METHANE (CH_4) AND NITROUS OXIDE (N_2O) EMISSIONS FROM SURFACE OF DECIDUOUS TREE STEMS AND SOIL IN FORESTS WITH DRAINED AND NATURALLY WET ORGANIC SOILS

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Abstract. In general, the groundwater level (GWL) in forests with organic soils plays a crucial role in greenhouse gas (GHG) emissions from both the soil and the surface of tree stems. High GWL typically leads to anaerobic conditions in the soil, reducing the emission of GHG like nitrous oxide (N_2O) and increasing methane (CH_4) emissions. Understanding and managing GWL in such ecosystems is therefore essential for mitigating GHG emissions. The scope of the study was to evaluate magnitude of fluxes of GHG (specifically CH_4 and N_2O) from the surface of deciduous tree stems and soil, as well as to find interrelationships with environmental factors like GWL and the soil temperature. CH_4 and N_2O fluxes from tree (black alder, silver birch and aspen) stems and soil were monitored in 10 study sites in forest stands with drained and naturally wet organic soils in Latvia in 2022 and 2023. We found that the surface of tree stems was a net source of CH_4 and N_2O emissions in forests with both drained and naturally wet organic soil. MeaN·magnitude of CH_4 fluxes from tree stems were 0.017 ± 0.003 mg $CH_4\text{-C}\cdot m^{-2}\cdot h^{-1}$ in forest stands with drained organic soil and 0.032 ± 0.010 mg $CH_4\text{-C}\cdot m^{-2}\cdot h^{-1}$ in forest stands with naturally wet organic soil, while meaN·magnitude of N_2O emissions were 0.002 ± 0.001 and 0.007 ± 0.002 mg $N_2O\text{-N}\cdot m^{-2}\cdot h^{-1}$, respectively. Thus, emissions from the surface of tree stems under naturally wet soil conditions were higher than under drained conditions; a statistically significant difference was found only for N_2O. Drained organic soils in the study sites were a net sink of CH_4 (small removals were observed), while naturally wet soils created emissions (mean 1.15 ± 0.89 mg $CH_4\text{-C}\cdot m^{-2}\cdot h^{-1}$). The magnitude of N_2O emissions from soil was similar for naturally wet and drained conditions (0.034 ± 0.017 and 0.028 ± 0.014 mg $N_2O\text{-N}\cdot m^{-2}\cdot h^{-1}$, respectively). In general, the study showed that drainage of organic soils in forest lands can reduce CH_4 and N_2O emissions; however, due to high variation in studied GHG fluxes, the number of measurement points should be increased to prove the significance of the difference.

Keywords: greenhouse gas emissions, methane, nitrous oxide, organic soil, tree stems, groundwater level.

Introduction

Soils can serve as both sinks and sources of greenhouse gases (GHGs) in the forest ecosystems. Management decisions, such as drainage, significantly influence the soil GHG balance. High groundwater level (GWL) typically leads to anaerobic conditions in the soil, reducing the emissions of carbon dioxide (CO_2) and increasing methane (CH_4) emissions. [1-3]. Conversely, lower GWL often results in aerobic conditions, increasing the decomposition of soil organiC·matter and thereby elevating CO_2 emissions [2; 4]. However, the effects on nitrous oxide (N_2O) emissions vary among different studies [1; 5-7]. It is discovered that oxygen regulates both nitrification, which occurs aerobically, and denitrification, which occurs anaerobically. Consequently, the groundwater depth significantly influences N_2O emissions [7]. In the study examining the effects of flooding in a riparian forest in Estonia, employing a fluctuating GWL, on GHG fluxes from the soil, an increase in CH_4 emissions but a decrease in N_2O emissions following flooding was observed [6]. Understanding and managing groundwater levels in such ecosystems is therefore essential for mitigating GHG emissions.

