COMPARISON OF NITROUS OXIDE (N_2O) AND METHANE (CH_4) FLUXES IN NATURALLY WET AND DRAINED MINERAL FOREST SOIL

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Abstract. The scope of the study is to determine the effect of drainage of mineral soil in forest on nitrous oxide (N_2O) and methane (CH_4) emissions from soil. We evaluated N_2O and CH_4 fluxes from soil in pine and birch stands with moderately fertile drained and naturally wet mineral soil. The N_2O and CH_4 fluxes in naturally wet and drained mineral forest soils are crucial for understanding their respective roles in climate change dynamics and informing sustainable land management practices that can mitigate greenhouse gas emissions. The study was implemented in eighteen stands. We took gas samples periodically (once per month in average) using the opaque chamber method (45 measurement points in total) during 18 months period. Samples were analysed in laboratory using the gas chromatography method. It was assumed that N_2O and CH_4 fluxes are constant during the whole rotation period, while the average annual fluxes were calculated as sum of average monthly fluxes. We also measured the groundwater (GW) depth, soil and air temperature during the gas sampling and periodically took water samples from perforated water wells for chemical analyses. We found that all measurement sites are net sinks of CH_4 removals and sources of N_2O emissions. We did not find higher CH_4 emissions in wet soil; however, one of the measurement years contained also one of the driest vegetation seasons, and GW level was deeper than usually, potentially resulting in reduction of CH_4 emissions. We did not find correlation between the air temperature and N_2O or CH_4 emissions, as well as between the groundwater level and efflux of these gases. However, higher groundwater level in wet areas is associated with periodic extremes of N_2O and CH_4 emissions, which cannot be expressed by regression equations. If these extremes are considered, then wet mineral soils are a significant source of N_2O emissions, however, they can also be omitted as a non-anthropogenic source.

Keywords: nitrous oxide, methane, emissions, drained mineral soil, wet mineral soil, forest land.

Introduction

Drainage of mineral forest soil in temperate and boreal climate zones may significantly influence greenhouse gas (GHG) emissions, primarily methane (CH_4) and carbon dioxide (CO_2). Research by Peacock et al. (2021) found that while the surface of dry ditches emits no CH_4, water-filled ditches often exhibit high CH_4 emissions, with almost all ditches acting as CO_2 sources, regardless of their water status [1]. These emissions are crucial to consider in forest GHG budgets to avoid underestimating anthropogenic emissions. Similarly, forest management practices, including thinning and clear-cutting, have been shown to affect GHG fluxes significantly. Thinning reduces soil CH_4 uptake, while clear-cutting caused clear-cut and stump-harvested plots become net sources of CH_4, with substantial GHG emissions dominated by CO_2 [2].

The moisture level in soil affected by drainage influences the soil CO_2 emissions, as indicated by Makhnykina et al. (2023), who noted an impact on soil carbon storage and release [3]. Cai and Chang (2020) emphasized the need for further investigation to fully understand the effects of drainage on the soil carbon storage and GHG emissions within forest ecosystems [4]. The acceleration of decomposition processes and alterations in organic matter characteristics due to drainage could lead to increased CO_2 emissions, with the impact varying based on the drainage channel proximity and land use types [5]. Earlier studies in Latvia did not demonstrate significant difference of soil carbon stocks between drained and naturally wet forest soils [6]. Significantly smaller anthropogenic soil carbon loss was found in organic forest soil in comparison to the reported soil carbon losses in the GHG inventory report [7]. Drainage significantly reduced CH_4 emissions from soil in forests with organic soils [8].

Additionally, drainage may lead to increased soil erosion [9], declines in soil pH, and extractable base cation content, impacting GHG emissions through leaching and nutrient sequestration processes [10]. Forest cover plays a crucial role in soil erosion and water quality, with increases in the forest cover significantly reducing soil erosion and river turbidity, highlighting the essential role of forests in mitigating erosion and improving water quality [11]. While in the hemiboreal climate zone indirect nutrient leaching through drainage systems may be a more significant issue to consider [12].

Therefore, the scope of this study is to compare N_2O and CH_4 emissions from soil in drained and naturally wet forests in Latvia to verify that the drainage of mineral soil is not an omitted source of

emissions in the national GHG inventory. In the study we also separated the forest stand types into nutrient poor and rich soil. Nutrient poor drained mineral soil is represented by *Callunosa mel.*, *Vacciniosa mel.* and *Myrtillosa mel.* stand types, nutrient rich drained mineral soil – by *Mercurialosa mel.* stand type; nutrient poor naturally wet mineral soil is represented by *Vaccinioso-sphagnosa* and *Myrtilloso-sphagnosa* stand types and nutrient rich naturally wet mineral soil – by *Myrtillosoi-polytrichosa* and *Drypteriosa* stand types.

