soil  $\text{NO}$  fluxes between rubber and jungle rubber in the loam Acrisol  
21 landscape as discussed below), even with the observed decreases in soil mineral N levels  
22 among land uses (i.e., generally lower  $\text{NH}_4^+$  and  $\text{NO}_3^-$  levels in rubber plantations than in the  
23 reference land uses at both landscapes; Appendix Table A3). In the same study sites, Allen et  
24 al. (2015) found differences in other indices of soil N availability with land-use change,  
25 particularly in the clay Acrisol landscape: microbial C and N, gross N mineralization and



1  $\text{NH}_4^+$  immobilization rates decrease with conversion of forest to rubber or oil palm  
2 plantations. N-oxide emissions generally account only a small fraction of soil available N  
3 (e.g.,  $\text{N}_2\text{O}$  + NO emissions comprise 0.03 % of gross N mineralization rates in a lowland  
4 forest on Cambisol and Nitisols soils in Panama; Corre et al., 2014). In our present study, the  
5 reference land uses on highly weathered Acrisol soils have low soil N availability and their  
6 conversion to these plantations further decreases the soil N-cycling rates (Allen et al., 2015).  
7 Hence, we reason that we did not detect differences in N-oxide fluxes with land-use  
8 conversion to rubber and oil palm plantations because we started with low soil N availability  
9 and low N-oxide emissions and any changes were probably too small to detect statistically.  
10 The temporal pattern of soil  $\text{N}_2\text{O}$  fluxes in the converted land uses were also controlled by  
11 soil  $\text{NO}_3^-$  contents (Table 3), emphasizing the first level of control of soil N availability on  
12 soil  $\text{N}_2\text{O}$  fluxes (HIP model; Davidson et al., 2000). Across landscapes, the correlations of  
13 annual soil  $\text{N}_2\text{O}$  fluxes from these converted land uses with sand contents (see Sect. 3.4) also  
14 suggested the indirect influence of soil texture on water holding capacity, or conversely soil  
15 aeration status, which is the second level of control on soil  $\text{N}_2\text{O}$  fluxes (HIP model).  
16 Consequently, the soil N-oxide emission footprint of smallholder oil palm and rubber  
17 plantations was similar to the original land uses (Table 1). This finding was in contrast to a  
18 study by Hewitt et al. (2009) conducted in Sabah, Malaysian Borneo, wherein they showed  
19 that oil palm plantations emit more N-oxides than rainforests, which may be explained by  
20 their higher fertilization rate ( $500 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ) compared to our smallholder oil palm  
21 plantations ( $48\text{-}88 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ). Thus, an increase in fertilizer usage, e.g., in large-scale  
22 plantations in our study region, might change this soil N-oxide emission footprint drawn  
23 mainly from smallholder plantations (see Sect. 4.3).

24         The lower soil NO fluxes in rubber compared to jungle rubber in the loam Acrisol  
25 (Table 1) partly supports our second hypothesis. These differences might be related to the

1 high soil  $\text{NO}_3^-$  contents and low WFPS in jungle rubber (Appendix Table A3), which could  
2 favor its relatively high soil NO emissions; this was also supported by the opposing  
3 correlations of soil NO flux with soil  $\text{NO}_3^-$  and WFPS (Table 3). Additionally, the low soil  
4 NO fluxes from rubber plantations could be the result of the effect of monoterpenes, produced  
5 by rubber trees, which reduce nitrification in soil (Wang et al., 2007; White, 1991). This is  
6 supported by low gross nitrification rates (measured in the same plots by Allen et al., 2015),  
7 low soil  $\text{NO}_3^-$  contents (Appendix Table A3) and consequently low soil NO fluxes in rubber  
8 plantations (Table 1).

9

#### 10 **4.3 Soil management effects on soil $\text{N}_2\text{O}$ and NO fluxes from oil palm plantations**

11 N fertilizer application, a commonly employed soil management in oil palm plantations (e.g.,  
12 Allen et al., 2015; Hassler et al., 2015), increases N-oxide emission for a relatively short  
13 period (e.g., Koehler et al. 2009). Our findings show that these fertilizer-induced N-oxide  
14 emissions were mainly limited to the small area around the palm base where fertilizer was  
15 commonly applied (4 % of the area in a hectare) and that N-oxide emissions peaked within 3  
16 weeks (Figs. 2 and 3). These N-fertilizer induced  $\text{N}_2\text{O}$  fluxes of 6–21 % of the annual soil  
17  $\text{N}_2\text{O}$  fluxes were similar in magnitude as the standard errors of the annual fluxes (estimated  
18 from the monthly measurements; Table 1). Thus, inclusion of these N-induced emissions in  
19 our annual estimates did not result in statistically significant effects of land-use change.

