CH_4 AND N_2O EMISSIONS FROM SURFACE OF DECIDUOUS TREE STEMS IN FORESTS WITH DRAINED AND NATURALLY WET MINERAL SOILS

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Abstract. Deciduous tree stems can become an important source of methane (CH_4) and nitrous oxide (N_2O) emissions especially in case of flooding or increase of the soil water-table level. So far, studies were mainly implemented in forests with organic soils, while limited information is available about mineral soils. Within this study we estimated the CH_4 and N_2O fluxes from the stem surface of silver birch, black alder and aspen in 16 study sites (forest stands) with drained and naturally wet mineral soils in Latvia to evaluate the impact of soil moisture conditions. We found that in forest stands with drained mineral soil, the mean CH_4 fluxes from the tree stems were 10.2 ± 3.2 μg CH_4-C·m^{-2}·h^{-1} for aspen, 1.3 ± 2.6 μg CH_4-C·m^{-2}·h^{-1} for black alder, 4.5 ± 2.9 μg CH_4-C·m^{-2}·h^{-1} for silver birch. In forest stands with wet mineral soil, CH_4 fluxes from the tree stems were higher for all tree species (21.1 ± 5.5 μg CH_4-C·m^{-2}·h^{-1} for aspen, 6.3 ± 2.4 μg CH_4-C·m^{-2}·h^{-1} for black alder, 10.3 ± 2.3 μg CH_4-C·m^{-2}·h^{-1} for silver birch) than in stands with drained soil. Similarly, higher N_2O fluxes from the stem surface were found in forest stands with wet mineral soils for aspen and silver birch (4.1 ± 1.5 and 4.0 ± 1.5 μg N_2O-N·m^{-2}·h^{-1}, respectively) than in forest stands with drained mineral soil (-0.8 ± 1.4 and 1.9 ± 1.5 μg N_2O-N·m^{-2}·h^{-1}, respectively), while N_2O fluxes for black alder were similar under drained and wet condition (3.8 ± 1.3 and 3.6 ± 1.3 μg N_2O-N·m^{-2}·h^{-1}, respectively). However, high variation in CH_4 and N_2O fluxes was observed and the difference in mean fluxes between drained and wet conditions was not statistically significant. In general, the study shows that forest drainage can reduce CH_4 and N_2O fluxes from the surface of tree stems; however, due to the high variation of the fluxes more data are necessary to increase accuracy of projections of the studied greenhouse gases.

Keywords: methane, nitrous oxide, tree stems, mineral soils, soil moisture conditions.

Introduction

Understanding the various sources and dynamics of methane (CH_4) and nitrous oxide (N_2O) emissions is crucial, given their impact on global warming and the urgent need for effective climate change mitigation strategies. CH_4 is commonly regarded as the second most impactful greenhouse gas (GHG) after carbon dioxide (CO_2). During the initial two post-emission decades, CH_4 exhibits approximately 80 times the potency of CO_2 as GHG, compared to CO_2. However, it undergoes a considerably faster removal from the atmosphere, typically within about a decade [1; 2]. N_2O is 300 times more potent than CO_2. While drainage proves effective in enhancing forest productivity and reducing CH_4 emissions, it also presents several adverse side effects, such as an increase in CO_2 and N_2O emissions [3]. Moreover, GHG emissions arise not only from the drained soils but also from the drainage ditches themselves [4].

In wetlands, floodplains, or peatlands, CH_4 is typically generated within anoxic soils by methanogenic bacteria. Previously, tree stem surfaces were considered inert in terms of CH_4 exchange with the atmosphere. Nonetheless, recent technological advancements in CH_4 analysis techniques, coupled with the establishment of stem chamber systems for gas flux determination, have facilitated extensive field measurements of CH_4 fluxes. These measurements now encompass not only soils but also tree stems. The net flux CH_4 arises from a complex system where various CH_4 sources, biochemical pathways, and gas transport mechanisms within the soil-plant-atmosphere continuum interact across different temporal scales [5]. There has been a longstanding debate regarding the origins of CH_4 emitted from stems: whether it is generated in the soil, transported through the roots, and released via degasification through the stems, or if it is produced internally within the tree stems themselves.

