https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021


Biogeosciences Discussions
Open Access
EGU

# High greenhouse gas fluxes from peatlands under various disturbances in the Peruvian Amazon

Jaan Pärn[1], Kaido Soosaar[1], Thomas Schindler[1,2], Katerina Machacova[1,2], Waldemar Alegría Muñoz[3], Lizardo Fachín[4], José Luis Jibaja Aspajo[3], Robinson I. Negron-Juarez[5], Martin Maddison[1], Jhon Rengifo[4], Danika Journeth Garay Dinis[3], Adriana Gabriela Arista Oversluijs[3], Manuel Calixto Ávila Fucos[3], Rafael Chávez Vásquez[3], Ronald Huaje Wampuch[3], Edgar Peas García[3], Kristina Sohar[1], Segundo Cordova Horna[3], Tedi Pacheco Gómez[3], Jose David Urquiza Muñoz[3,6], Rodil Tello Espinoza[3], and Ülo Mander[1,2]

[1] Department of Geography, Institute of Ecology and Earth Sciences, University of Tartu, Estonia (jaan.parn@ut.ee)
[2] Department of Ecosystem Trace Gas Exchange, Global Change Research Institute of the Czech Academy of Sciences, Brno, Czech Republic
[3] School of Forestry, National University of the Peruvian Amazon (UNAP), Iquitos, Peru
[4] Peruvian Amazon Research Institute (IIAP), Iquitos, Peru
[5] Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[6] Max-Planck Institute for Biogeochemistry, Jena, Germany

*Correspondence to*: Jaan Pärn (jaan.parn@ut.ee)

**Abstract.** Amazonian peat swamp forests remove large amounts of carbon dioxide ($CO_2$) but anaerobic decomposition of the peat produces methane ($CH_4$). Drought or cultivation cuts down on the $CH_4$ production but may increase the $CO_2$ emission. Varying oxygen content in nitrogen-rich peat produces nitrous oxide ($N_2O$). Despite the potentially tremendous changes, greenhouse gas emissions from peatlands under various land uses and environmental conditions have rarely been compared in the Amazon. We measured $CO_2$, $CH_4$ and $N_2O$ emissions from the soil surface with manual opaque chambers, and environmental characteristics in three sites around Iquitos, Peru from September 2019 to March 2020: a pristine peat swamp forest, a young forest and a slash-and-burn manioc field. The manioc field showed moderate peat respiration and $N_2O$ emission. The swamp forests under slight water table drawdown emitted large amounts of CO2 and $N_2O$ while retaining their high $CH_4$ emissions. Most noticeably, a heavy shower after the water-table drawdown in the pristine swamp forest created a hot moment of $N_2O$. Nitrifier denitrification was the likely source mechanism, as we rule out nitrification and heterotrophic denitrification. We base the judgement on the lack of both nitrate and oxygen, and the suppressed denitrification potential in the topsoil. Overall, our study shows that even moderate drying in Peruvian palm swamps may create a devastating feedback on climate change through $CO_2$ and $N_2O$ emissions.

## 1 Introduction

Peatlands are an enormous sink of carbon and nitrogen (IPCC, 2019). Natural and human disturbances may release them as greenhouse gases (GHG). The threat is particularly acute in tropical peatlands (IPCC, 2019). Amazonian swamp forests hold almost a half of tropical peatlands globally (Leifeld and Menichetti, 2018). Most of them are isolated from major population centres and roads, and thus inaccessible to logging and agriculture (Lilleskov et

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021




al., 2019). Undisturbed peat swamp forests sequester carbon (C) for tens of kyr (Ruwaimana et al, 2020). Anoxic decomposition of peat under high water table yields methane ($CH_4$; Teh et al., 2017; Hergoualc'h et al., 2020), and suboxic processes in nitrogen-rich peat under intermediate (50 to 60%) water content produce nitrous oxide ($N_2O$; Melillo et al., 2001; Jauhiainen et al., 2012; Rubol et al., 2012; Hu et al., 2015; Pärn et al., 2018; Hergoualc'h et al., 2020). The 5.4 million $km^2$ Amazon rainforest is the biggest hotspot of $N_2O$ in the world (Figure 1; Ricaud et al., 2009) emitting 1,300 Gg $N_2O$-N $yr^{-1}$ (Melillo et al., 2001). The contribution of swamp forests to the hotspot is poorly known (van Lent et al., 2015; Guilhen et al., 2020) but a Peruvian palm peat swamp emitted 0.5 to 2.6 kg $N_2O$-N $ha^{-1}$ $yr^{-1}$ (van Lent et al., 2015). This was similar to swamp forests of Southeast Asia that emit 2.7 ± 1.7 kg $N_2O$-N $ha^{-1}$ $yr^{-1}$ (average ± standard deviation; van Lent et al., 2015). The major source mechanism behind $N_2O$ emissions is denitrification, as identified from $N_2O$ profiles and porewater nitrogen forms in wetting experiments on intact soil cores (Butterbach-Bahl et al., 2013; Liengaard et al., 2014; Hu et al., 2015). $N_2O$ is an intermediate product of denitrification in either suboxic soil or under varying oxygen availability both in time and between anoxic soil aggregates and air-filled pores (Butterbach-Bahl et al., 2013; Hu et al., 2015). Only after depletion of nitrate ($NO_3^-$) is $N_2O$ reduced to inert $N_2$ (Liengaard et al., 2014). However, the Amazon has an exceptionally high 10% share of nitrification in $N_2O$ production (Inatomi et al., 2019). In a Peruvian palm peat swamp forest, Hergoualc'h et al. (2020) identified nitrifier denitrification as the probable source process for the high $N_2O$ emission. Brazil is also a major contributor to the global increase in $N_2O$ emissions during the last decades, owing to the increase in nitrogen (N) fertilisation (Thompson et al., 2019).