20 The percentages of soil  $\text{N}_2\text{O}$  and NO fluxes to the applied N fertilizer rate were  
21 smaller than those reported from other agricultural land uses in humid tropical regions (6.4–  
22 8.6 %; Veldkamp and Keller, 1997; Veldkamp et al., 1998). Usually the percentage of soil N-  
23 oxide emissions to applied N fertilizer rate increases with increasing N fertilization rates  
24 (Hoben et al., 2011; Pennock and Corre, 2001). Since the fertilization rates in our studied  
25 smallholder oil palm plantations (48–88 kg N  $\text{ha}^{-1}$   $\text{yr}^{-1}$ ) were lower compared to the

1 fertilization rates in these other studies (300–360 kg N ha<sup>-1</sup> yr<sup>-1</sup>; Veldkamp and Keller, 1997;  
2 Veldkamp et al., 1998), our quantified N-oxide loss from N fertilizer were also low. The  
3 relatively high soil N<sub>2</sub>O fluxes from the large-scale oil palm plantation PTPN VI, although  
4 not statistically different from the smallholder plantations (Table 1), could be attributed to its  
5 high N fertilization rate (196 kg N ha<sup>-1</sup> yr<sup>-1</sup>). Summing the fertilizer-induced N-oxide fluxes  
6 and the annual soil N-oxide emissions based on the monthly measurements (Table 1), these  
7 values from the smallholder plantations were low relative to the annual flux from the large-  
8 scale plantation (Table 1). Based on our finding that soil N<sub>2</sub>O fluxes following fertilizer  
9 application (chamber location F2) were higher in the clay than loam Acrisol landscapes (most  
10 likely due to higher WFPS in the clay (61 ± 8 %) than loam Acrisol (27 ± 3 %) during this  
11 measurement period), soil N-oxide fluxes from large-scale plantations on clay soils could be  
12 even higher than what we measured here from a large-scale plantation on a loam soil. Our  
13 findings reinforced the need to quantify these climate-relevant N-oxide gases in large-scale  
14 plantations, which constitute ~50 % of the land area under oil palm plantation in whole of  
15 Sumatra (BPS, 2014).

16 Temporal patterns of soil N-oxide fluxes following fertilizer application were also  
17 controlled by soil N availability, as reflected by their positive correlations with soil NH<sub>4</sub><sup>+</sup>  
18 and/or NO<sub>3</sub><sup>-</sup> contents (Table 4). The application of N fertilizer provides temporary surplus of  
19 mineral N that was lost via gaseous emission and leaching (Kurniawan, 2016), and such effect  
20 diminished with time as the mineral N is incorporated into the soil N-cycling processes (Allen  
21 et al., 2015). The positive correlation between soil N<sub>2</sub>O fluxes and WFPS (i.e., chamber  
22 locations F1 and F2 in site 1 of the loam Acrisol; Table 4) and the negative correlation  
23 between soil NO fluxes and WFPS (i.e., chamber location F2 in site 3 of the clay Acrisol  
24 landscape; Table 4) again attested that when the first level of control (soil N availability) was  
25 favorable (i.e., high soil mineral N contents in these fertilized chamber locations) the control

1 of soil moisture on aeration status was enhanced, as such correlation was not seen in the  
2 unfertilized area (chamber location NF) or in the monthly measured fluxes (Tables 3 and 4).  
3 These correlations indicated that following fertilizer application soil NO fluxes decreased  
4 whereas soil N<sub>2</sub>O fluxes increased with increase in WFPS. In site 3 of the loam Acrisol, the  
5 seemingly contradicting negative correlation of soil N<sub>2</sub>O fluxes with WFPS (Table 4) was  
6 only because there was a decreasing WFPS following fertilizer application with concurrently  
7 increasing soil mineral N contents - the latter dominantly driving the increases in soil N<sub>2</sub>O  
8 fluxes (i.e., positive correlations with NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup>; Table 4). In summary, the short-term  
9 effect of fertilization also depicted the two levels of controls on soil N-oxide fluxes as  
10 exemplified in the HIP model.

11

## 12 **5 Conclusions**

13 Our study provides the first spatially replicated study with a full year of measurements (at  
14 monthly interval) of soil N<sub>2</sub>O fluxes and the first reported soil NO fluxes from this region of  
15 hotspot of land-use conversion for globally important tree cash crops. In contrast to our first  
16 hypothesis (H1), soil texture, through its role on soil fertility, did not directly affect soil N-  
17 oxide fluxes (as shown by the comparable fluxes between landscapes with soil textural  
18 differences) but indirectly influenced the landscape-scale pattern of annual soil N<sub>2</sub>O fluxes in  
19 the converted land uses (i.e., negative correlation between annual N<sub>2</sub>O fluxes and sand  
20 content) most likely through its role on soil moisture availability. The generally low soil N-  
21 oxide fluxes from the reference land uses were due to the low soil N availability in these  
22 highly weathered Acrisol soils (Allen et al., 2015). Forest or jungle rubber conversion to  
23 rubber and oil palm by smallholders also did not show significant changes in soil N-oxide  
24 fluxes, except for the decrease in soil NO fluxes in rubber plantations and for the short-term  
25 pulse of soil N-oxide fluxes following fertilizer application in oil palm plantations. These

1 partly support our second hypothesis (H2). Using a conservative estimate of N-oxide ( $\text{N}_2\text{O} +$   
2  $\text{NO}$ ) loss from the applied N fertilizer in oil palm plantations (average of 0.5 % from the loam  
3 and clay Acrisol landscapes), and a conservative average N fertilization rate across  
4 smallholder and large-scale plantations of  $100 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , with the total land area of oil  
5 palm in Jambi province of 721000 ha (BPS, 2014), we estimated an annual soil N-oxide  
6 emission from N fertilization of 361 tons  $\text{N yr}^{-1}$ . The N fertilization rates in our smallholder  
7 oil palm plantations were only about one-fourth to one-half of what is commonly practiced in  
8 large-scale industrial plantations (e.g.,  $130\text{--}260 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  in Jambi, Indonesia; Pahan,  
9 2010), and our measurements from a large-scale oil palm plantation PTPN VI showed  
10 relatively high soil N-oxide fluxes. To improve estimate of soil N-oxide fluxes at regional  
11 level, future studies should focus on large-scale plantations (which constitute 38 % of oil  
12 palm land area in Jambi province; BPS, 2014) with frequent measurements during 2 months  
13 following fertilizer application, and particularly during wet season for  $\text{N}_2\text{O}$  flux  
14 measurements and during dry season for  $\text{NO}$  flux measurements.

