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Nitrous oxide as second most important greenhouse gas in tropical peatlands

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Abstract

Earth's climate largely depends on carbon and nitrogen exchange between the atmosphere and tropical peatland ecosystems. Permanently wet peatlands take up carbon dioxide in plants and accumulate organic carbon in soil but release methane. Man-made drainage releases carbon dioxide from peat soils. Carbon and nitrous gas exchange and their relationships with tropical peatland conditions are poorly understood. We analysed natural peat swamp forests and fens, moderately drained and dry peatlands under a wide variety of land uses. The tropical peat swamp forests were large greenhouse gas sinks while tropical peatlands under moderate and low soil moisture levels emitted carbon dioxide and nitrous oxide. Carbon dioxide uptake of 160 mg m^{-2} h^{-1} dominated the net greenhouse gas budgets overall, while nitrous oxide emission of 90 mg CO_2-equivalent m^{-2} h^{-1} on average was the second most important contributor (ahead of average methane emissions of 36 mg CO_2-equivalent m^{-2} h^{-1}) across the whole tropical peat moisture range.

1 Introduction

Peatlands function as a substantial reservoir of carbon (C) and nitrogen (N) (Leifeld and Menichetti, 2018, Loisel et al., 2021). In undisturbed conditions, specifically within permanently waterlogged peat swamp forests, C accumulates in the peat over extended periods, spanning tens of thousands of years (Melling et al., 2005a; Ruwaimana et al., 2020). Natural and anthropogenic disturbances have the potential to release stored C and N as greenhouse gases (GHG). This potential is particularly high in tropical peatlands (IPCC, 2021). Drought, an increasingly prevalent ecological change in tropical zones, accelerates ecosystem alterations by shortening the growth period (IPCC, 2021), and elevating ecosystem respiration (ER) (Karhu et al., 2014; Jassey et al., 2021). In dry seasons, ecosystem respiration may surpass gross primary production (GPP) by an average of 600 mg C day^{-1}, even when the soil is still wet (Griffis et al., 2020; Pärn et al., 2023). We are still short of fully understanding the total effect of soil-moisture variations on C balances in low-latitude peatlands, necessitating further research efforts (Zhou et al., 2023).

The anoxic decomposition of peat in conditions of a high water table results in the production of methane (CH_4) (Melling et al., 2005b; Teh et al., 2017; Hergoualc'h et al., 2020). CH_4 is a potent greenhouse gas, exhibiting a global warming potential equivalent to 28 times that of carbon dioxide (CO_2) (IPCC, 2021). The CH_4 generated within a peat layer escapes to the topsoil, where it may be either consumed by methanotrophs or be emitted. The latter can happen either directly through the peat or facilitated through plant conduits (Soosaar et al., 2022). As a result, the hydroclimate, biogeochemistry of distinct peat layers, as well as the type of vegetation and land use, emerge as potential influencing factors for CH_4 emissions in tropical peatlands.

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Suboxic processes occurring within N-rich peat under moderate water content (50 to 60%) lead to the production of 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; Pärn et al., 2023). Globally, regions such as the Amazon rainforest, Congo, and Southeast Asia exhibit the highest N_2O emissions (Ricaud et al., 2009). Amazonia alone yields 1,300 Gg N_2O-N yr^{-1} (Melillo et al., 2001). The conversion of peatlands for agriculture, particularly in Southeast Asia, produces huge amounts of N_2O (Hadi et al., 2000; Melling et al., 2007). Brazil, due to increased fertilization, is also a major contributor to the global rise in N_2O emissions (Thompson et al., 2019). The role of peatlands in the total tropical N_2O emissions remains poorly understood (van Lent et al., 2015; Guilhen et al., 2020). Peat swamps in Peru and Southeast Asia exhibit varying N_2O emissions, with a Peruvian palm peat swamp producing 0.5 to 2.6 kg N_2O-N ha^{-1} yr^{-1} and Southeast Asian peat swamp forests producing 2.7 ± 1.7 kg N_2O-N ha^{-1} yr^{-1} (average ± standard deviation; van Lent et al., 2015). However, the sources of N_2O (nitrate (NO_3^-) or ammonium (NH_4^+)) and their susceptibility to climatic changes, such as water table, oxygen (O_2), and temperature fluctuations, remain unclear. Studies on mineral soil are deemed unreliable for comprehending the impact of climate change on peatlands due to their fundamentally different biogeochemistry (Rydin and Jeglum, 2013). Where undrained, peatlands are water-saturated throughout the year, shielding the C and N stocks (Turetsky et al., 2015). However, deforestation, often with fire, jeopardizes the C and N stocks (Turetsky et al., 2015; Lilleskov et al., 2019; Swails et al., in press).