Besides GWL, the soil temperature also needs to be considered to explain variations in GHG emissions. An increase in the soil temperature results in increased CH_4 and N_2O emissions and soil respiration rates through accelerated microbial metabolism, forming a positive feedback loop. The sequential occurrence of numerous temperature-sensitive microbial processes within the nitrogen (N) cycle, which convert reactive N compounds through various oxidation states, results in an amplifying impact of temperature increase on soil N_2O fluxes [8]. According to a study carried out in a deciduous forest stand in Italy, the soil temperature along with moisture explained 86% of the variations of N_2O emissions [9]. Temperature also plays a crucial role in regulating freeze-thaw events, which in turn force gas emissions from soils [10]. It is estimated that this component of N_2O emissions may account for as much as 50% of the total annual N_2O emissions [11].

Another source/sink of GHGs besides soils that has gained attention is tree stems. It has been a debate for a while, whether CH_4 and N_2O are produced by stems themselves or stems act as conduits, through which these GHGs are transported from the soil [12]. A study carried out in forested coastal

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freshwater wetland showed that the tree stem contribution to the net ecosystem flux of CH_4 was most significant during flooded conditions, accounting for 49.9% and 70.2% of the total net ecosystem CH_4 efflux, yet it was less notable during dry periods, comprising only 3.1% and 28.2%. GWL emerged as the primary determinant of tree stem CH_4 fluxes. However, it is noteworthy that tree emissions reached their peak upon soil inundation, and did not increase proportionally with deeper water levels [13]. A study carried out in Finland shows that all common boreal tree species are net annual sources of N_2O and there is a clear seasonality of N_2O fluxes [14]. A study carried out in Estonia shows not only seasonal but also diurnal patterns of CH_4 and N_2O emissions from tree stems and soil [15].

The objective of our study was to assess the magnitude of GHG (specifically CH_4 and N_2O) fluxes from organic soil as well as from the stem surface of black alder, silver birch and aspen in forest stands with drained and naturally wet organic soils in Latvia, and to examine their correlations with environmental factors such as GWL and the soil temperature.

Materials and methods

In total, 10 study sites in forest stands with drained and naturally wet organic soils in Latvia (European hemiboreal zone) were selected for the study (Table 1). Dominant tree species in these stands were black alder (*Alnus glutinosa* (L.) Gaertb.), silver birch (*Betula pendula* Roth.) and aspen (*Populus tremula* L.). For monitoring of CH_4 and N_2O fluxes from tree stems, sample trees of dominant tree species were selected in each study site (the main characteristics of sample trees are shown in Table 1). CH_4 and N_2O fluxes from the surface of deciduous tree stems were monitored during the frost-free period in 2022 (May-November) and 2023 (April-October). For monitoring of CH_4 and N_2O fluxes from the soil, tree permanent collars with circular form were positioned in the soil at a five cm depth in each study site. Collars (area 0.1995 m^2) were positioned in the soil at least one month before gas sampling was started avoiding disturbance to the vegetation. CH_4 and N_2O fluxes from soil were monitored in the period from May 2022 to October 2023. In Latvia, the mean annual air temperature in 2022 and 2023 was + 7.3 and + 7.8 °C, respectively, while the mean annual precipitation was 685.8 mm in 2022 and 761.1 mm in 2023 [16].

Table 1

General description of the study sites and sample trees in deciduous tree forest stands with drained and naturally wet organic soils in Latvia (n – number of study sites)

Soil moisture con-ditions	Tree species	Study site identifier	Location of study site (WGS84)		Mean tree diameter at 1.3 m height of selected tree species in forest stand, cm	Characteristics of sample trees (range)	
			X	Y		Diameter at 1.3 m height, cm	Height, m
Drained (n = 6)	Silver birch (n = 2)	OS5	56.67388	25.89674	30.5	27.0-42.3	26.3-29.3
		OS8	56.71001	26.05986	11.7	14.6-20.0	16.6-20.5
	Black alder (n = 2)	OS3	56.6847	25.88981	14.8	15.9-21.9	15.9-17.2
		OS6	56.64171	26.01253	32.1	29.8-39.7	30.6-32.5
	Aspen (n = 2)	OS1	56.4466	22.85432	12.7	14.6-23.1	18.0-23.1
		OS2	56.42684	22.77874	21.7	13.8-29.4	18.9-28.2
Naturally wet (n = 4)	Silver birch (n = 2)	OS4	56.68495	25.88707	10.5	11.9-18.8	13.9-20.1
		OS7	56.71074	26.05881	25.0	14.2-36.4	16.9-20.6
	Aspen (n = 2)	OS9	57.30307	26.03518	32.5	25.2-49.4	30.9-31.5
		OS10	57.29077	25.99702	21.0	15.8-25.5	20.0-24.7