Materials and methods

The study was implemented in eighteen forest sites in forests with drained and naturally wet mineral soil in the central part of Latvia, including nine sites with drained soil and nine sites with wet soil. The sites representing nutrient-rich conditions (site types with naturally wet soil *Myrtillosoi-polytrichosa* and *Drypteriosa* and with drained soil – *Myrtillosa mel.* and *Mercurialosa mel.*) are 12; and six sites representing nutrient-poor conditions, nutrient-rich conditions (site types with naturally wet soil *Vaccinioso-sphagnosa* and *Myrtilloso-sphagnosa* and with drained soil – *Callunosa mel.* and *Vacciniosa mel.*) Measurement points are located in the area of a compartment representing vegetation typical for the respective stand types and the peat layer is not thicker than 5 cm. Species represented in the study were aspen (nutrient-rich sites), birch (nutrient-rich and poor sites), black alder (*Alnus Glutinosa* L.) Gaertn., nutrient-rich sites) and Scots pine (*Pinus sylvestris* L., nutrient-poor sites, Table 1).

Table 1

Study sites in drained and naturally wet forests

Object	Dominant tree species	Moisture regime	Nutrition regime	Mean GW level, cm	Mean topsoil moisture, %	Mean air temp., °C
LZP-AJ-MRD	Aspen	Drained	Rich	127.7 ± 1.6	26.4 ± 1.5	14.7 ± 1.4
LZP-AJ-MRW	Aspen	Wet	Rich	49.4 ± 8.6	43.7 ± 1.2	12.6 ± 4.7
LZP-AM-MRD	Aspen	Drained	Rich	113.9 ± 4	21.3 ± 1.1	12.7 ± 1
LZP-AM-MRW	Aspen	Wet	Rich	65.1 ± 6.3	30.2 ± 1	11.6 ± 2.3
LZP-BJ-MPD	Birch	Drained	Poor	75.2 ± 4.7	35.8 ± 1.5	11.5 ± 1.6
LZP-BJ-MPW	Birch	Wet	Poor	39.2 ± 6.2	59.3 ± 1.2	13.3 ± 3.8
LZP-BJ-MRD	Birch	Drained	Rich	88.1 ± 5.4	41.2 ± 1.4	12.0 ± 2.1
LZP-BJ-MRW	Birch	Wet	Rich	37.2 ± 4.9	61.4 ± 1.4	11.1 ± 4.1
LZP-BM-MPD	Birch	Drained	Poor	77.2 ± 6.2	41.8 ± 1.3	12.4 ± 2.3
LZP-BM-MPW	Birch	Wet	Poor	69.6 ± 5.6	32.9 ± 1.6	14.3 ± 2.7
LZP-BM-MRD	Birch	Drained	Rich	101.1 ± 4.3	34.8 ± 1.5	12.5 ± 2.7
LZP-BM-MRW	Birch	Wet	Rich	53.8 ± 5.2	44.6 ± 2	10.5 ± 3.8
LZP-MJ-MRD	Black alder	Drained	Rich	129.3 ± 3.6	23.4 ± 1.3	13.3 ± 0.9
LZP-MJ-MRW	Black alder	Wet	Rich	56.4 ± 6.6	43.7 ± 1.2	14.7 ± 3.2
LZP-MM-MRD	Black alder	Drained	Rich	120.8 ± 2.6	31.8 ± 1.5	12.2 ± 1.7
LZP-MM-MRW	Black alder	Wet	Rich	26.4 ± 4.5	65.8 ± 1.5	11.8 ± 3.3
LVM-PJ-MPD	Pine	Drained	Poor	77.7 ± 7.4	49.9 ± 1.3	11.6 ± 3.5
LVM-PM-MPW	Pine	Wet	Poor	20.9 ± 2.8	88.5 ± 2.2	10.7 ± 3.2

The measurement programs implemented in all plots are manual measurement of the groundwater level in perforated groundwater wells; greenhouse gas (CH_4 and N_2O) sampling for gas chromatography (GC) analyses (5 permanent collars in every measurement point); soil temperature measurements at 10 cm depth during site visits. Measurement sites were visited once per month during 18 months period,

from 06.05.2022 to 26.10.2023. Sampling for CH_4 and N_2O measurements were continued during the whole measurement period (at least 18 sample sets per measurement site were acquired).