Several studies support the notion that CH_4 emitted from tree stems originates in soil, as there are correlations between stem CH_4 fluxes and various soil parameters: soil CH_4 concentrations, soil CH_4 fluxes, water table level and soil moisture content [6-9]. Moreover, the presence of a similar isotopic signal ($\delta^{13}C$-CH_4) between CH_4 found in the sediments and that emitted from the base of trees in a mangrove forest indicates a common soil origin [10]. A model introduced by Takashi et al. suggests that stem CH_4 emission involves at least two distinct processes: one dependent on sap flux, contributing to diurnal variations, and another independent of sap flux, contributing to a continuous background emission [11]. The proportions contributed by these two processes vary depending on the season. The continuous background emission likely arises from the diffusive transport of gaseous CH_4 from the roots

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to the upper trunk. Analysis of root anatomy suggested that the intercellular spaces within the cortex and empty xylem cells in fine roots could serve as pathways for the transport of gaseous CH_4. Consequently, CH_4 fluxes often exhibit a decrease with the stem height, with emissions being higher at the base of trees [6-9; 12].

In upland forests, CH_4 emitted from stems might be produced by methanogenic archaea residing within the stems. This production could result from acetate fermentation, CO_2 reduction, or methylotrophic reduction processes [9; 13; 14]. The presence of methanogenic communities in the wood, while necessary for internal stem CH_4 production, does not guarantee active CH_4 generation. CH_4 produced from wood incubations under anoxic conditions links stem fluxes with methanogenic communities [15]. When internal production is the source, there is typically no discernible vertical CH_4 flux pattern observed with the stem height and no correlation with the soil properties or soil CH_4 fluxes and concentrations [15-17]. However, in this case there is a notable correlation with stem attributes, such as wood moisture, stem diameter, or wood pH [13]. Additionally, growing evidence indicates that, depending on the environmental conditions, stem fluxes can either originate in the soil and be further transported to the atmosphere or originate within the stems themselves [18].

In natural ecosystems such as forests and grasslands, N_2O primarily originates from the soil microbial processes of nitrification and denitrification during the re-mineralization of organic matter [19; 20]. Plants can impact ecosystem N_2O exchange through various mechanisms. These include taking up N_2O from soil water and releasing it into the atmosphere through the transpiration stream, directly producing N_2O in plant tissues, consuming N_2O from the atmosphere via unspecified mechanisms, and modifying nitrogen turnover processes in the surrounding soil. Although high N_2O emissions have been observed in laboratory settings, typically from seedlings grown under artificially elevated N_2O concentrations in soils, ecologically relevant studies involving mature trees in natural field conditions are scarce. These studies have generally shown low N_2O emissions or even consistent N_2O uptake from the atmosphere [19]. Frankia, the genus of nitrogen-fixing actinobacteria, has the ability to form root nodules in certain plant species, including alders. Under certain conditions this aspect may contribute to atmospheric N_2O emissions.

Fluxes of CH_4 and N_2O also may show seasonal and diurnal variations. A study carried out in boreal riparian forests in Sweden suggested that there is a marked increase in stem flux during the spring flood period, although the magnitude or consistency of this increase varied to some extent. Additionally, no significant difference in flux was observed between spruces and birches, and the proximity to the stream did not demonstrate a clear, significant effect on stem flux [21]. A study carried out in the United Kingdom indicated large daytime and intra-specific variations in CH_4 fluxes from stems of deciduous trees encompassing both emissions and uptake. However, seasonal or inter-specific variations were not observed [22]. A study carried out in a drained peatland forest in Estonia shows that during the winter period, tree stems act as a net source of CH_4 and nitrous N_2O [23]. The study conducted in Finland measured seasonal variations in nitrous oxide N_2O fluxes from both soil and stems of boreal trees, demonstrating distinct seasonality in stem N_2O fluxes correlated with tree physiological activity, particularly processes of CO_2 uptake and release. Stem N_2O emissions peak during the vegetation season, decline sharply in October, and persist at low but noteworthy levels throughout the winter dormancy period, contributing significantly to the annual totals [19].