Gas sampling from both the surface of tree stems and soils was conducted once a month. Gas samples from the surface of tree stems were taken using manual chambers (volume 2.48-2.86 L) attached to the sample tree stems (area 158-280 cm^2) at a height of 1.3 m. Gas samples from the soil were taken using closed static opaque chambers (volume 65.5 L) positioned on the permanent circular collars installed in the soil. Gas samples were taken using underpressurized (0.3 mbar) glass vials (volume 100 mL). Each set of gas samples consisted of four consecutive measurements obtained immediately after sealing the chamber, followed by additional samples obtained at 10-minute intervals (i.e. at 10, 20, and 30 minutes after sealing). The gas samples underwent transportation to the laboratory at the Latvian State Forest Research Institute "Silava," where the concentrations of CH_4 and N_2O (measured in parts per billion, ppb) were analyzed using gas chromatography (GC) with a Shimadzu Nexis GC-230 instrument. Quality control of the GC results involved assessing the conformity of changes in CH_4 and N_2O concentrations over time to linear regression. Each set of four consecutive gas samples was analyzed separately for this purpose. CH_4 and N_2O fluxes (mg m^{-2} h^{-1}) were determined using the Ideal Gas Law, employing the slopes obtained from the linear regressions constructed to represent the changes in CH_4 and N_2O concentrations over time, as detailed by Petaja et al. in the previous study conducted in Latvia [17].

In addition, during each study site survey, several environmental parameters were monitored. The air temperature was measured using a COMET temperature data logger and Pt1000 probe. Soil temperature at 5 cm depth was measured using a Yieryi YY-1000 soil temperature meter. Groundwater level (GWL) was determined by measuring the water level below the soil surface using groundwater wells (PVC pipes) installed vertically in the soil in each study site.

Statistical analysis and graphical representation were conducted using the R software environment (version 4.3.1) with the ggplot2 package. Both CH_4 and N_2O flux datasets showed non-normal distribution (Shapiro-Wilk normality test, $p < 0.001$). To examine the statistical variances between independent variables, the Wilcoxon rank sum exact test was applied. Spearman's correlation coefficient (ρ) was computed to evaluate the degree of dependence between variable pairs. All statistical analyses were performed with a significance level of 95% ($\alpha = 0.05$).

Results and discussion

During the study period (May 2022-October 2023) the mean GWL below the soil surface among the study sites (Fig. 1) varied in a wide range from 14 cm in study site OS10 (naturally wet site) to 86 cm in study site OS8 (drained study site). Although the mean GWL in drained study sites was deeper (65 ± 9 cm) than in naturally wet study sites (35 ± 12 cm), no statistically significant difference in the mean GWL between drained and naturally wet study sites was observed ($p = 0.067$). During the study period, the air temperature ranged from -9.5 to 29.2 ºC, while the soil temperature at 5 cm depth ranged from -0.7 to 24.8 ºC.