After arrival to the measurement site the opaque chambers were flushed and located over permanently installed collars (5 collars per measurement site). Gas samples of 100 cm^3 volume each were collected in vacuumized glass bottles every 10 min, during 30 min (4 samples per set). Volume of the chamber is 0.0655 m^3 (bottom diameter 50.0 cm, top diameter 42.5 cm, height 39.5 cm). CH_4 and N_2O were determined in the collected samples in the laboratory using the gas chromatography technology (Shimadzu Nexis GC-2030, produced in Japan).

The perforated water wells were emptied after measurement of the groundwater (GW) level and before collection of water samples to acquire fresh water samples. Spreadsheet application and formula 1

No. were used to calculate GHG fluxes in GC data. Measurements with $R^2 < 0.95$ for linear regression of the concentration changes were excluded from evaluation of GHG fluxes, except values close to the detection limit of the GC analyser. No other outliers, e.g. high N_2O and CH_4 outputs, were excluded following to recommendation in the IPCC guidelines [13]. The applied CO_2 equivalent of CH_4 is 28 and of N_2O – 265 [14].

$$N_2O - N \text{ or } CH_4 - C \left[\mu g\, N(C) \cdot m^{-2} \cdot h^{-1}\right] = \frac{M\left[g \cdot mol^{-1}\right] \cdot P[Pa] \cdot V\left[m^3\right] \cdot \delta v[ppm(v)]}{R\left[m^3 \cdot Pa \cdot K^{-1} \cdot mol^{-1}\right] \cdot T[K] \cdot A\left[m^2\right] \cdot ppm}, \quad (1)$$

where P – 101300 Pa;
R – 8.3143 $m^3 \cdot Pa \cdot K^{-1} \cdot mol^{-1}$;
V – 0.0655 m^3 and 0.023 m^3;
A – 0.19625 m^2 and 0.076 m^2;
M – N_2O – 44.01 $g \cdot mol^{-1}$, CH_4 – 16.04 $g \cdot mol^{-1}$.

Monthly average and yearly fluxes were calculated for every site, species nutritional and moisture conditions. Correlation and regression analysis was done to identify factors affecting GHG fluxes, particularly, the air temperature and groundwater level, demonstrating the largest correction with GHG fluxes. Uncertainty is expressed as a standard error of mean. Data analysis was done using Libreoffice Calc software. Significance of difference was determined using the Wilcoxon Signed-Rank Test.

Results and discussion

Monthly averages of GHG fluxes depending on the dominant species, moisture and nutritional regime are summarized in Fig. 1. Total CH_4 and N_2O emissions in aspen stands with drained mineral soil are 0.729 ± 0.578 tons CO_2 eq.$\cdot ha^{-1} \cdot yr^{-1}$ and with wet mineral soil – 0.593 ± 0.384 tons CO_2 eq.$\cdot ha^{-1} \cdot yr^{-1}$. There is no significant difference between the values. N_2O, particularly in spring is the largest source of the emissions. In birch stands with nutrient-poor drained soil the emissions are 0.784 ± 0.428 tons CO_2 eq.$\cdot ha^{-1} \cdot yr^{-1}$, with wet soil – 0.318 ± 0.253 tons CO_2 eq.$\cdot ha^{-1} \cdot yr^{-1}$; with nutrient-rich drained soil – 0.646 ± 0.211 tons CO_2 eq.$\cdot ha^{-1} \cdot yr^{-1}$, with wet soil – 1.316 ± 0.598 tons CO_2 eq.$\cdot ha^{-1} \cdot yr^{-1}$. In spite there is no statistically significant difference between different sites, the nutrient-rich naturally wet mineral soil tends to be the largest source of the emissions, particularly due to N_2O emissions in spring. In black alder stands with nutrient-rich drained soil the emissions were 0.261 ± 0.227 tons CO_2 eq.$\cdot ha^{-1} \cdot yr^{-1}$, in wet soil – 0.487 ± 0.199 tons CO_2 eq.$\cdot ha^{-1} \cdot yr^{-1}$. Nutrient-poor soil in pine stands is the smallest source of emissions; drained soil produces 0.289 ± 0.322 tons CO_2 eq.$\cdot ha^{-1} \cdot yr^{-1}$, wet soil – 0.005 ± 0.220 tons CO_2 eq.$\cdot ha^{-1} \cdot yr^{-1}$. In all sites N_2O in spring is the largest source of the emissions, and sites with wet soils tend to be a bigger source of N_2O and CH_4 emissions. Nutrient rich soil tends to be a bigger source of the emissions; however, the difference is not significant.