15

## 16 **Data availability**

17 The underlying research data of this study is deposited at the EFForTS-IS data repository  
18 (<https://efforts-is.uni-goettingen.de>), an internal data exchange-platform, which is accessible  
19 to all members of the Collaborative Research Center (CRC) 990 (see Acknowledgements).  
20 Based on data sharing agreement within the CRC 990, these data are currently not publicly  
21 accessible but will be made available through a written request to the senior authors.

22

## 23 **Competing interests**

24 The authors declare that they have no conflict of interest.

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20

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5

1 **Table 1.** Mean ( $\pm$ SE,  $n = 4$  sites) soil N<sub>2</sub>O (with 12 monthly measurements) and NO fluxes  
2 (with four monthly to bimonthly measurements) and annual soil N<sub>2</sub>O fluxes from different  
3 land uses within each landscape in Jambi, Indonesia. Means followed by different lowercase  
4 letters indicate significant differences among land uses within each landscape and different  
5 capital letters indicate significant differences between landscapes within each land use (linear  
6 mixed-effect models with Fisher's LSD test at  $P \leq 0.09$ ). For soil NO fluxes in the clay  
7 Acrisol, forest was excluded in the comparison among land uses because measurements were  
8 only carried out in two sites. Annual soil N<sub>2</sub>O fluxes are calculated from the monthly fluxes  
9 using trapezoidal rule. For smallholder oil palm plantations, values in italics were the  
10 fertilizer-induced annual soil N<sub>2</sub>O fluxes (see Sect. 2.2). In the loam Acrisol landscape, soil  
11 N<sub>2</sub>O fluxes were additionally measured in a large-scale oil palm plantation (mean $\pm$ SE,  $n = 4$   
12 replicates); these fluxes did not differ from those of smallholder plantations within the same  
13 landscape (linear mixed-effect models with Fisher's LSD test at  $P = 0.15$ ).

Land-use type	N <sub>2</sub> O fluxes ( $\mu\text{g N m}^{-2} \text{h}^{-1}$ )	NO fluxes ( $\mu\text{g N m}^{-2} \text{h}^{-1}$ )	Annual N <sub>2</sub> O fluxes ( $\text{kg N ha}^{-1} \text{year}^{-1}$ )
clay Acrisol landscape			
Forest	$12.8 \pm 5.6^{\text{a,A}}$	$(1.7 \pm 0.3)$	$1.0 \pm 0.4$
Jungle rubber	$6.7 \pm 1.5^{\text{a,A}}$	$-0.6 \pm 0.7^{\text{a,A}}$	$0.6 \pm 0.1$
Rubber	$5.6 \pm 2.5^{\text{a,A}}$	$-1.0 \pm 0.2^{\text{a,A}}$	$0.5 \pm 0.2$
Oil palm (smallholder plantation)	$11.5 \pm 2.9^{\text{a,A}}$	$-0.2 \pm 1.2^{\text{a,A}}$	$1.0 \pm 0.3$ <i><math>0.2 \pm 0.0</math></i>
loam Acrisol landscape			
Forest	$9.8 \pm 1.5^{\text{a,A}}$	$1.9 \pm 1.3^{\text{ab}}$	$0.9 \pm 0.2$
Jungle rubber	$14.0 \pm 6.7^{\text{a,A}}$	$5.7 \pm 5.8^{\text{a,A}}$	$1.2 \pm 0.6$

Rubber	$8.6 \pm 2.0^{a,A}$	$-1.2 \pm 0.5^{b,A}$	$0.7 \pm 0.2$
Oil palm (smallholder plantation)	$12.2 \pm 6.1^{a,A}$	$0.7 \pm 0.7^{ab,A}$	$1.1 \pm 0.5$ $0.1 \pm 0.0$
Oil palm (large-scale plantation)	$42.3 \pm 24.2^{a,A}$	-	$3.3 \pm 1.7$

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1



1 **Table 2.** Mean ( $\pm$ SE,  $n = 3$  oil palm trees) soil N<sub>2</sub>O and NO fluxes from three chamber  
2 locations during a fertilization in three (for N<sub>2</sub>O) or one (for NO) smallholder oil palm  
3 plantation within each landscape, measured 6 to 11 times during 3–8.5 weeks following  
4 fertilization. Means followed by different letters indicate significant differences among  
5 chamber locations within each site (linear mixed-effect models with Fisher's LSD test at  
6  $P \leq 0.05$ ). Chamber F1, F2 and NF were placed at 0.3 m (with incidental fertilization), 0.8 m  
7 (fertilized area), and 4–4.5 m (non-fertilized area, serving as the reference chamber),  
8 respectively, from the stem base. 0.32 kg N tree<sup>-1</sup> was applied in the clay Acrisol and 0.26 kg  
9 N tree<sup>-1</sup> in the loam Acrisol in accordance to the smallholders' practices.