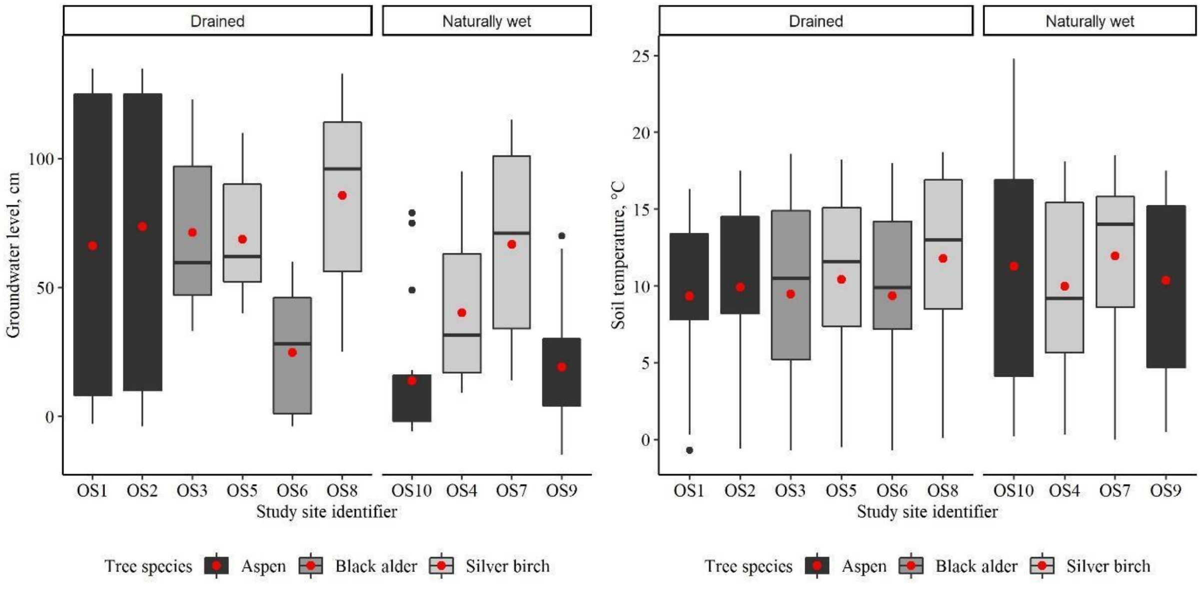

Fig. 1. **Groundwater level below the soil surface and the soil temperature at 5 cm depth in study sites with drained and naturally wet organic soil:** the medians are bold horizontal lines in the boxes, the mean values are red dots, and the black dots are outliers of the datasets

During the study period, the mean CH_4 fluxes from drained organic soil were -0.010 ± 0.010 mg $CH_4\text{-}C \cdot m^{-2} \cdot h^{-1}$ reflecting small removals, while the mean CH_4 fluxes from naturally wet organic soil was 1.15 ± 0.89 mg $CH_4\text{-}C \cdot m^{-2} \cdot h^{-1}$ (Fig. 2). Among study sites with naturally wet organic soils, the highest mean CH_4 fluxes were observed in study site OS10 (mean 3.75 mg $CH_4\text{-}C \cdot m^{-2} \cdot h^{-1}$) where simultaneously the highest mean GWL was observed. However, no statistically significant difference in the mean CH_4

fluxes between drained and naturally wet study sites was observed ($p = 0.257$). In general, a moderate negative correlation between instantaneous CH_4 fluxes and GWL ($\rho = -0.41$, $p < 0.001$, all sites pooled) as well as a strong negative correlation between the study site mean CH_4 fluxes and mean GWL ($\rho = -0.70$, $p = 0.031$) was found. No correlations between instantaneous CH_4 fluxes and air and soil temperature were found ($\rho = -0.18$ and $\rho = -0.16$, respectively). In another study carried out in Latvia with organic soils, the average yearly CH_4 emissions from both drained and undrained soil were -4.6 ± 1.3 and 134.1 ± 134.7 kg CH_4 ha^{-1} yr^{-1}, respectively, which is equal to -0.039 ± 0.011 and 1.15 ± 1.15 mg $CH_4\text{-}C\cdot m^{-2}\cdot h^{-1}$, respectively [18]. In the study carried out in Estonia, at the Agali Drained Peatland Forest Research Station, the soil also acted as a net sink of CH_4 annually (-6.44 ± 0.76 μg $C\cdot m^{-2}$ ground area$\cdot h^{-1}$) [19]. In a study carried out in the USA through different habitat types, the mean soil CH_4 fluxes in wetland, transitional, and upland habitats were 0.052 ± 0.034, 0.002 ± 0.007, and -0.018 ± 0.002 mg $CH_4\text{-}C\cdot m^{-2}$ h^{-1}, respectively [20]. In the case of the wetland habitat, the results are lower than our estimates, but in the case of the upland habitat, the results are similar to ours.