Limited studies have compared greenhouse gas fluxes across different land uses and water regimes in tropical peatlands. Here, we analyse GHG exchange based on field chamber measurements of ER, N_2O and CH_4 fluxes (Pärn et al., 2018, 2023 and unpublished) and satellite data of gross primary production (GPP) in 12 tropical peatlands in South America, Africa and Southeast Asia during the wet and dry seasons. We further investigate explanatory factors of the GHG fluxes mostly focusing on drainage, soil temperature and soil chemistry.

2 Methods

2.1 Field sampling

We conducted a survey of CO_2, CH_4 and N_2O fluxes and potentially controlling environmental variables at peatland sites in the Peruvian Amazon, French Guiana, Uganda, Burma, and the Malaysian Borneo states of Sarawak and Sabah during both the dry season (i.e. annual water table minimum) and rainy period (annual water table maximum) of each site between 2013 and 2022. We selected a total of 12 forested, fen, grassland, arable and oil palm plantation sites (Fig. 1) in the rainy tropical (A) climate zones of the Köppen classification from our global wetland soil database (Pärn et al., 2018, 2023 and unpublished; Fig. 1). The hydrology and trophic status of the natural sites ranged from groundwater-fed swamps and fens to rain-fed peat swamp forests. We also selected the sites to represent the full typical range of land uses of the rainy tropical belt. Accordingly, our study sites represent peatlands that have been arable for >5 years (Borneo, Burma, Peru and Uganda), intensively (more than once a year) grazed peat meadows (Uganda), and drained fens (Guiana (Espenberg et al., 2018) and Burma), swamp forests (Peru, Sabah and Sarawak) and fens (Espenberg et al., 2018) under no direct human influence in each study region. To capture the full variety of GHG fluxes at a site, we set up transects of 2–3 plots, each containing 3–4 opaque chambers, arranged along 25–100 m of terrain. We sampled gas from the chambers during 3–6-day campaigns. We measured ER (in mg CO_2 m^{-2} h^{-1}), CH_4 and N_2O fluxes (both in mg m^{-2} h^{-1}) from the samples using a gas chromatograph (Pärn et al., 2018; Bahram, Espenberg, Pärn et al., 2022). We collected soil samples of 150–200 g from the chambers at 0–10 cm depth after the final gas sampling, and transported them to laboratories in Tartu, Estonia.

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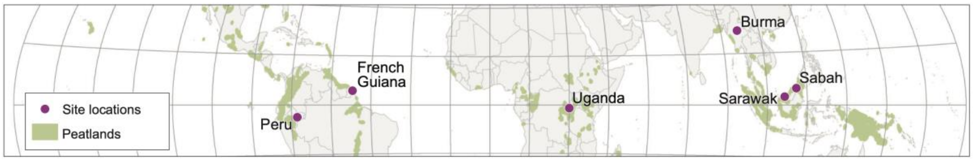

Fig. 1. Location of peatland study sites. Each location contains a natural peatland and an equivalent peatland under direct human impact. Data from Pärn et al. (2018, 2023 and partly unpublished (Sarawak)). Global peatland map: Leifeld and Menichetti (2018).

2.2 Estimation of GPP

As an estimate of GPP, we used MOD17A2H V006 data (Running et al., 2015) developed from the MODIS sensor onboard the Terra and Aqua remote sensing satellites and expressed in mg CO_2 m^{-2} h^{-1}. MOD17A2H V006 is based on the radiation use efficiency concept (Montheith, 1972) with three major components. The first assumption is that GPP is directly related to the solar energy absorbed by plants. Second, the concept assumes a connection between absorbed solar energy and satellite-derived spectral indices such as NDVI. The third assumption is that for biophysical reasons, the actual conversion efficiency of absorbed solar energy is lower than the theoretical value. The calculation of GPP (Equation 1) requires radiation use efficiency and absorbed photosynthetically active radiation (APAR) measurements. APAR calculates the available leaf area index (LAI) to absorb incident solar energy. This estimate is then converted into GPP by multiplying APAR with radiation use efficiency (ε) (Equations 1 and 2). Remote sensing data usually provide the fraction of photosynthetically active radiation (FPAR; Equation 3). APAR can be calculated by Equation 4 (Sellers, 1987). This requires estimation of incidental photosynthetically active radiation (IPAR) (Equation 5), which is extracted from the GMAO/NASA dataset (Running et al., 2015).

$$GPP = \varepsilon * APAR \quad (1)$$

$$\varepsilon = \varepsilon_{max} * T_{min\_scalar} * VPD\_scalar \quad (2)$$

$$FPAR = APAR/PAR \approx NDVI \quad (3)$$

$$APAR = IPAR * FPAR \quad (4)$$

$$IPAR = SWR_{rad} * 0.45 \quad (5)$$

ε_{max} is the maximum radiation conversion efficiency in kg C MJ^{-1} which is obtained from the Biome Properties Look-Up Table (BPLUT) of the at-launch land cover product of MODIS (MOD12; Friedl and Sulla-Menashe, 2020).