Oil palm site	Chamber location	N <sub>2</sub> O fluxes (μg N m <sup>-2</sup> h <sup>-1</sup> )	NO fluxes (μg N m <sup>-2</sup> h <sup>-1</sup> )
clay Acrisol landscape			
1	F1	156.7 ± 86.8 <sup>b</sup>	-
	F2	910.1 ± 410.0 <sup>a</sup>	-
	NF	6.9 ± 3.3 <sup>c</sup>	-
2	F1	130.6 ± 34.6 <sup>b</sup>	-
	F2	692.7 ± 144.1 <sup>a</sup>	-
	NF	9.9 ± 3.0 <sup>c</sup>	-
3	F1	45.5 ± 3.7 <sup>b</sup>	4.7 ± 1.7 <sup>b</sup>
	F2	1281.0 ± 486.7 <sup>a</sup>	535.3 ± 194.5 <sup>a</sup>
	NF	1.1 ± 1.6 <sup>c</sup>	1.5 ± 1.5 <sup>b</sup>
Oil palm site	Chamber location	N <sub>2</sub> O fluxes (μg N m <sup>-2</sup> h <sup>-1</sup> )	NO fluxes (μg N m <sup>-2</sup> h <sup>-1</sup> )
loam Acrisol landscape			

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1	F1	$33.5 \pm 9.8^b$	-
	F2	$133.4 \pm 34.9^a$	-
	NF	$11.8 \pm 6.1^b$	-
2	F1	$129.7 \pm 46.2^a$	$46.2 \pm 19.6^b$
	F2	$205.3 \pm 24.2^a$	$157.1 \pm 35.7^a$
	NF	$7.9 \pm 4.8^b$	$0.7 \pm 0.3^b$
3	F1	$5.2 \pm 1.0^b$	-
	F2	$104.5 \pm 81.9^a$	-
	NF	$3.7 \pm 1.7^b$	-

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1

1 **Table 3.** Pearson correlation coefficients between soil N<sub>2</sub>O flux ( $n = 48$ ;  $\mu\text{g N m}^{-2} \text{h}^{-1}$ ), soil  
2 NO flux ( $n = 16$ ;  $\mu\text{g N m}^{-2} \text{h}^{-1}$ ), water-filled pore space (WFPS; %, top 0.05 m depth), soil  
3 temperature ( $^{\circ}\text{C}$ , top 0.05 m depth) and extractable mineral N ( $\text{mg N kg}^{-1}$ , top 0.05 m depth)  
4 across landscapes for the reference and converted land uses. Correlation was conducted using  
5 the means of the four replicate plots per land use on each of the 12 monthly measurements  
6 (for soil N<sub>2</sub>O fluxes) and four monthly to bimonthly measurements (for soil NO fluxes).

Land-use type	Variable	WFPS	Soil temp.	NH <sub>4</sub> <sup>+</sup>	NO <sub>3</sub> <sup>-</sup>
Reference land uses (forest and jungle rubber)	Soil N <sub>2</sub> O flux	-0.21	-0.09	-0.23	0.38 <sup>c</sup>
	Soil NO flux	-0.74 <sup>c</sup>	-0.15	-0.48 <sup>a</sup>	0.69 <sup>c</sup>
Converted land uses (rubber and oil palm)	Soil N <sub>2</sub> O flux	0.11	0.15	0.23	0.37 <sup>c</sup>
	Soil NO flux	-0.05	0.09	-0.05	0.23

<sup>a</sup> $P \leq 0.09$ , <sup>b</sup> $P \leq 0.05$ , <sup>c</sup> $P \leq 0.01$ .