No correlation was found between N_2O and CH_4 emissions and the air temperature, partly because in summer months, when the temperature increases, the GW level drops and emissions of these gases decrease. Similarly, no correlation was found between the GW level and GHG emissions, CH_4 and N_2O emissions tend to be higher if the GW level is higher, especially CH_4 emissions increase if the GW level increases above 20 cm. Fig. 2 shows that there is significant difference in the GW level between drained and wet sites; however, in summer months this difference tends to decrease and drops below 60 cm. In

drained sites GW is below 50 cm during the entire year, and, most probably, does not affect directly the level of CH_4 and N_2O emissions [8].

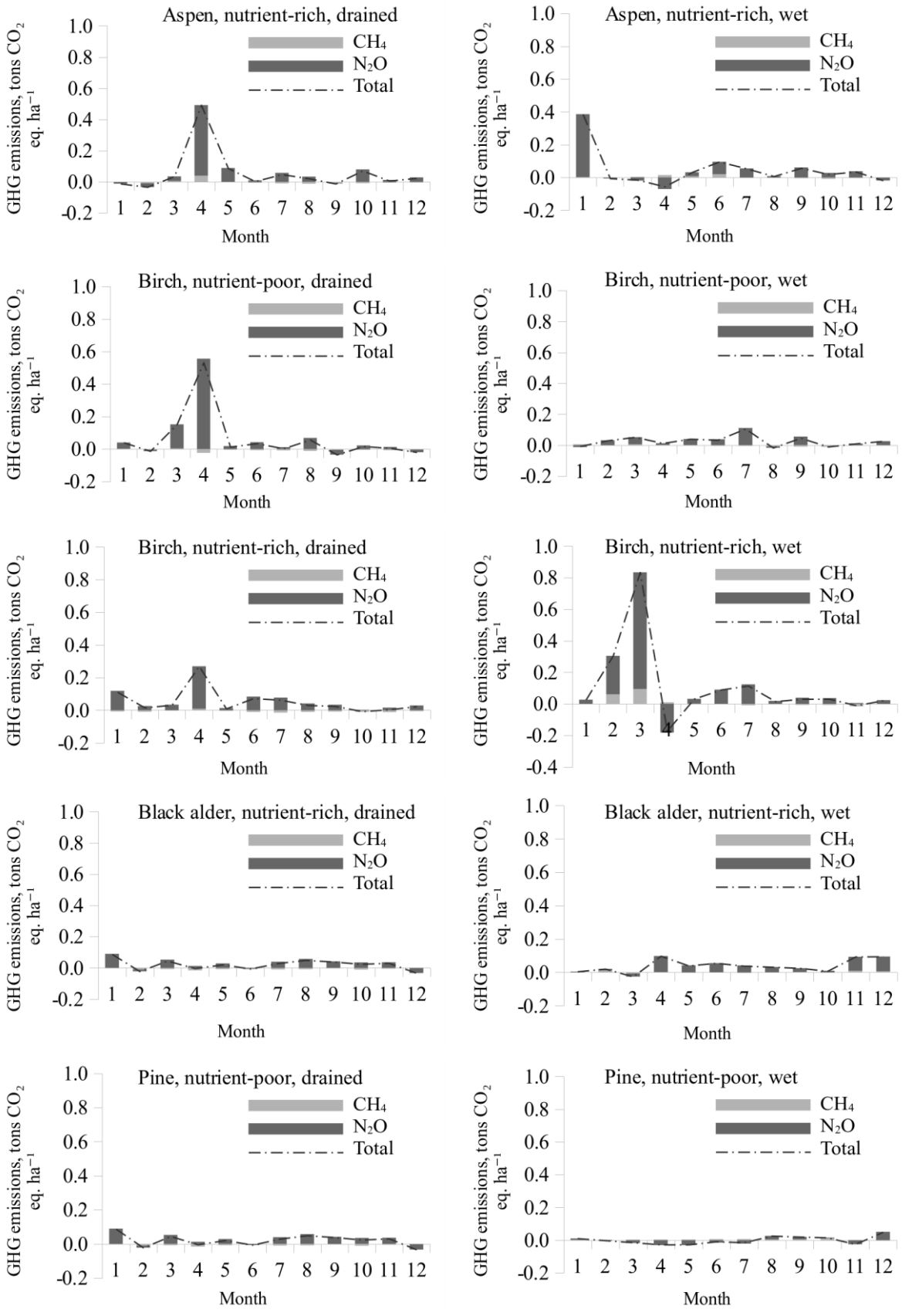

Fig. 1. **Average monthly GHG emissions in measurement sites**

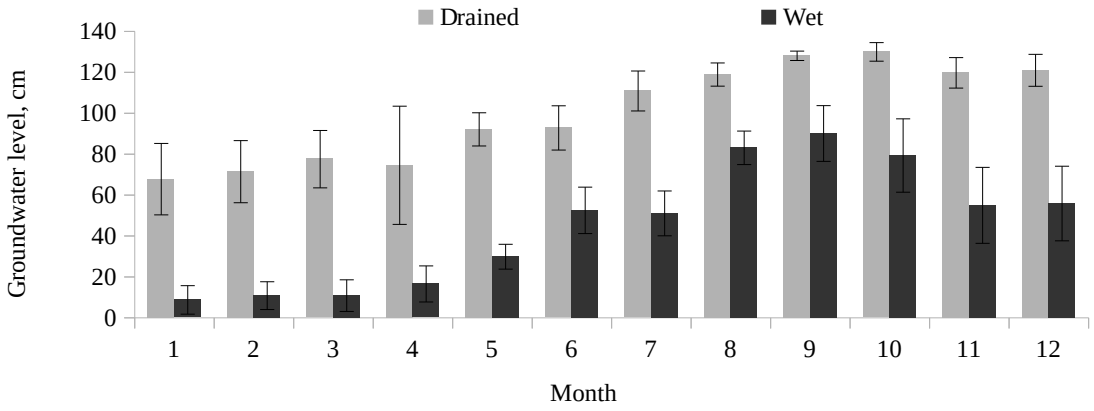

Fig. 2. **Average monthly groundwater level**

The study results do not confirm the assumption that drainage increases the N_2O emissions, e.g. in [15], and results of studies in organic soils demonstrating bigger CH_4 emissions from naturally wet soils [8]. At the same time, the study confirms that potentially significant amount of emissions (0.56 tons CO_2 eq.$\cdot ha^{-1}\cdot yr^{-1}$) due to N_2O fluxes is not accounted in the National greenhouse gas inventory, reporting N_2O losses only in case of net CO_2 losses from soil. However, since the drainage is not increasing the N_2O emissions, they can be omitted as a non-anthropogenic source. The study also did not reveal any difference between nutrient-rich and -poor soils reported by other authors [16; 17]. This can be explained by the fact that the primary subject of these studies is organic soil. However, other authors did not find correlation between the content of plant nutrients, e.g. nitrogen, potassium or phosphorus, in organic soils and GHG emissions [8; 18].