T_{min_scalar} and VPD_scalar are the ramp functions of T_{min} and VPD. This calculation requires the following parameters extractable from the GMAO/NASA dataset (Running et al., 2015):

T_{min_max} (ºC) – the daily minimum temperature at which $\varepsilon = \varepsilon_{max}$ for an optimal VPD

T_{min_min} (ºC) – the daily minimum temperature at which $\varepsilon = 0$ at any VPD

VPD_{max} (Pa) – the daylight average vapor pressure deficit at which $\varepsilon = \varepsilon_{max}$ for an optimal T_{min}

VPD_{max} (Pa) – the daylight average vapor pressure deficit at which $\varepsilon = 0.0$ at any T_{min}

SWR_{rad} = Incident shortwave radiation used for calculating IPAR.

We extracted GPP values for our sites from the dataset (kg C m^{-2} 8 $days^{-1}$) for the ground measurement dates and expressed the values in mg C m^{-2} h^{-1}.

A >50% underestimate of the negative effect of drought on the MODIS GPP product has been suspected (Stocker et al., 2019). We tested the significance of this possible underestimate by multiplying the GHG exchange values from our dry (<0.4 m^3 m^{-3} SWC) by a factor of 0.5 and using them in the regression analyses. The patterns of GHG exchange values vs. SWC after this reduction became less pronounced but retained their significance.

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2.3 NEE calculation

We calculated NEE from GPP and ER as follows (IPCC, 2021) (Equation 6):

$$NEE = ER - GPP \quad (6)$$

GHG exchange was calculated for each chamber following Equation 7.

$$GHG\ exchange = CH_4 \cdot GWP_{CH4} + N_2O \cdot GWP_{N2O} + NEE, \text{ where:} \quad (7)$$

GHG exchange was the greenhouse gas exchange in CO_2 equivalents (CO_2eq),
CH_4 was the field-observed methane flux, mg CH_4 m^{-2} h^{-1},
GWP_{CH4} was 28 CO_2eq, the 100-year global warming potential of CH_4 without climate–carbon feedbacks (IPCC, 2021) ,
N_2O was the field-observed nitrous oxide flux, mg N_2O m^{-2} h^{-1},
GWP_{N2O} was 265 CO_2eq, the 100-year global warming potential of N_2O without climate–carbon feedbacks (IPCC, 2021), and NEE was the net ecosystem exchange of CO_2 (Equation 6).
We considered carbon, N_2O and CH_4 runoff as insignificant (Swails et al., in press) although they may evade in drained peatlands (Wilson et al., 2016, Taillardat et al., 2022, Nishida et al., 2023).

2.4 Laboratory inorganic chemical and soil physical analyses

The homogenised samples were divided into subsamples for physical-chemical analyses and DNA extraction. Plant-available phosphorus (P, NH_4-lactate extractable) was determined on a FiaStar5000 flow-injection analyser. Plant-available potassium (K) was determined from the same solution by the flame-photometric method and plant-available magnesium (Mg) was determined from a 100mL NH_4-acetate solution with a titanium-yellow reagent on the flow-injection analyser. Plant-available calcium (Ca) was analysed using the same solution by a flame-photometrical method. Soil pH was determined using a 1N KCl solution; soil NH_4 and NO_3 were determined on a 2M KCl extract of soil by flow-injection analysis (APHA, 2005). Total N and C contents of oven-dry samples were determined by a dry-combustion method on a varioMAX CNS elemental analyser (Elementar Analysensysteme GmbH, Germany). Organic matter content of dry matter was determined by loss on ignition (McLaren and Cameron, 2012). We determined SWC from gravimetric water content (GWC), dry matter content and empirically established bulk densities of mineral and organic matter fractions (Pärn et al., 2018) and calibrated them with field measurements using a handheld GS3 sensor connected to a ProCheck handheld reader (Decagon Devices, Pullman, WA, USA) and a Teros 12 sensor (METER Group, USA).