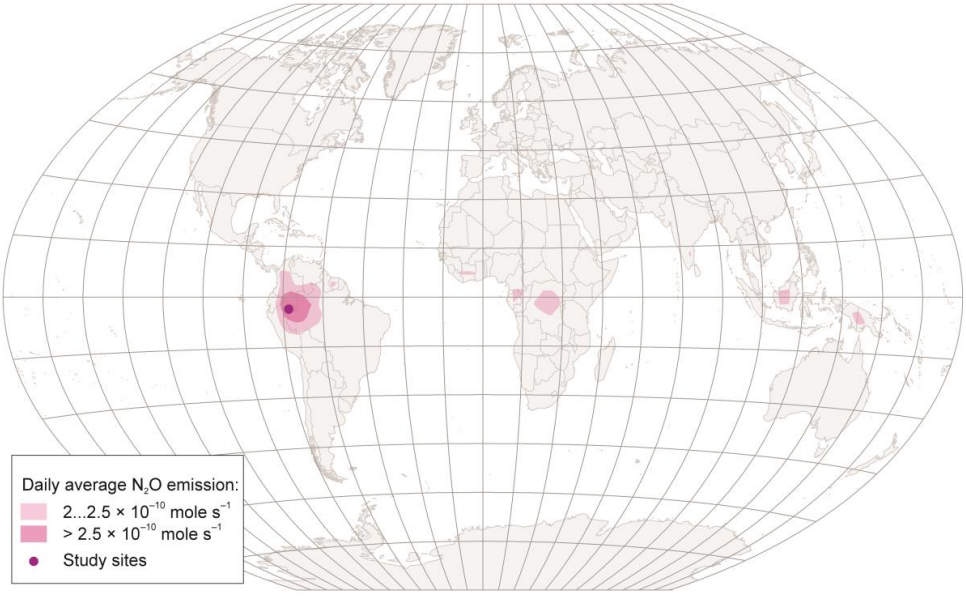



**Figure 1: Global hotspots of $N_2O$ emission measured in upper troposphere by IASI satellite (Ricaud et al., 2009), and location of study sites.**

C sequestration dominates the GHG balance in natural peat swamps (Frolking and Roulet, 2009) whereas disturbances increase GHG emissions (Turetsky et al., 2015; IPCC, 2019). In the Amazon, drought is a quickly increasing disturbance which is shortening the growth period and imposing tree decline (IPCC, 2019). Droughts increase ecosystem respiration. Microbes that respire much of the $CO_2$ rapidly acclimatise with the rising

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021




temperature which may send the ecosystems down a positive feedback loop (Karhu et al., 2014). Thus, drought-induced tree mortality is saturating the Amazon C sink (Hubau et al., 2020).

The studies made on mineral soil are unreliable for the climate-change effects on peat swamps. In contrast to mineral soils, water table stays above or near the ground in peat swamps throughout the dry season, making the carbon and nitrogen stocks resistant (Turetsky et al., 2015). On the other hand, peatland clearing, commonly with fire, renders the peat carbon and nitrogen stocks vulnerable (Turetsky et al., 2015; Lilleskov et al., 2019). However, few studies have compared greenhouse gas fluxes across a variety of land uses and water tables in Amazonian peat swamps. To fill the knowledge gap, we set an objective to identify environmental drivers of $CO_2$, $CH_4$ and $N_2O$ fluxes across gradients of land use and water table, we held a measurement campaign around Iquitos, the Peruvian Amazon.

## 2 Material and Methods

We observed fluxes of the three GHGs using opaque soil chambers and measured potential environmental factors in three current or former *Mauritia flexuosa* palm dominated swamps under various disturbance histories (Figure 2): 1 — "Swamp", a natural forest in the Quistococha lake floodplain (6 m peat; see Roucoux et al., 2013 for detailed physical description) 3°50'03.9" S, 73°19'08.1" W, 2 — "Slope", a 12-year old secondary forest grown over a fallow pasture and banana plantation on an alluvial toe slope (0.1 to 0.3 m peat) 3°50'10.7" S, 73°21'45.0" W and 3 — "Manioc", a slash-and-burn manioc (*Manihot esculenta*) field (0.03 to 0.15 m peat), 3°51'00.0" S, 73°22'45.8" W.

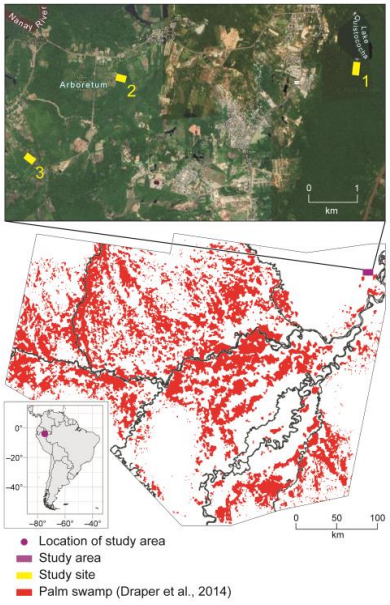



**Figure 2: Location of study sites (1 – Swamp, 2 – Slope, and 3 – Manioc) and distribution of palm swamp forests in the Pastaza-Marañon Basin (data from Draper et al., 2014). Background image for the site location map above © Google Maps.**

On the Slope and Manioc sites, we established three toposequent stations at an interval of 15 m. Each station received three chambers three to five meters apart from each other. $CO_2$, $CH_4$ and $N_2O$ were sampled using the

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021


Biogeosciences Discussions

static chamber method with PVC collars of 0.5 m diameter and 0.1 m depth installed in the peat. The inside of collars at the Slope site was covered with sparse < 0.2 m tall *Pteridaceae* ferns while the collars in the Swamp and Manioc sites contained no plants. We used white 65 L PVC truncated conical gas sampling chambers. We did not use extra cover against sunlight but the chamber design is generally regarded as opaque (Hutchinson and Livingston, 1993). They were placed into water-filled rings on the collars (Mander et al., 2014). Gas was sampled from chamber headspace into a pre-evacuated 50 mL glass vial every 20 minutes during a 1 h session (Hutchinson and Livingston, 1993). The sessions were held between 8 and 11 hours of daytime, to represent the average diurnal emissions (according to Figures 11 and 12 in Griffis et al., 2020). We conducted nine sampling sessions in the Swamp forest from September 2019 to March 2020, four sessions in the Slope forest in September 2020 and nine sessions in the Manioc field fro September 2019 to March 2020 according to the schedule presented in Table 1. Before the first sampling in September, young manioc saplings had been planted. By 15 February, they had grown to 3 m height covering the whole field with a sparse canopy ( > 30% shading). No manioc plant grew directly out of the stationary gas sampling collars at any time. The manioc was harvested in late February, leaving a bare field for the March sampling. The gas samples were transported to a laboratory at the University of Tartu and analysed by gas chromatography (GC-2014; Shimadzu, Kyōto, Japan) equipped with an electron capture detector for detection of $N_2O$ and a flame ionisation detector for $CH_4$, and Loftfield-type autosamplers. An individual gas flux was determined on the basis of linear regression obtained from consecutive concentrations (Hutchinson and Livingston, 1993). A $p$ level of < 0.05 was accepted for the goodness of fit to linear regression. Insignificant fluxes ($p$ > 0.05) below the accuracy of gas chromatograph (regression change of gas concentration $\delta v$ < 10 ppb) were included in the analysis as zeros. Each station was equipped with a 1 m deep observation well (a 0.05 m perforated PP-HT pipe wrapped in filter textile). Water table height was recorded from the observation wells during the gas sampling. Soil moisture was measured with a GS3 sensor connected to a ProCheck handheld reader (Decagon Devices, Pullman, WA, USA). Soil temperature was measured between 0.1 to 0.4 m depth at an interval of 0.1 m. Soil oxygen ($O_2$) content was measured with a stand-alone fibre optic oxygen meter (PreSens, Regensburg, Germany) at 0.05 m and 0.005 m depths in September and March.