The mean N_2O fluxes from drained organic soil were 0.028 ± 0.014 mg $N_2O\text{-}N\cdot m^{-2}$ h^{-1}, while the mean N_2O fluxes from naturally wet organic soil were 0.034 ± 0.017 mg $N_2O\text{-}N\cdot m^{-2}\cdot h^{-1}$ (Fig. 2), no statistically significant difference in the mean N_2O fluxes between drained and naturally wet study sites was observed ($p = 0.914$). No correlations between instantaneous N_2O fluxes and GWL, air and soil temperature were found ($\rho = 0.09$, $\rho = 0.09$ and $\rho = 0.11$, respectively), while a strong positive correlation between the study site mean N_2O fluxes and the mean GWL ($\rho = 0.62$, $p = 0.039$) was found. In another study carried out in Latvia, N_2O emissions from undrained soil (4.1 ± 1.4 kg N_2O ha^{-1} yr^{-1} which is equal to 0.030 ± 0.010 mg $N_2O\text{-}N\cdot m^{-2}\cdot h^{-1}$) were greater than those from drained soil (1.7 ± 0.6 kg N_2O ha^{-1} yr^{-1} which is equal to 0.012 ± 0.004 mg $N_2O\text{-}N\cdot m^{-2}\cdot h^{-1}$) and the differences were statistically significant [18]. In a study carried out in Finland, the forest floor emitted in total of 9.4 mg N_2O m^{-2} soil area per year (equals to 0.001 ± 0.001 mg $N_2O\text{-}N\cdot m^{-2}\cdot h^{-1}$), while the emissions from birch stems amounted to 0.38 mg N_2O m^{-2} per year (equals to 0.043 ± 0.028 μg $N_2O\text{-}N\cdot m^{-2}\cdot h^{-1}$) [14]. In a study carried out in Estonia, in drained peatland forest, the soil was a net source of N_2O (41.68 ± 3.15 μg $N_2O\text{-}N\cdot m^{-2}\cdot h^{-1}$), which is slightly higher than our estimates [19].

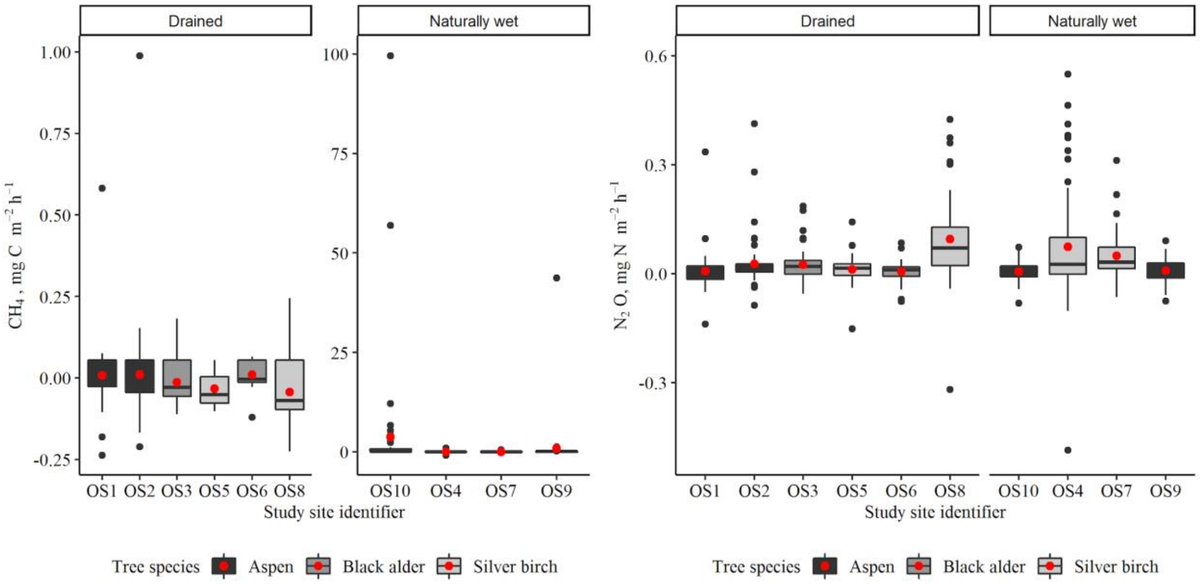

Fig. 2. **Variation of CH_4 and N_2O fluxes from organic soil among study sites:** the medians are bold horizontal lines in the boxes, the mean values are red dots, and the black dots are outliers of the datasets