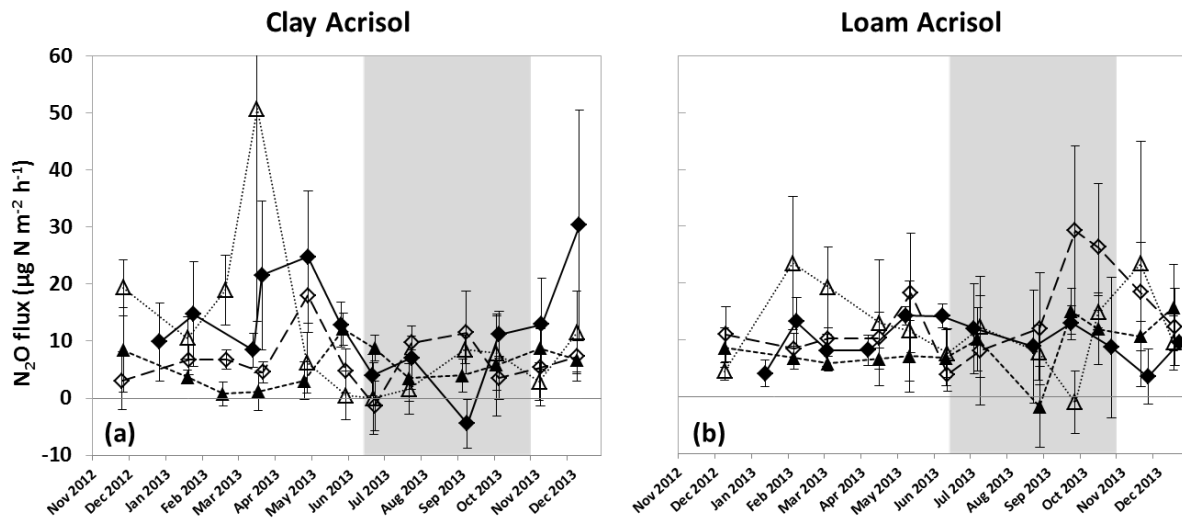
7

1 **Table 4.** Pearson correlation coefficients ( $n = 6-11$  measurements following fertilization)  
2 between N-oxide fluxes ( $\mu\text{g N m}^{-2} \text{h}^{-1}$ ), water-filled pore space (WFPS; %, top 0.05m depth)  
3 and extractable mineral N ( $\text{mg N kg}^{-1}$ , top 0.05 m depth), measured at different chamber  
4 locations (F1, F2 and NF were at 0.3 m (with incidental fertilization), 0.8 m (fertilized area)  
5 and 4–4.5 m (non-fertilized area), respectively, from the stem base). Correlation was  
6 conducted using the means of the three replicate trees per chamber location on each sampling  
7 day following fertilization.

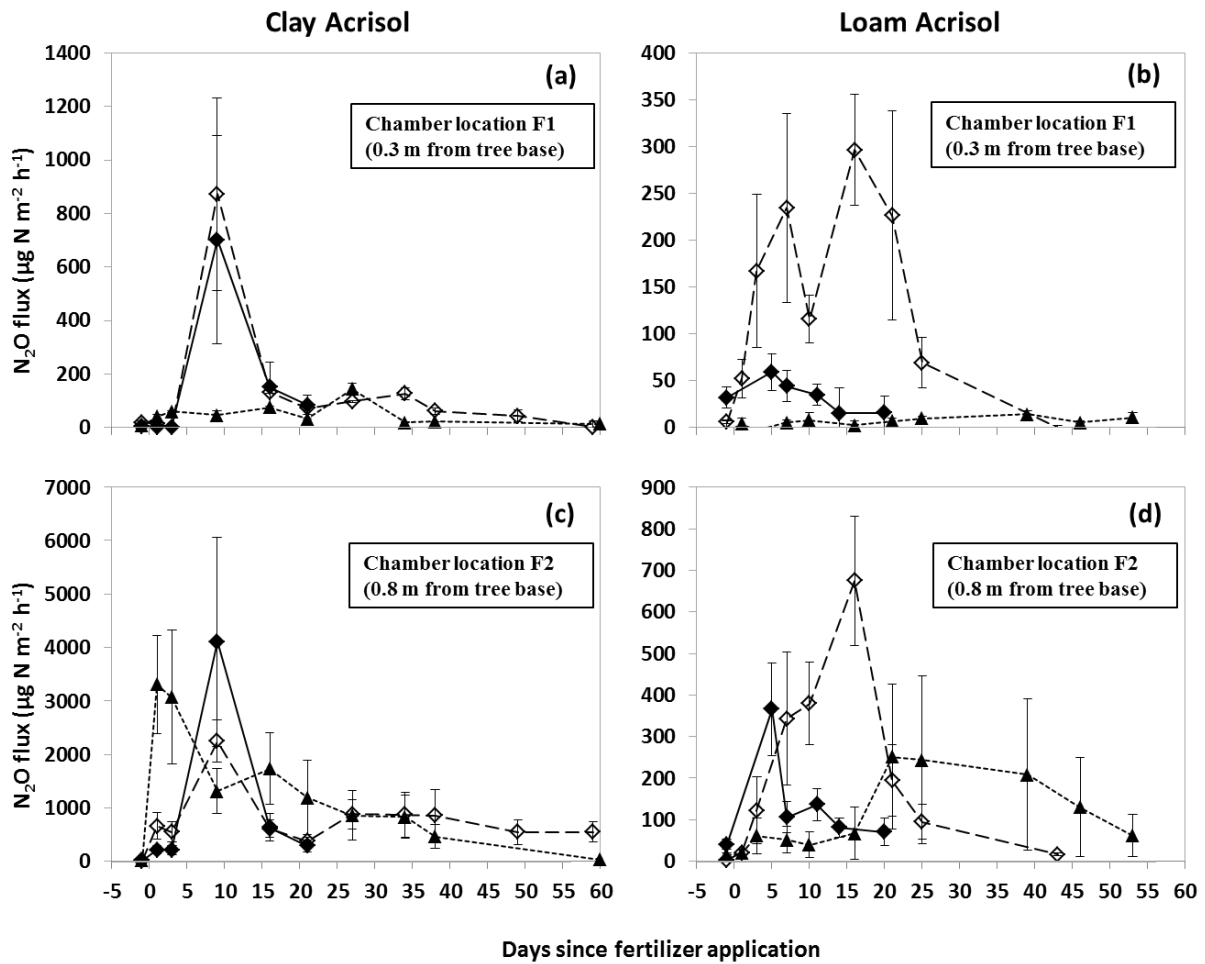
Oil palm plantation site	Chamber location	Variable	WFPS	$\text{NH}_4^+$	$\text{NO}_3^-$
clay Acrisol landscape					
1 ( $n = 6$ measurements)	F1	Soil $\text{N}_2\text{O}$ flux	0.55	0.88 <sup>b</sup>	0.46
	F2		0.57	-0.22	-0.31
	NF		0.37	-0.64	-0.44
2 ( $n = 11$ measurements)	F1	Soil $\text{N}_2\text{O}$ flux	0.11	0.93 <sup>c</sup>	0.95 <sup>c</sup>
	F2		0.08	0.05	-0.06
	NF		0.09	-0.44	-0.45
3 ( $n = 10$ measurements)	F1	Soil $\text{N}_2\text{O}$ flux	-0.19	0.10	0.09
	F2		0.05	0.86 <sup>c</sup>	0.85 <sup>c</sup>
	NF		-0.32	0.06	-0.44
3 ( $n = 10$ measurements)	F1	Soil NO flux	-0.34	0.44	0.48
	F2		-0.61 <sup>a</sup>	0.10	-0.04
	NF		0.59 <sup>a</sup>	-0.14	-0.13
loam Acrisol landscape					
1 ( $n = 6$ measurements)	F1	Soil $\text{N}_2\text{O}$ flux	0.96 <sup>c</sup>	-0.18	0.03
	F2		0.78 <sup>a</sup>	0.61	-0.40
	NF		-0.06	-0.29	<0.01
2 ( $n = 9$ )	F1	Soil $\text{N}_2\text{O}$ flux	-0.55	0.71 <sup>b</sup>	-0.03
	F2		0.35	-0.20	0.89 <sup>c</sup>