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021


Biogeosciences Discussions

**Table 1: Time schedule of sampling sessions in the study sites. X marks one sampling session.**

| Date | Swamp | Slope | Manioc |
|---|---|---|---|
| 16.09.2019 | X | | |
| 17.09.2019 | X | | |
| 19.09.2019 | | XX | |
| 20.09.2019 | | XX | |
| 21.09.2019 | | | XX |
| 22.09.2019 | | | XX |
| 24.09.2019 | X | | |
| 25.09.2019 | X | | |
| 04.01.2020 | | | X |
| 11.01.2020 | X | | |
| 18.01.2020 | | | X |
| 25.01.2020 | X | | |
| 04.02.2020 | | | X |
| 08.02.2020 | X | | |
| 15.02.2020 | | | X |
| 22.02.2020 | X | | |
| 02.03.2020 | | | X |
| 03.03.2020 | | | X |
| 04.03.2020 | X | | |

A peat sample of 150 to 200 g was collected from each chamber between 0 to 0.1 m depth after the sampling sessions in September and March. The soil samples were stored at 5 °C and transported under the same temperature to Estonian University of Life Sciences for chemical and physical analyses. At the laboratory, plant-available (KCl extractable) phosphorus (P) was determined on a FIAstar 5000 flow injection analyser (FOSS, Hilleroed, Denmark; Ruzicka and Hansen, 1981). Plant available potassium (K) was determined from the same solution by the flame-photometric method, and plant available magnesium (Mg)was determined from a 100 mL ammonium acetate solution with a titanium-yellow reagent on the flow injection analyser (Ruzicka and Hansen, 1981). Calcium (Ca) was analysed using the same solution by the flame photometrical method (Ruzicka and Hansen, 1981). Soil pH was determined on a 1N KCl solution. Soil ammonium ($NH_4^+$) and nitrate ($NO_3^-$) contents were determined on a 2M KCl extract of soil by flow-injection analysis (Ruzicka and Hansen, 1981). Total N and C contents of oven-dry samples were determined using a dry combustion method on a varioMAX CNS elemental analyser. The soil organic matter (SOM) content of the oven-dry samples was determined by loss on ignition at 360° C.

For use with the He–$O_2$ method at our University of Tartu laboratory, we collected intact soil cores (0.068 m diameter, 0.06 m height) from the top 0.1 m from each chamber after the last gas sampling sessions in September and March. The helium-atmosphere soil-incubation technique (Espenberg et al., 2018) was used to measure potential $N_2O$ and molecular nitrogen ($N_2$) fluxes from soil cores in the same laboratory. The cylinders with the intact soil cores were placed into special gas-tight incubation vessels locating in the climate chamber. Gases were removed by flushing with an artificial gas mixture (21.0% $O_2$, 358 ppm $CO_2$, 0.313 ppm $N_2O$, 1.67 ppm $CH_4$, 5.97 ppm $N_2$ and the rest He). The new atmosphere equilibrium by continuously flushing the vessel headspace with the artificial gas mixture at 20 mL per min was established after 12–24 h. The flushing time depended on the

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021




soil moisture. The temperature was kept similar to the field temperature during the incubation. Concentrations of $N_2O$ and $N_2$ were analysed by the GC-2014 (Shimadzu, Japan). Flux rates were calculated from the actual gas concentration of the continuous flow rate from the vessel headspace after subtraction of a blank value from a vessel without a soil core, which is equivalent to concentrations from the artificial $He–O_2$ gas mixture.

We tested normal distribution of the samples by the Kolmogorov–Smirnov and Shapiro–Wilk's tests using the *stats* package in R. As data for most of the sites were not normally distributed ($p > 0.05$), we analysed relationships between the GHG fluxes and environmental characteristics by the nonparametric generalised additive models (GAM) usinge the simplest smoothing term (k=3) in the *mgcv* package in R, and principal component analysis (PCA) using the *stats* package in R. For each cluster of replicate measurements we plotted a normal data ellipse with size defined as a normal probability equal to 0.68. Significance of differences between sites was checked by the unpaired two-sided Wilcoxon rank sum test (the *wilcox.test* function, *stats* package in R).

## 3 Results and Discussion

The PCA clearly separated our three sites along a water table gradient closely followed by soil $O_2$ content, soil temperature and $NO_3^-$ content gradients (Figure 2). The waterlogged swamp peat did not contain a detectable amount of $NO_3^-$. No fertiliser was added according to our knowledge on our sites. Therefore, the high amount of $NO_3^-$ in the manioc field was probably produced by nitrification induced by the slash-and-burn and subsequent water-table drawdown. Within the sites, the PCA distinguished the gas-sampling chambers along a soil nutrient gradient (Ca, Mg, pH, P, total N, $NH_4^+$) independent from the water table changes. The nutrients may have enhanced heterotrophic $CO_2$ and $N_2O$ production. Within-site differences in water table were still remarkable. The water table in the slope forest varied between –0.09 and –0.13 m at the wet station, between –0.115 and –0.15 m at the middle and around –0.7 m at the dry station. The water table in the palm swamp varied from –0.12 to –0.085 m in mid-September, rose to –0.03 m after a 30 mm shower 6 hours before the 24 September session and dropped to –0.07 m during the next dry day. From January to March, the water table in the palm swamp was steadily –0.03 m. Soil $O_2$ content remained < 0.1 mg $L^{-1}$ at both 0.005 and 0.05 m depth throughout the observations in the Swamp forest.