In general, both CH_4 and N_2O fluxes from the surface of tree stems ranged in a narrower range than fluxes from organic soil. During the study period, the mean CH_4 fluxes from surface of tree stems in study sites with drained organic soil was 0.017 ± 0.003 mg $CH_4\text{-}C\cdot m^{-2}\cdot h^{-1}$, while the mean CH_4 fluxes from tree stems in study sites with naturally wet organic soil was 0.032 ± 0.010 mg $CH_4\text{-}C\cdot m^{-2}\cdot h^{-1}$ (Fig. 3). Similar to CH_4 fluxes from naturally wet organic soil, the highest mean CH_4 fluxes from tree stems were observed in study site OS10 (mean 0.061 mg CH_4-C·m^{-2}·h^{-1}) where simultaneously the highest mean GWL was observed. However, no statistically significant difference iN·mean CH_4 fluxes from the surface of tree stems between drained and naturally wet study sites was observed ($p = 0.114$). No correlations between instantaneous CH_4 fluxes from the surface of tree stems and GWL, air and soil temperature were found ($\rho = -0.11$, $\rho = 0.03$ and $\rho = 0.08$, respectively), as well as only a weak negative correlation between the study site mean CH_4 fluxes and the mean GWL ($\rho = -0.34$, $p = 0.313$) was found. Among study sites grouped by tree species and the soil moisture condition (drained or naturally wet), the highest mean CH_4 fluxes from the surface of tree stems were found for aspen under naturally wet conditions (mean 0.046 ± 0.015 mg CH_4-C·m^{-2}·h^{-1}).

In previous study in Latvia conducted in forest land with nutrient-rich organic soil (Petaja et al., 2023), CH_4 fluxes from tree (birch and black alder) stems ranged from slight removals for black alder in summer (−0.66 ± 0.20 µg CH_4-C·m^{-2}·h^{-1}) to significant emissions for birch in summer (32.51 ± 11.54 µg CH_4-C·m^{-2} h^{-1}), which is similar to our estimates in study sites with naturally wet organic soil. In a study carried out in the USA, in the wetland habitat, the mean CH_4 emissions from tree stems were 0.155 ± 0.048 mg CH_4-C·m^{-2} h^{-1}, while for the transitional and upland habitats, they were 0.049 ± 0.015 and 0.019 ± 0.004 mg CH_4-C·m^{-2}·h^{-1}, respectively [20]. Their results from upland sites are similar to our estimates in sites with drained soil, while their results in wetland sites are higher than our estimates in sites with naturally wet soil and, furthermore, CH_4 emissions from stems were higher than those from the soil. In a study carried out in Estonia, birch trees emitted an annual average of CH_4 (0.38 ± 0.09 µg CH_4-C·m^{-2}·h^{-1}), which is lower than our estimates [19].

The mean N_2O flux from the surface of tree stems in study sites with drained organic soil was 0.002 ± 0.001 mg N_2O-N·m^{-2}·h^{-1}, while the mean N_2O flux from tree stems in study sites with naturally wet organic soil was 0.007 ± 0.002 mg N_2O-N·m^{-2}·h^{-1} (Fig. 3), furthermore, statistically significant difference in the mean N_2O fluxes from tree stems between drained and naturally wet study sites was observed ($p = 0.038$). No correlations between instantaneous N_2O fluxes and GWL, air and soil temperature were found ($\rho = -0.08$, $\rho = 0.01$ and $\rho = -0.05$, respectively), as well as no correlations between the study site mean N_2O fluxes from tree stems and the mean GWL were found ($\rho = -0.15$). Among study sites grouped by tree species and the soil moisture condition (drained or naturally wet), the highest mean N_2O fluxes from the surface of tree stems were found for silver birch under naturally wet conditions (mean 0.009 ± 0.002 mg N_2O-N·m^{-2}·h^{-1}).