measurements)	NF		0.34	<0.01	-0.35
3	F1		-0.68 <sup>b</sup>	0.67 <sup>b</sup>	0.62 <sup>b</sup>
( <i>n</i> = 11	F2	Soil N <sub>2</sub> O	-0.27	-0.2	0.57 <sup>a</sup>
measurements)	NF	flux	0.36	0.19	0.06
2	F1		-0.07	0.18	-0.27
( <i>n</i> = 9	F2	Soil NO	0.07	-0.11	0.96 <sup>c</sup>
measurements)	NF	flux	-0.16	0.12	-0.23

1 <sup>a</sup>*P* ≤ 0.09, <sup>b</sup>*P* ≤ 0.05, <sup>c</sup>*P* ≤ 0.01.

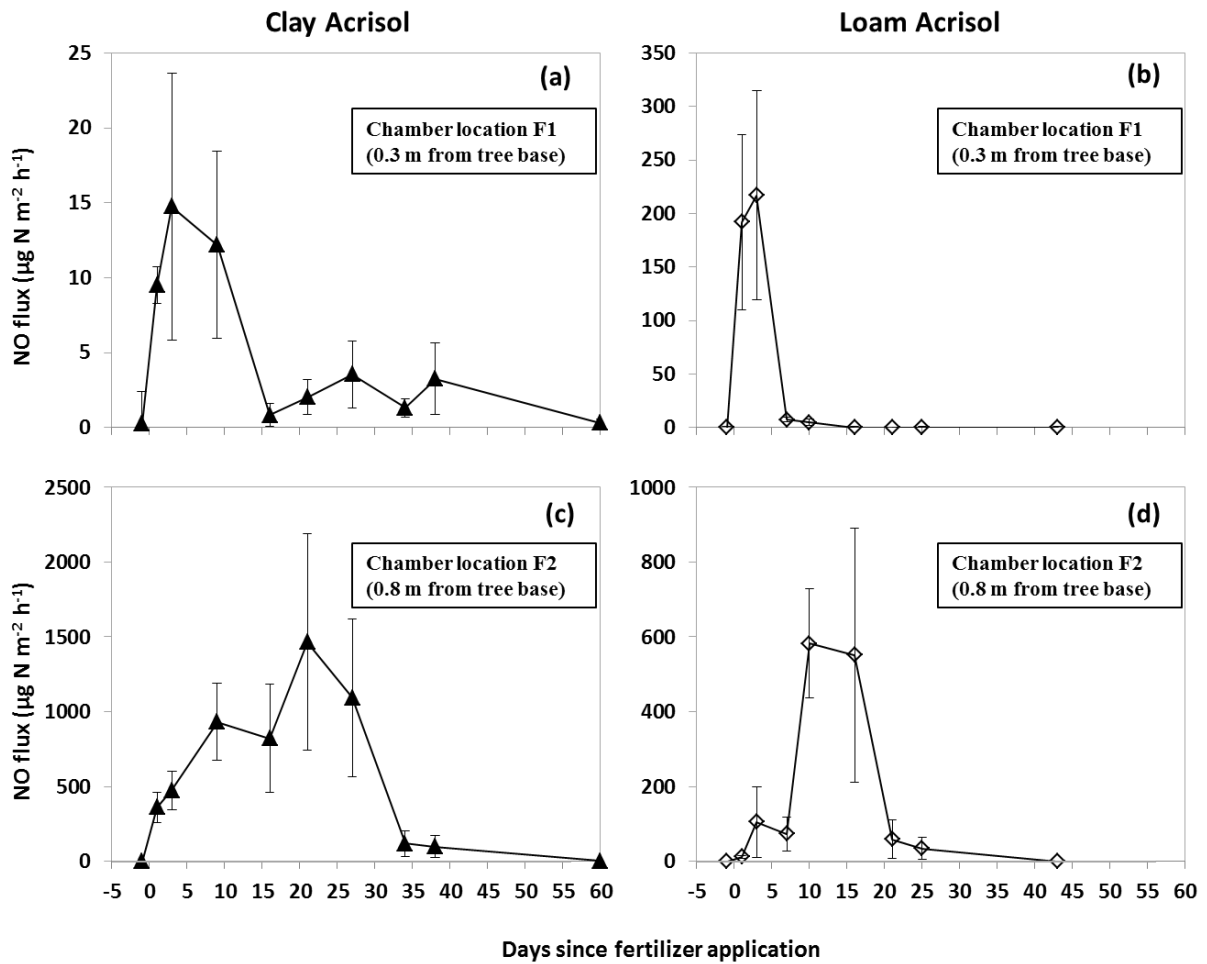


1  
 2 **Figure 1.** Mean ( $\pm$ SE,  $n = 4$  sites) soil N<sub>2</sub>O fluxes from forest ( $\blacklozenge$ ), jungle rubber ( $\diamond$ ),  
 3 rubber ( $\blacktriangle$ ) and oil palm ( $\triangle$ ), located within the clay (a) and loam Acrisol (b) landscapes in  
 4 Jambi, Indonesia. Measurements were carried out monthly from December 2012 to December  
 5 2013; grey shadings mark the dry season.



1

2 **Figure 2.** Mean ( $\pm$ SE,  $n = 3$  oil palm trees) soil  $N_2O$  fluxes during a fertilization in  
 3 smallholder oil palm plantations 1 ( $\blacklozenge$ ), 2 ( $\blacktriangle$ ) and 3 ( $\blacktriangle$ ) in the clay (a and c) and loam Acrisol  
 4 (b and d) landscapes. Smallholders fertilized around the base of each tree at about 0.8–1 m  
 5 from the tree base. Fluxes were measured at F1 = 0.3 m from the tree base (a and b) and at F2  
 6 = 0.8 m from the tree base on the fertilized location (c and d) with  $0.32 \text{ kg N tree}^{-1}$  in the clay  
 7 Acrisol and  $0.26 \text{ kg N tree}^{-1}$  in the loam Acrisol in accordance to the smallholders' practices.



1

2 **Figure 3.** Mean ( $\pm$ SE,  $n = 3$  oil palm trees) soil NO fluxes during a fertilization in a  
 3 smallholder oil palm plantation in the clay (a and c) and loam Acrisol (b and d) landscapes.  
 4 Smallholders fertilized around the base of each tree at about 0.8–1 m from the tree base.  
 5 Fluxes were measured at F1 = 0.3 m from the tree base (a and b) and at F2 = 0.8 m from the  
 6 tree base on the fertilized location (c and d) with  $0.32 \text{ kg N tree}^{-1}$  in the clay Acrisol and  $0.26$   
 7  $\text{kg N tree}^{-1}$  in the loam Acrisol in accordance to the smallholders' practices.



## 1 **Appendix A: Detailed description of the linear mixed-effect models application**

2 For analysis of differences in N-oxide fluxes among land uses or between soil landscapes, we  