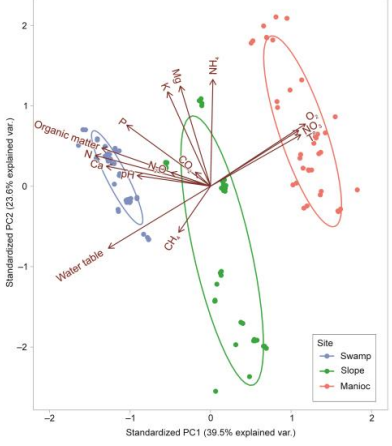



**Figure 3: Principal component analysis (PCA) of GHG fluxes and environmental characteristics in September 2019. Each data point represents one GHG flux replicate measurement. A normal data ellipse is shown around points from each site.**

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021




The dry station (water table –0.7 m; soil water content 0.26 $m^3$ $m^{-3}$; soil temperature around 26 ºC at 10 cm depth) of the young swamp forest respired the largest amount of $CO_2$ (session averages of 130 to 210 mg C $m^{-2}$ $h^{-1}$). That station apparently represents the optimal moisture for soil respiration (Byrne et al., 2005; Balogh et al., 2011). The respiration declined with the increase in the water table (session averages of 43 to 91 mg C $m^{-2}$ $h^{-1}$ at the wettest station). The similarly dry but hotter manioc field (soil water content 0.15 to 0.24 $m^3$ $m^{-3}$; soil temperature 26 to 34 ºC at 0.1 m depth during all months) respired steadily 75 to 98 mg C $m^{-2}$ $h^{-1}$ throughout the study period (Figure 5a), regardless of the noticeable changes in manioc rooting, height and canopy from September to March. The Swamp peat ($O_2$ < 0.1 mg $L^{-1}$ at both 0.005 and 0.05 m depth) respired 49 to 150 mg C $m^{-2}$ $h^{-1}$ as session average (Figure 5a) in negative linear relationship with water table. Although soil water content remained above 0.8 $m^3$ $m^{-3}$ and soil $O_2$ content stayed < 0.1 mg $L^{-1}$ at both 0.005 and 0.05 m depth from 24 September onward, the aerenchymous palm roots probably provided $O_2$ in the deeper soil zones (van Lent et al., 2019). Most of the respired C was offset in the gross primary production (GPP) of trees (as observed by the EC technique above the canopy; Griffis et al., 2020). However, during the dry season of 2019 including the September, ecosystem respiration of the whole Quistococha swamp forest increased and exceeded the concurrently declining GPP by a steady average of 600 mg C $day^{-1}$ (EC measured; Griffis et al., 2020). This shows that peat respiration will prevail the C balance of the palm swamp during the dry season even when the peat remains wet.

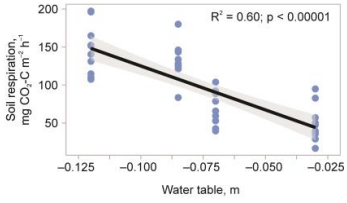



**Figure 4: Relationship between soil respiration and water table in the Swamp forest.**

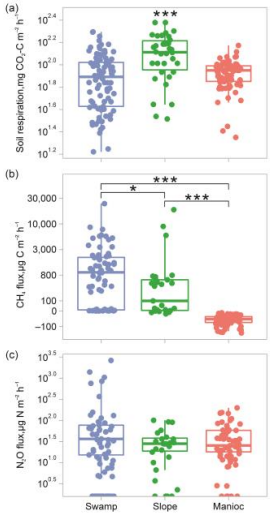



**Figure 5: Box plots of soil $CO_2$ (a), $CH_4$ (b) and $N_2O$ (c) fluxes in study sites. Significant differences according to Wilcoxon test are shown with asterisks as follows: * – p < 0.05; ** – p < 0.01; *** – p < 0.001. Asterisks directly above box without brackets denote significant difference from all other sites in the plot.**

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021


Biogeosciences Discussions Open Access EGU

The wet swamp forest floor emitted session averages of 530 to 9,100 µg $CH_4$-C $m^{-2}$ $h^{-1}$ (Figure 5b) owing to the high –0.03 to –0.12 m water table (Hergoualc'h et al., 2020). This lay within the range of $CH_4$ fluxes reported from Brazilian flooded swamp forest soils (*igapo* and *varzea*; Pangala et al., 2017). The similarly high 2,000 to 3,200 µg C $m^{-2}$ $h^{-1}$ reported earlier from nearby peat swamp forest (Hergoualc'h et al., 2020), and the 600 to 1,300 µg C $m^{-2}$ $h^{-1}$ measured above the canopy with water table between –0.03 and –0.12 m (Griffis et al., 2020) show that even during the dry season the palm swamp emits a lot of $CH_4$ and a large part of it reaches the atmosphere. The dry slash-and-burn manioc field consumed $CH_4$ at a session mean rate of 49 to 83 µg C $m^{-2}$ $h^{-1}$ (Figure 5b). The natural swamp peat produced session averages of 65 and 58 µg $N_2O$-N $m^{-2}$ $h^{-1}$ during the 0.12–0.085 m water-table drawdown on 16 and 17 September, respectively. A 30 mm shower on the night before 24 September restored the water table to –0.03 m, caused a 2-fold drop in peat respiration (Figure 4), and initiated session-average peaks of 360 and 420 µg N $m^{-2}$ $h^{-1}$ from the 190 mg dry $kg^{-1}$ soil $NH_4^+$-N on 24 and 25 September. During January to March, a steady average of 11.6 µg N $m^{-2}$ $h^{-1}$ (session averages of 2.3 to 27 µg N $m^{-2}$ $h^{-1}$) was produced from the 120 mg dry $kg^{-1}$ soil $NH_4^+$-N (Figure 6a) regardless of rainfall immediately before some of the sampling sessions. Across the study period, the fluxes correlated log-linearly with soil $NH_4^+$ content (Figure 6a). The DNDC model calculates $N_2O$ fluxes driven by decomposition of organic N and denitrification following rainfall events (Li et al., 1992). However, more records of $N_2O$ peaks after rainfall events are needed to feed a model properly. Our measured emissions were relatively high compared to the average 31 ± 22 µg $N_2O$-N $m^{-2}$ $h^{-1}$ (average ± standard deviation across studies) from the 410 ± 120 mg dry $kg^{-1}$ soil $NH_4^+$-N in Southeast Asian wetland forests (van Lent et al., 2015). Our measured fluxes were higher than model-predicted emissions of 21 µg N $m^{-2}$ $h^{-1}$ for the Amazon Basin (Guilhen et al., 2020) but agreed with huge $N_2O$ emissions from floodplains soils of the Brazilian Amazon by Figueiredo et al. (2019).