Conclusions

1. No significant difference of the emissions is found between drained and naturally wet soils as well as between nutrient-rich and -poor soils, while there is a trend of increase of N2O emissions from wet soils, particularly in spring. N2O also is the dominant source of the emissions.
2. N2O is a considerable source of emissions from soil; however, since the N2O emissions are not increasing in drained sites, this source can be omitted in the National GHG inventory; however, further studies are necessary to clarify potential reduction of the emissions after drainage.
3. The smallest N2O and CH4 emissions from soil were found in pine and black alder sites; however, further studies are necessary to evaluate this finding, because it is mainly associated with absence of the N2O peaks in spring, characteristic for other sites with high level of N2O and CH4 emissions, while the baseline without peaks is similar in all sites.

Acknowledgements

The study is elaborated within the scope of the project “Evaluation of factors affecting greenhouse gas (GHG) emissions from surface of tree stems in deciduous forests with drained and wet soil”. Fundamental and applied research projects, agreement No.: LZP-2021/1-0137. Part of the data used in the study were acquired within the scope of the project “Prototype of Carbon-binding Forestry Planning Program and Calculation Operation Data Sets” under the auspices of the “Forest Sector Competence centre” Ltd., with project contract number: 5.1.1.2.i.0/1/22/A/CFLA/007 (P10).

Author contributions

Conceptualization. A.L.; methodology. A.L. and I.S.; software. A.L.; investigation. I.S., G.S. and E.M.; data curation. A.L.; writing – original draft preparation. A.L. and I.S.; writing – review and editing. A.L.; project administration. A.L. All authors have read and agreed to the published version of the manuscript.

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