3 used the means of the four chambers representing each replicate plot on a sampling day.  
4 Linear mixed-effect (LME) models (Crawley, 2007) were used to assess differences between  
5 landscapes for the reference land uses (testing H1) or differences among land uses within each  
6 landscape (testing H2). In the LME models, either landscape or land use was considered as  
7 fixed effect whereas replicate plots and sampling days were considered as random effects. For  
8 comparison of soil N<sub>2</sub>O fluxes between the large-scale (PTPN VI) and smallholder oil palm  
9 plantations within the loam Acrisol landscape, we also used the means of the three chambers  
10 per replicate plot on each sampling day in the PTPN VI site, as there were no significant  
11 differences between these chamber locations (based on LME models with chamber location as  
12 fixed effect and replicates as well as sampling days as random effects;  $P = 0.70$ ). We then  
13 used the LME model with plantation types (i.e., large scale vs. smallholder) as a fixed effect  
14 and replicates and sampling days as random effects. For analysis of fertilization (i.e., as  
15 represented by the chamber locations F1, F2 and NF) on soil N-oxide fluxes from smallholder  
16 oil palm plantations, this was conducted for each site with oil palm trees as replicates. In the  
17 LME model for this experiment, chamber location was the fixed effect whereas replicate palm  
18 trees and sampling days were the random effects. To assess differences in N-oxide fluxes  
19 between landscapes following fertilization for chamber locations F1 and F2, we also used  
20 LME models with landscape as fixed effect and with replicate plots (for N<sub>2</sub>O) or replicate  
21 palm trees (for NO) and sampling days as random effects. In all LME models, we included (1)  
22 a variance function that allows different variances of the fixed effect, and/or (2) a first-order  
23 temporal autoregressive function to account for decreasing correlation between sampling days  
24 with increasing time difference, if these functions improved the relative goodness of the  
25 model fit based on the Akaike information criterion.

1 **Table A1.** Location and year of measurement.