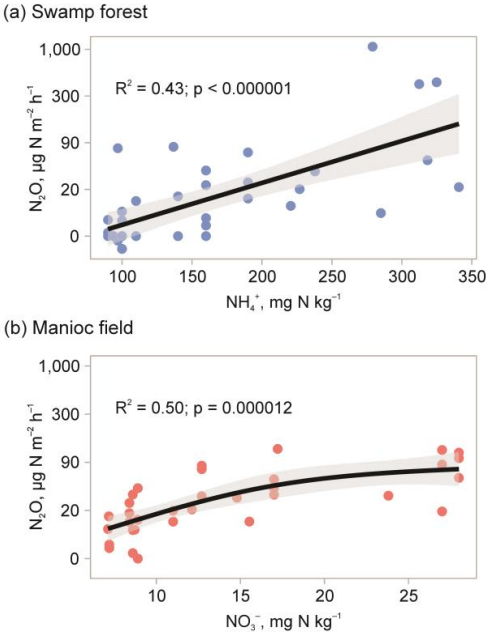



**Figure 6: Relationships between monthly average $N_2O$ emission and soil N forms.**

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021


Biogeosciences Discussions Open Access EGU

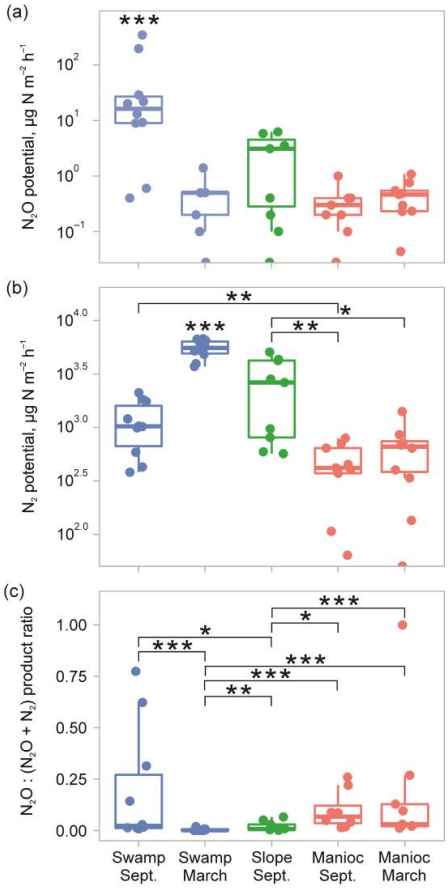
Soil $NO_3^-$ content was below the detection limit in most of the anaerobic peat samples. This contradicts previous knowledge on low-$NO_3^-$ water-saturated peat as a negligible source of $N_2O$ (Rubol et al., 2012; Teh et al., 2017; Pärn et al., 2018). However, Melillo et al. (2001) do report > 50 µg $N_2O$-N $m^{-2}$ $h^{-1}$ in an Amazon rainforest peaking at low $NO_3^-$ content. Most of anaerobic $N_2O$ production pathways use $NO_3^-$ as the source (Baggs, 2011; Butterbach-Bahl et al., 2013; Hu et al., 2015). Among the few exceptions, nitrifier denitrification avoids $NO_3^-$ reducing $NO_2^-$ straight into $N_2O$ (Wrage-Mönnig et al., 2018). Hergoualc'h et al. (2020) identified nitrifier denitrification in the palm swamp. It is a well-documented process in mineralised peats (Wrage-Mönnig et al., 2018; Masta et al., 2020). Anaerobic $NH_4^+$ oxidation (anammox) involves nitric oxide (NO) as an intermediate product which could serve as an important substrate for $N_2O$ formation by $NH_4^+$ oxidisers or denitrifiers (Hu et al., 2015). Alternatively, co-denitrification reduces nitrogen dioxide ($NO_2^-$) or NO into $N_2O$ (Spott et al., 2011; Butterbach-Bahl et al., 2013). As another possible mechanism, the $O_2$ supplied by aerenchymous palm roots (van Lent et al., 2019) may have driven incomplete nitrification with the derived $NO_3^-$ immediately used up by plants and denitrifiers in heavy competition on the $NO_3^-$ (Kuzyakov and Xu, 2013). The latter in turn may have produced a part of the $N_2O$ in the anaerobic soil zone (in agreement with van Lent et al., 2019). As a third potential source, we may consider denitrification in cryptogams such as lichens and fungi in other symbioses on the litter (Lenhart et al., 2015). The peat in our dry sites also emitted considerable 43 µg (12 to 55 µg as session average) $N_2O$-N $m^{-2}$ $h^{-1}$ in a log-saturation curve relationship with soil $NO_3^-$ content (Figures 5c, 6b).

Across the sites, the potential $N_2$ flow exceeded the potential $N_2O$ flow by 1 to 2 orders of magnitude (Figure 7). $N_2O$ production potential in the intact soil cores collected from the Quistococha palm swamp forest after the September hot moment was 64 µg N $m^{-2}$ $h^{-1}$. The soil cores collected in March and from other locations in all other sampling times showed near-zero $N_2O$ production potential. The product potential of $N_2$ in the palm swamp was 1,100 µg $m^{-2}$ $h^{-1}$ in late September and 5,500 µg $m^{-2}$ $h^{-1}$ in March. This shows that denitrification potential was deficient in September whereas in March practically all $N_2O$ was converted to $N_2$. In the manioc field, $N_2$ production potential was low, further explaining the significant $N_2O$ emissions (Figure 6b) with incomplete denitrification. In the toe-slope swamp forest, $N_2$ potential was intermediate between the natural palm swamp and the manioc field, completing the clear $N_2$ potential gradient according to the duration of the high water table.

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021




238 The field $N_2O$ : ($N_2O$ + $N_2$ potential) product ratio was the highest at the Swamp in September, owing to huge
239 $N_2O$ emission and moderate $N_2$ potential. These can probably be explained, again, by the water-table drawdown
240 and heavy shower before the sampling. In March the $N_2O$ : ($N_2O$ + $N_2$) ratio showed near-zero values in the
241 Swamp, due to low $N_2O$ emission and very high $N_2$ potential. Thus, the $N_2O$ likely produced from nitrifier
242 denitrification in March was consumed by denitrification. That likely resulted from the December rainfall after
243 which high water table settled in for months. The Slope also showed a low $N_2O$ : ($N_2O$ + $N_2$) ratio owing to
244 moderate $N_2O$ emission and high $N_2$ potential. The $N_2O$ : ($N_2O$ + $N_2$) ratio in the Manioc site was moderate, due
245 to moderate $N_2O$ emissions and low $N_2$ potential in the dry soil.