2.5 Correlation analysis of GHG against environmental factors

We calculated a correlation matrix between our individual GHG fluxes and their total CO_2eq exchange values, environmental factors, relative abundances of functional groups of microbes and ratios between them. We used linear and non-parametric GAM models applying variable smoothness factors (starting from minimal smoothness: k=3; Pärn et al., 2018). We assessed normality of our data using visual approaches and the Shapiro-Wilk test. Where necessary, we log-transformed the values. For the GHG flux rates, we considered the following environmental predictor variables: soil and water temperature, water table, volumetric SWC, soil chemistry (pH, total C%, organic matter, total N%, C:N ratio, ammonium, nitrate, calcium, magnesium, potassium and phosphorus), water oxygen content. We calculated Pearson correlations using the R programming language (*stats* and *mgcv* packages). We reported correlations with a significance level of p=0.05.

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3 Results and Discussion

CO_2 dominated the GHG budgets with overall net ecosystem uptake 160 mg m^{-2} h^{-1} (Figs. 2, 3). The wet (SWC >0.8 m^3 m^{-3}) peat swamp forests and the drained Sabah oil palm plantation were the large net CO_2 and thus overall GHG sinks. This corroborates the conclusion of the IPCC (2021) and several other global studies on CO_2 as the predominant GHG, with CH_4 as a minor component. The rest of dry and moderately drained peatlands were evenly distributed between sinks and sources of CO_2. (Fig. 2). N_2O emission contributed overall 90 mg CO_2-equivalent m^{-2} h^{-1}. The moderately drained peatlands (SWC 0.35–0.70 m^3 m^{-3}) contributed the largest N_2O fluxes. The peak N_2O emissions in moderately drained peat soils is well known (Pärn et al. 2018). At the two extremes of the SWC spectrum, the dry Peruvian arable field (<0.25 m^3 m^{-3} SWC) and the wet but oxygenated ammonium-rich Peruvian swamp forest emitted considerable amounts of N_2O – 41 and 90 mg CO_2-equivalent m^{-2} h^{-1}, respectively. Our measured N_2O emissions contrasted the earlier-reported negligible emissions from a Peruvian palm peat swamp forest (Teh et al. 2017) and 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_2O-N m^{-2} h^{-1} for the Amazon Basin (Guilhen et al. 2020). Our N_2O emissions were log-log linear positively related to soil nitrate content and formed a unimodal relationship with SWC (Pärn et al., 2018). However, it has been observed that a large part of the soil N_2O never leaves the forest canopy space (Mander et al., 2021), either due to physical processes or the canopy microbiome (van Groningen et al., 2015, Guerreri et al., 2021). Alternatively, nitrogen-fixing cryptogamic covers on forest canopy surfaces can be additional sources of N_2O (Lenhart et al, 2015).

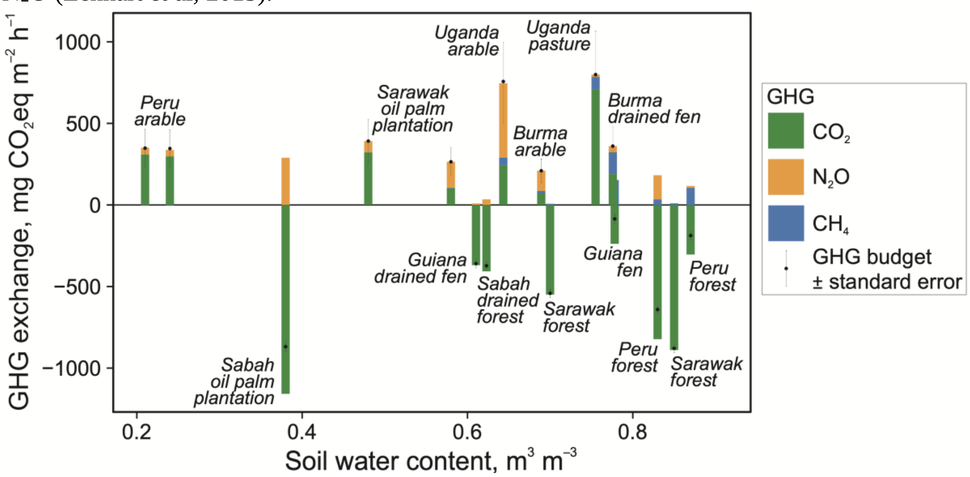

Fig. 2. GHG exchange in peatland sites along the soil water content gradient. Breakdown of GHG budgets into individual fluxes along soil water content gradient. Site average (bars for individual gases and points for total GHG budget) and standard error (whiskers) are shown. Data from Pärn et al. (2018, 2023 and partly unpublished (Sarawak)).