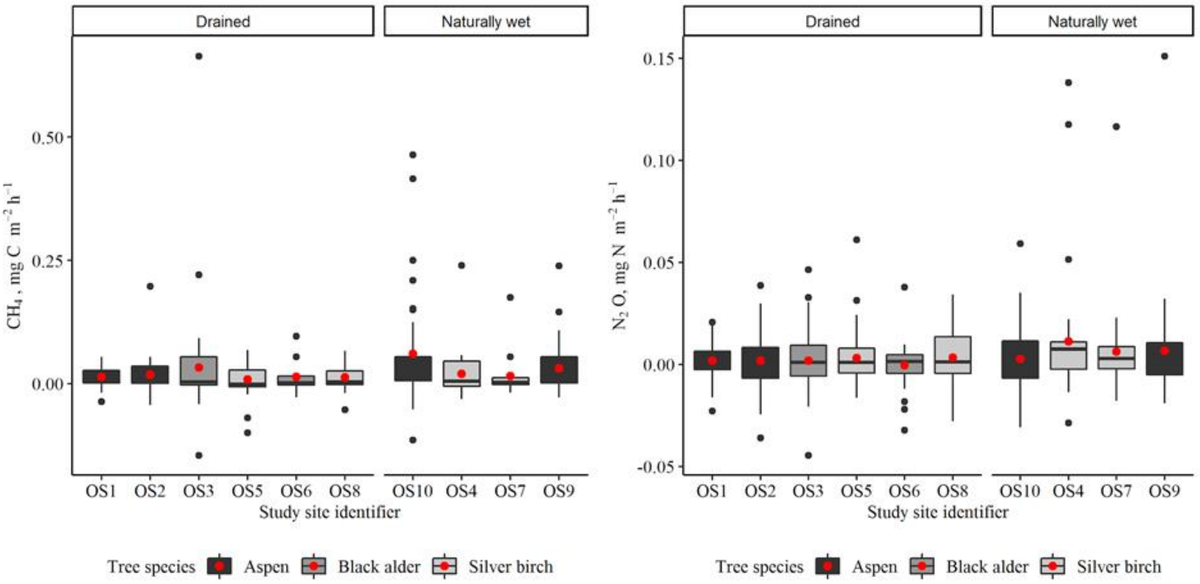

Fig. 3. **Variation of CH_4 and N_2O fluxes from the surface of tree stems among study sites:** the medians are bold horizontal lines in the boxes, the mean values are red dots, and the black dots are outliers of the datasets

In a previous study in Latvia conducted in forest land with nutrient-rich organic soil, N_2O fluxes from tree (birch and black alder) stems ranged from slight removals for birch in the autumn

(-0.85 ± 0.55 µg N_2O-N·m^{-2}·h^{-1}) to emissions for black alder in summer (0.30 ± 2.33 µg N_2O-N·m^{-2}·h^{-1}), which is lower than our mean estimates of N_2O fluxes from tree stems [17]. In a study carried out in Estonia, birch stems were a net source of N_2O (0.94 ± 0.32 µg N_2O-N·m^{-2}·h^{-1}), which is lower than our estimates [19].

Conclusions

1. Both drained and naturally wet organic soils were sources of CH_4 and N_2O emissions, excluding drained organic soil, which was a slight CH_4 sink.
2. CH_4 emissions from naturally wet organic soil were higher than from drained soils and the mean CH_4 emissions tended to increase with higher GWL (closer to the soil surface). N_2O emissions from organic soils were similar for both naturally wet and drained conditions and, contrary to the CH_4 emissions, tended to increase with lower GWL.
3. Stems of the studied tree species (black alder, silver birch and aspen) were the source of CH_4 and N_2O emissions. Furthermore, higher CH_4 and N_2O emissions from tree stems were observed in forest stands with naturally wet organic soil than under drained conditions.
4. Drainage of organic soils in forest lands can alter (mostly reduce) CH_4 and N_2O emissions. However, due to high variation in the studied GHG fluxes, the number of measurement points should be increased to prove the significance of the difference.

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Author contributions

Conceptualization, A.B., methodology, G.P and I.S., software, G.P., validation, D.P., formal analysis, I.S. and D.P., investigation, I.S. and D.P., data curation, D.P., writing – original draft preparation, G.P. and I.S., writing – review and editing, G.P. and A.B., visualization, G.P., project administration, A.B. All authors have read and agreed to the published version of the manuscript.

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