246

247 **Figure 7: Production potential of $N_2O$ and $N_2$ measured from intact soil cores, and product ratio of field-observed $N_2O$**
248 **flux (Figures 5c and 6) to sum of field-observed $N_2O$ flux and $N_2$ production potential. Significant differences according**
249 **to Wilcoxon test are shown with asterisks as follows: * – $p < 0.05$; ** – $p < 0.01$; *** – $p < 0.001$. Asterisks directly**
250 **above box without brackets denote significant difference from all other sites in the plot.**

251 Upscaling our $N_2O$ measurements to the 27,732 ± 1,101 $km^2$ of palm swamp in the Pastaza-Marañon Basin
252 (Figure 2; Draper et al., 2014) yields 30 Gg N $yr^{-1}$. This constitutes roughly 2% of the 1,300 Gg N $yr^{-1}$ from the
253 5.4 million $km^2$ rainforest of the Amazon Basin (Melillo et al., 2001), a relatively small addition to the natural
254 fluxes, and emissions from land conversion, fertilisation and drainage (van Lent et al., 2015; Thompson et al.,
255 2019) in the biggest $N_2O$ hotspot of the world (Figure 1; Ricaud et al., 2009). On the other hand, conversion of

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021




the 27,732 ± 1,101 km$^2$ of palm swamp in the Pastaza-Marañon Basin (Figure 2; Draper et al., 2014) to manioc fields could induce $CO_2$ emissions of 1.5 to 2.0 Tg C per month. This would add at least 4% to the current 1,500 Tg $CO_2$ emission from Latin American land use (IPCC, 2019). Current Peruvian policy does not explicitly restrict agricultural development of peat swamps outside nature reserves and lands assigned to indigenous communities. Thus, a large share of the Peruvian peat carbon stocks is hanging on the isolation from population centres and low population density (Lilleskov et al., 2019).

## Conclusions

The arable peatland in the Peruvian Amazon emitted relatively high amounts of $CO_2$ and $N_2O$ but the peat swamp forests under suppressed water table showed considerably larger $CO_2$ and $N_2O$ emissions while mostly retaining their naturally high $CH_4$ production. The likely mechanism behind the elevated GHG production was access of oxygen to the root zone. This caused high respiration and nitrifier denitrification while suppressing the full denitrification pathway. Further investigation is needed on the impact of global changes on the C and N stocks and cycles in tropical peatlands.

## Acknowledgements

The study was supported by the Estonian Research Council (PRG352 and MOBERC-20 grants) and the EU through the European Regional Development Fund (ENVIRON and EcolChange Centres of Excellence, Estonia and the MOBTP101 returning researcher grant by the Mobilitas Pluss programme), the European Social Fund (Doctoral School of Earth Sciences and Ecology), LIFE programme project “Demonstration of climate change mitigation potential of nutrients rich organic soils in Baltic States and Finland” (LIFE OrgBalt, LIFE18 CCM/LV/001158), Czech Science Foundation (17-18112Y), and project SustES – Adaptation strategies for sustainable ecosystem services and food security under adverse environmental conditions (CZ.02.1.01/0.0/0.0/16_019/0000797). Dr. Negron-Juarez was supported by the Next Generation Ecosystem Experiments – Ttropics funded by the U.S Department of Energy, Office of Biological and Environmental Research. We would like to thank staff of the U. S. Department of Energy, U. S. Agency for International Development, U. S. Forest Service, University of Minnesota, University of Missouri, Michigan Technological University, Arizona State University, Oak Ridge National Laboratory, SilvaCarbon, Directorate of Foreign Commerce, Tourism and Crafts (DIRCETURA), Regional Government of Loreto (GORE-Loreto), and Quistococha Park for economic, managerial and scientific support.

## References

Baggs, E. M.: Soil microbial sources of nitrous oxide: recent advances in knowledge, emerging challenges and future direction, Current Opinion in Environmental Sustainability, 3, 321-327, 2011.

Balogh, J., Pintér, K., Fóti, S., Cserhalmi, D., Papp, M., and Nagy, Z.: Dependence of soil respiration on soil moisture, clay content, soil organic matter, and $CO_2$ uptake in dry grasslands, Soil Biology and Biochemistry, 43, 1006-1013, 2011.

Butterbach-Bahl, K., Baggs, E. M., Dannenmann, M., Kiese, R., and Zechmeister-Boltenstern, S.: Nitrous oxide emissions from soils: how well do we understand the processes and their controls?, Philosophical Transactions of the Royal Society B: Biological Sciences, 368, 2013.

Byrne, K. A., Kiely, G., and Leahy, P.: $CO_2$ fluxes in adjacent new and permanent temperate grasslands, Agricultural and Forest Meteorology, 135, 82-92, 2005.

Draper, F. C., Roucoux, K. H., Lawson, I. T., Mitchard, E. T. A., Honorio Coronado, E. N., Lähteenoja, O., Torres Montenegro, L., Valderrama Sandoval, E., Zaráte, R., and Baker, T. R.: The distribution and amount of carbon in the largest peatland complex in Amazonia, Environmental Research Letters, 9, 124017, 2014.