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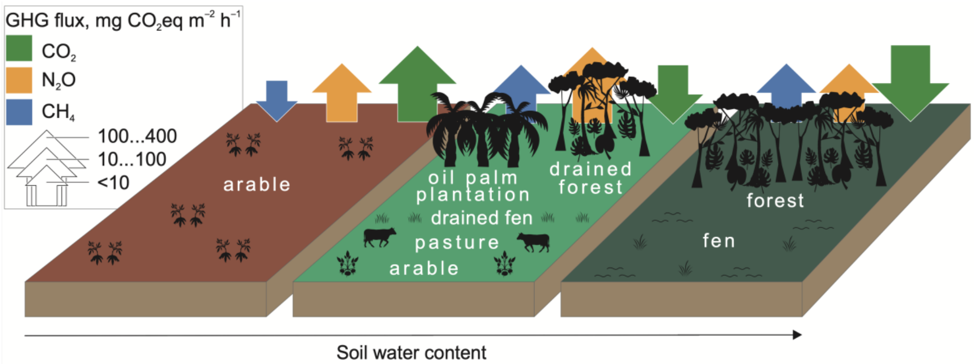

Fig. 3. GHG fluxes and land use along the soil water content gradient. Data from Pärn et al. (2018, 2023 and partly unpublished (Sarawak)).

Surprisingly for peatlands, CH_4 comprised only a minor share of the GHG budgets – on average, 36 mg CO_2-equivalent m^{-2} h^{-1} across the full soil moisture spectrum. The emissions followed SWC in a GAM function that peaked at 0.8 m^3 m^{-3} SWC (k=6; R^2= 0.51), which corresponded to anoxic conditions created by stagnant ground-level water table, and decreased again towards the fully submerged peatlands under mobile water. Turetsky and colleagues (2014) have shown a similar distribution in extratropical peatlands. Accordingly, our wetter peat soils (>0.76 m^3 m^{-3} SWC) produced practically all the CH_4 while the drier peat soils (<0.6 m^3 m^{-3} SWC) emitted CH_4 negligibly (<4 mg CO_2-equivalent m^{-2} h^{-1}) or took it up (Figs. 2, 3). Our observed CH_4 fluxes were similar to reports from Brazilian swamp forest soils (*igapo* and *varzea*; Pangala et al. 2017). The moderate explanatory power of our GAM model can be explained by the intrinsic confinement of CH_4 emissions to individual emission hot spots (Becker et al., 2008). However, as CH_4 was a minor component of GHG exchange (Fig. 2), the >40% uncertainty in CH_4 flux estimates does not translate into large uncertainty in GHG exchange across the tropical belt. Permanently anoxic environments normally show high CH_4 production (Turetsky et al., 2014, IPCC, 2021). The low share of CH_4 in the GHG exchange of our wet peatlands suggests indirect human influence through a legacy of climatic drying. In the forests, however, tree trunks and leaves can conduct or produce additional CH_4 into the atmosphere (Keppler et al., 2006; Pangala et al., 2017; Soosaar et al., 2022).

4 Conclusions

The tropical peatlands showed high GHG turnover rates, varying between sinks and sources of CO_2. N_2O was the second most important part of the GHG budget, particularly in the nitrogen-rich peatlands. The resulting high GHG emissions demand close monitoring of soil moisture and nitrogen in tropical peatlands. We highlight the need to consider not only carbon but all three main greenhouse gases (CO_2, N_2O and CH_4) in tropical peatland GHG budgets. Management of tropical peatlands should be aware of the impact changes in soil moisture and nitrogen availability have on GHG emissions. Conservation of swamp forests is the safest way to keep up the carbon uptake and minimise the GHG emissions. Future impacts of global change on GHG exchange and the state of peatland ecosystems will be accordingly determined by drying and mineralisation of peat. Future studies will have to account for the production and consumption rates of CH_4 as well as N_2O in all parts of the soil–tree–atmosphere continuum.

Data Availability

The study is mostly based on data published in Pärn et al., (2018, 2023). Additional source data (CO_2 and CH_4 fluxes and unpublished data from Sarawak) are provided with this paper.

Author Contribution

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Jaan Pärn and Ülo Mander designed and managed the study. Jaan Pärn, Mikk Espenberg, Kaido Soosaar, Kuno Kasak, Thomas Schindler, Lulie Melling, Lizardo Fachín, Reti Ranniku and Ülo Mander planned and participated in the field sampling. Sandeep Thayamkottu extracted the remotely sensed GPP data. Jaan Pärn analysed the data and wrote the paper with conceptual input from Ülo Mander, Mikk Espenberg, Kaido Soosaar, Sandeep Thayamkotu and Kristina Sohar.

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Competing Interest

The authors declare that they have no conflict of interest.

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