Measurement	Sampling location	N-oxide determined	Measurement year
clay Acrisol landscape			
Four land uses (forest, jungle rubber, rubber, oil palm)	all 16 replicate plots	N <sub>2</sub> O and NO	2013
Intensive measurements following fertilization (oil palm)	three oil palm replicate plots	N <sub>2</sub> O	2013–2014
Intensive measurements following fertilization (oil palm)	one oil palm replicate plot	NO	2013
loam Acrisol landscape			
Four land uses (forest, jungle rubber, rubber, oil palm)	all 16 replicate plots	N <sub>2</sub> O and NO	2013
Intensive measurements following fertilization (oil palm)	three oil palm replicate plots	N <sub>2</sub> O	2013-2014
Intensive measurements following fertilization (oil palm)	one oil palm replicate plot	NO	2013
Large-scale oil palm plantation	PTPN VI	N <sub>2</sub> O	2014-2015

2

1 **Table A2.** Mean ( $\pm$ SE,  $n = 4$  sites) soil physical and biochemical characteristics in the top 0.10 m depth (except sand content with  $n = 3$  sites)  
 2 from different land uses within each landscape in Jambi, Sumatra, Indonesia. These soil factors and gross nitrification were reported by Allen  
 3 et al. (2015).

Soil characteristics	Land-use type			
	Forest	Jungle rubber	Rubber	Oil palm
clay Acrisol landscape				
Sand (%)	36 $\pm$ 11	27 $\pm$ 20	35 $\pm$ 7	11 $\pm$ 2
Soil C:N ratio	13.1 $\pm$ 1.3	13.0 $\pm$ 0.3	14.3 $\pm$ 0.6	13.5 $\pm$ 0.2
Microbial C (mg C kg <sup>-1</sup> )	1048 $\pm$ 20	922 $\pm$ 223	561 $\pm$ 61	617 $\pm$ 112
Gross nitrification rate (mg N kg <sup>-1</sup> day <sup>-1</sup> )	0.9 $\pm$ 0.3	1.0 $\pm$ 0.2	0.7 $\pm$ 0.2	2.0 $\pm$ 0.8
loam Acrisol landscape				
Sand (%)	39 $\pm$ 8	42 $\pm$ 19	26 $\pm$ 13	43 $\pm$ 14
Soil C:N ratio	14.3 $\pm$ 0.2	13.7 $\pm$ 0.8	11.7 $\pm$ 0.7	12.5 $\pm$ 0.5
Microbial C (mg C kg <sup>-1</sup> )	514 $\pm$ 48	578 $\pm$ 45	461 $\pm$ 58	403 $\pm$ 24
Gross nitrification rate (mg N kg <sup>-1</sup> day <sup>-1</sup> )	1.9 $\pm$ 0.4	0.9 $\pm$ 0.2	0.9 $\pm$ 0.2	1.2 $\pm$ 0.5

**Table A3.** Mean ( $\pm$ SE,  $n = 4$  sites) soil water-filled pore space (WFPS) and extractable mineral N in the top 0.05 m depth for different land uses within each landscape in Jambi, Sumatra, Indonesia. Means followed by different lowercase letters indicate significant differences among land uses within each landscape and different capital letters indicate significant differences between landscapes within each land use (linear mixed-effect models with Fisher's least significant difference (LSD) test at  $P \leq 0.05$ ). These soil factors were reported by Hassler et al. (2015).

Land-use type	WFPS (%)	NH <sub>4</sub> <sup>+</sup> (mg N kg <sup>-1</sup> )	NO <sub>3</sub> <sup>-</sup> (mg N kg <sup>-1</sup> )
clay Acrisol landscape			
Forest	73.0 $\pm$ 12.3 <sup>a,A</sup>	7.0 $\pm$ 1.0 <sup>a,A</sup>	2.2 $\pm$ 0.4 <sup>a,A</sup>
Jungle rubber	86.7 $\pm$ 5.9 <sup>a,A</sup>	7.3 $\pm$ 0.2 <sup>a,A</sup>	0.2 $\pm$ 0.1 <sup>b,B</sup>
Rubber	61.5 $\pm$ 7.4 <sup>a,A</sup>	4.3 $\pm$ 0.2 <sup>b,A</sup>	0.1 $\pm$ 0.0 <sup>b,B</sup>
Oil Palm	74.0 $\pm$ 7.3 <sup>a,A</sup>	5.8 $\pm$ 0.6 <sup>a,A</sup>	0.8 $\pm$ 0.5 <sup>b</sup>
loam Acrisol landscape			
Forest	64.0 $\pm$ 3.3 <sup>a,A</sup>	5.9 $\pm$ 0.4 <sup>a,A</sup>	0.6 $\pm$ 0.2 <sup>ab,B</sup>
Jungle rubber	53.9 $\pm$ 3.7 <sup>a,B</sup>	5.6 $\pm$ 0.3 <sup>a,B</sup>	1.3 $\pm$ 0.6 <sup>a,A</sup>
Rubber	72.6 $\pm$ 5.7 <sup>a,A</sup>	4.1 $\pm$ 0.6 <sup>b,A</sup>	0.1 $\pm$ 0.0 <sup>b,A</sup>
Oil Palm	59.0 $\pm$ 6.7 <sup>a,A</sup>	4.2 $\pm$ 1.1 <sup>b,B</sup>	0.6 $\pm$ 0.4 <sup>ab,B</sup>