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021




297 Espenberg, M., Truu, M., Mander, Ü., Kasak, K., Nõlvak, H., Ligi, T., Oopkaup, K., Maddison, M., and Truu, J.: Differences
298 in microbial community structure and nitrogen cycling in natural and drained tropical peatland soils, Scientific Reports, 8,
299 4742, 2018.
300 Figueiredo, V., Pangala, S., Peacock, M., Gauci, V., Bastviken, D., and Enrich-Prast, A.: Contribution of trees to the $N_2O$
301 budget of Amazon floodplain forest, EGU General Assembly, Vienna, 2019.
302 Frolking, S., and Roulet, N. T.: Holocene radiative forcing impact of northern peatland carbon accumulation and methane
303 emissions, Global Change Biology, 13, 1079-1088, 2007.
304 Granville, J.-J. d.: Aperçu sur la structure des pneumatophores de deux espèces des sols hydromorphes en Guyane: *Mauritia*
305 *flexuosa* L. et *Euterpe olerácea* Mart. (*Palmae*). Généralisation au système respiratoire racinaire d'autres palmiers, Cahiers
306 ORSTOM. Série Biologie, 3-22, 1974.
307 Griffis, T. J., Roman, D. T., Wood, J. D., Deventer, J., Fachin, L., Rengifo, J., Del Castillo, D., Lilleskov, E., Kolka, R.,
308 Chimner, R. A., del Aguila-Pasquel, J., Wayson, C., Hergoualc'h, K., Baker, J. M., Cadillo-Quiroz, H., and Ricciuto, D.
309 M.: Hydrometeorological sensitivities of net ecosystem carbon dioxide and methane exchange of an Amazonian palm
310 swamp peatland, Agricultural and Forest Meteorology, 295, 108167, 2020.
311 Guilhen, J., Al Bitar, A., Sauvage, S., Parrens, M., Martinez, J. M., Abril, G., Moreira-Turcq, P., and Sánchez-Pérez, J. M.:
312 Denitrification and associated nitrous oxide and carbon dioxide emissions from the Amazonian wetlands, Biogeosciences,
313 17, 4297-4311, 2020.
314 Hergoualc'h, K., Dezzeo, N., Verchot, L. V., Martius, C., van Lent, J., del Aguila-Pasquel, J., and López Gonzales, M.: Spatial
315 and temporal variability of soil $N_2O$ and $CH_4$ fluxes along a degradation gradient in a palm swamp peat forest in the
316 Peruvian Amazon, Global Change Biology, 26, 7198-7216, 2020.
317 Hu, H.-W., Chen, D., and He, J.-Z.: Microbial regulation of terrestrial nitrous oxide formation: understanding the biological
318 pathways for prediction of emission rates, FEMS Microbiology Reviews, 39, 729-749, 2015.
319 Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E.
320 N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Sunderland, T. C. H., Taedoumg, H., Thomas, S.
321 C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., Amani, C. A., Baker, T. R., Banin, L. F., Baya, F., Begne, S. K.,
322 Bennett, A. C., Benedet, F., Bitariho, R., Bocko, Y. E., Boeckx, P., Boundja, P., Brienen, R. J. W., Brncic, T., Chezeaux,
323 E., Chuyong, G. B., Clark, C. J., Collins, M., Comiskey, J. A., Coomes, D. A., Dargie, G. C., de Haulleville, T., Kamdem,
324 M. N. D., Doucet, J.-L., Esquivel-Muelbert, A., Feldpausch, T. R., Fofanah, A., Foli, E. G., Gilpin, M., Gloor, E.,
325 Gonmadje, C., Gourlet-Fleury, S., Hall, J. S., Hamilton, A. C., Harris, D. J., Hart, T. B., Hockemba, M. B. N., Hladik, A.,
326 Ifo, S. A., Jeffery, K. J., Jucker, T., Yakusu, E. K., Kearsley, E., Kenfack, D., Koch, A., Leal, M. E., Levesley, A., Lindsell,
327 J. A., Lisingo, J., Lopez-Gonzalez, G., Lovett, J. C., Makana, J.-R., Malhi, Y., Marshall, A. R., Martin, J., Martin, E. H.,
328 Mbayu, F. M., Medjibe, V. P., Mihindou, V., Mitchard, E. T. A., Moore, S., Munishi, P. K. T., Bengone, N. N., Ojo, L.,
329 Ondo, F. E., Peh, K. S. H., Pickavance, G. C., Poulsen, A. D., Poulsen, J. R., Qie, L., Reitsma, J., Rovero, F., Swaine, M.
330 D., Talbot, J., Taplin, J., Taylor, D. M., Thomas, D. W., Toirambe, B., Mukendi, J. T., Tuagben, D., Umunay, P. M., van
331 der Heijden, G. M. F., Verbeeck, H., Vleminckx, J., Willcock, S., Wöll, H., Woods, J. T., and Zemagho, L.: Asynchronous
332 carbon sink saturation in African and Amazonian tropical forests, Nature, 579, 80-87, 2020.
333 Hutchinson, G. L., and Livingston, G. P.: Use of chamber systems to measure trace gas fluxes, in: Agricultural Ecosystem
334 Effects on Trace Gases and Global Climate Change, edited by: Harper, L. A., Mosier, A. R., Duxbury, J. M., Rolston, D.
335 E., Peterson, G. A., Baenziger, P. S., Luxmoore, R. J., and Kral, D. M., 63-78, 1993.
336 Inatomi, M., Hajima, T., and Ito, A.: Fraction of nitrous oxide production in nitrification and its effect on total soil emission:
337 A meta-analysis and global-scale sensitivity analysis using a process-based model, PLOS ONE, 14, e0219159, 2019.
338 IPCC: Land–climate interactions, in: Climate Change and Land: an IPCC special report on climate change, desertification,
339 land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, edited
340 by: P.R. Shukla, J. S., E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors,
341 R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley,
342 K. Kissick, M, Belkacemi, J. Malley, In press, 2019.
343 Jauhiainen, J., Silvennoinen, H., Hamalainen, R., Kusin, K., Limin, S., Raison, R. J., and Vasander, H.: Nitrous oxide fluxes
344 from tropical peat with different disturbance history and management, Biogeosciences, 9, 1337-1350, 2012.
345 Karhu, K., Auffret, M. D., Dungait, J. A. J., Hopkins, D. W., Prosser, J. I., Singh, B. K., Subke, J.-A., Wookey, P. A., Ågren,
346 G. I., Sebastià, M.-T., Gouriveau, F., Bergkvist, G., Meir, P., Nottingham, A. T., Salinas, N., and Hartley, I. P.:
347 Temperature sensitivity of soil respiration rates enhanced by microbial community response, Nature, 513, 81-84, 2014.
348 Kuzyakov, Y., and Xu, X.: Competition between roots and microorganisms for nitrogen: mechanisms and ecological
349 relevance, New Phytologist, 198, 656-669, 2013.
350 Leifeld, J., and Menichetti, L.: The underappreciated potential of peatlands in global climate change mitigation strategies,
351 Nature Communications, 9, 1071, 2018.
352 Lenhart, K., Weber, B., Elbert, W., Steinkamp, J., Clough, T., Crutzen, P., Pöschl, U., and Keppler, F.: Nitrous oxide and
353 methane emissions from cryptogamic covers, Global Change Biology, 21, 3889-3900, 2015.
354 van Lent, J., Hergoualc'h, K., and Verchot, L. V.: Reviews and syntheses: Soil $N_2O$ and NO emissions from land use and land-
355 use change in the tropics and subtropics: a meta-analysis, Biogeosciences, 12, 7299-7313, 2015.
356 van Lent, J., Hergoualc'h, K., Verchot, L., Oenema, O., and van Groenigen, J. W.: Greenhouse gas emissions along a peat
357 swamp forest degradation gradient in the Peruvian Amazon: soil moisture and palm roots effects, Mitigation and
358 Adaptation Strategies for Global Change, 24, 625-643, 2019.
359 Li, C., Frolking, S., and Frolking, T. A.: A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model
360 structure and sensitivity, Journal of Geophysical Research: Atmospheres, 97, 9759-9776, 1992.

https://doi.org/10.5194/bg-2021-46
Preprint. Discussion started: 3 March 2021




Liengaard, L., Figueiredo, V., Markfoged, R., Revsbech, N. P., Nielsen, L. P., Prast, A. E., and Kühl, M.: Hot moments of $N_2O$ transformation and emission in tropical soils from the Pantanal and the Amazon (Brazil), Soil Biology and Biochemistry, 75, 26-36, 2014.

Lilleskov, E., McCullough, K., Hergoualc'h, K., del Castillo Torres, D., Chimner, R., Murdiyarso, D., Kolka, R., Bourgeau-Chavez, L., Hribljan, J., del Aguila Pasquel, J., and Wayson, C.: Is Indonesian peatland loss a cautionary tale for Peru? A two-country comparison of the magnitude and causes of tropical peatland degradation, Mitigation and Adaptation Strategies for Global Change, 24, 591-623, 2019.

Mander, Ü., Well, R., Weymann, D., Soosaar, K., Maddison, M., Kanal, A., Lõhmus, K., Truu, J., Augustin, J., and Tournebize, J.: Isotopologue ratios of $N_2O$ and $N_2$ measurements underpin the importance of denitrification in differently N-loaded riparian alder forests, Environmental Science & Technology, 48, 11910-11918, 2014.

Melillo, J. M., Steudler, P. A., Feigl, B. J., Neill, C., Garcia, D., Piccolo, M. C., Cerri, C. C., and Tian, H.: Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon, Journal of Geophysical Research: Atmospheres, 106, 34179-34188, 2001.

Pangala, S. R., Enrich-Prast, A., Basso, L. S., Peixoto, R. B., Bastviken, D., Hornibrook, E. R. C., Gatti, L. V., Marotta, H., Calazans, L. S. B., Sakuragui, C. M., Bastos, W. R., Malm, O., Gloor, E., Miller, J. B., and Gauci, V.: Large emissions from floodplain trees close the Amazon methane budget, Nature, 552, 230-234, 2017.

Pärn, J., Verhoeven, J. T. A., Butterbach-Bahl, K., Dise, N. B., Ullah, S., Aasa, A., Egorov, S., Espenberg, M., Järveoja, J., Jauhiainen, J., Kasak, K., Klemedtsson, L., Kull, A., Laggoun-Défarge, F., Lapshina, E. D., Lohila, A., Lõhmus, K., Maddison, M., Mitsch, W. J., Müller, C., Niinemets, Ü., Osborne, B., Pae, T., Salm, J.-O., Sgouridis, F., Sohar, K., Soosaar, K., Storey, K., Teemusk, A., Tenywa, M. M., Tournebize, J., Truu, J., Veber, G., Villa, J. A., Zaw, S. S., and Mander, Ü.: Nitrogen-rich organic soils under warm well-drained conditions are global nitrous oxide emission hotspots, Nature Communications, 9, 1135, 2018.

Ricaud, P., Attié, J. L., Teyssèdre, H., El Amraoui, L., Peuch, V. H., Matricardi, M., and Schluessel, P.: Equatorial total column of nitrous oxide as measured by IASI on MetOp-A: implications for transport processes, Atmospheric Chemistry and Physics, 9, 3947-3956, 2009.

Roucoux, K. H., Lawson, I. T., Jones, T. D., Baker, T. R., Coronado, E. N. H., Gosling, W. D., and Lähteenoja, O.: Vegetation development in an Amazonian peatland, Palaeogeogr., Palaeoclimatol., Palaeoecol., 374, 242-255, 2013.

Rubol, S., Silver, W. L., and Bellin, A.: Hydrologic control on redox and nitrogen dynamics in a peatland soil, Science of the Total Environment, 432, 37-46, 2012.

Ruwaimana, M., Anshari, G. Z., Silva, L. C., and Gavin, D. G.: The oldest extant tropical peatland in the world: a major carbon reservoir for at least 47 000 years, Environmental Research Letters, 15, 114027, 2020.

Ruzicka, J., and Hansen, E. H.: Flow Injection Analysis, J. Wiley & Sons, New York, 1981.

Schindler, T., Mander, Ü., Machacova, K., Espenberg, M., Krasnov, D., Escuer-Gatius, J., Veber, G., Pärn, J., and Soosaar, K.: Short-term flooding increases $CH_4$ and $N_2O$ emissions from trees in a riparian forest soil-stem continuum, Scientific Reports, 10, 3204, 2020.

Spott, O., Russow, R., and Stange, C. F.: Formation of hybrid $N_2O$ and hybrid $N_2$ due to codenitrification: First review of a barely considered process of microbially mediated N-nitrosation, Soil Biology and Biochemistry, 43, 1995-2011, 2011.

Teh, Y. A., Wayne, M., Berrio, J.-C., Boom, A., and Page, S. E.: Seasonal variability in methane and nitrous oxide fluxes from tropical peatlands in the western Amazon basin, Biogeosciences, 2017.

Thompson, R. L., Lassaletta, L., Patra, P. K., Wilson, C., Wells, K. C., Gressent, A., Koffi, E. N., Chipperfield, M. P., Winiwarter, W., Davidson, E. A., Tian, H., and Canadell, J. G.: Acceleration of global $N_2O$ emissions seen from two decades of atmospheric inversion, Nature Climate Change, 9, 993-998, 2019.

Turetsky, M. R., Benscoter, B., Page, S., Rein, G., van der Werf, G. R., and Watts, A.: Global vulnerability of peatlands to fire and carbon loss, Nature Geoscience, 8, 11-14, 2015.

Wrage-Mönnig, N., Horn, M. A., Well, R., Müller, C., Velthof, G., and Oenema, O.: The role of nitrifier denitrification in the production of nitrous oxide revisited, Soil Biology and Biochemistry, 123, A3-A16, 2018.