Most of the studies carried out so far focused on organic soils, while limited information is available about mineral soils. In Latvia, roughly half of the forests experience periodic rises in soil water-table levels or flooding under natural conditions. Among these, half are situated in regions with mineral soils, and half of them have been subject to drainage measures. Therefore, the objective of the study is to determine the CH_4 and N_2O emissions from the stems of deciduous trees (silver birch, black alder, and aspen) and to evaluate the disparities between drained and naturally wet soils.

Materials and methods

The study was conducted in 16 study sites in deciduous tree forest stands with drained and naturally wet mineral soils in Latvia in 2022 and 2023 (Table 1). Both young stands and mature stands were included in the study. In each study site, tree sample trees of dominated tree species (silver birch (*Betula pendula* Roth.), black alder (*Alnus glutinosa* (L.) Gaertb.) or aspen (*Populus tremula* L.)) were selected for gas sampling. Sample trees are representing trees of I-III Kraft classes (dominant stand).

The mean annual air temperature in Latvia in 2022 and 2023 was + 7.3 and + 7.8 ºC, which was 0.5 and 1.0 ºC above the climatic standard norm (1991-2020), respectively, while the mean annual amount of precipitation was 685.8 mm in 2022 and 761.1 mm in 2023 [24].

Table 1

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

Tree species	**Soil moisture conditions**	**Study site ID**	**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**
Silver birch (*Betula pendula* Roth.) (n = 8)	Drained (n = 4)	MS7	56.69546	25.91823	32.1	27.2-42.4	19.9-23.8
		MS9	56.67298	25.92981	10.6	16.5-24.6	16.5-17.9
		MS10	56.67387	25.95422	9.8	11.9-17.8	16.4-18.0
		MS11	56.64225	25.88585	16.3	15.3-22.4	19.9-22.2
	Naturally wet (n = 4)	MS6	56.71843	23.71185	11.4	14.5-19.4	21.3-22.0
		MS12	56.64084	26.02172	13.4	15.3-23.7	20.8-24.0
		MS13	56.71167	26.0677	25.9	22.2-47.8	25.2-34.6
		MS16	57.29669	25.91146	17.4	18.6-34.1	24.8-32.1
Black alder (*Alnus glutinosa* (L.) Gaertb.) (n = 4)	Drained (n = 2)	MS5	56.6752	23.8021	12.9	12.4-16.4	11.9-12.8
		MS8	56.69571	25.91685	29.1	16.7-34.4	21.8-26.4
	Naturally wet (n = 2)	MS1	56.42817	22.81406	12.6	13.2-17.1	13.3-15.4
		MS15	57.28826	25.95323	33.2	28.9-42.6	29.0-31.4
Aspen (*Populus tremula* L.) (n = 4)	Drained (n = 2)	MS2	56.46009	22.94493	38.8	32.0-49.5	30.5-33.8
		MS14	56.68532	26.02663	14.3	13.6-24.6	20.2-21.3
	Naturally wet (n = 2)	MS3	56.46216	23.00448	33.7	24.1-47.2	29-35.2
		MS4	56.42211	22.75263	10.7	11.8-15.1	12.9-14.0

Gas sampling was conducted once a month during the vegetation seasons in 2022 (May-November) and 2023 (April-October). Gas samples were taken using manual chambers (volume 2.48-2.86 L) attached to sample tree stems (area 158-280 cm^2) at a height of 1.3 m and underpressurized (0.3 mbar) glass vials (volume 100 mL). Each gas sampling set includes sampling of four consecutive samples taken immediately after chamber closing and then with 10-minute intervals (i.e. after 10, 20 and 30 minutes). Gas samples were transported to the laboratory at the Latvian State Forest Research Institute “Silava”, where CH_4 and N_2O concentrations (ppb) in gas samples were determined with the gas chromatography (GC) method (Shimadzu Nexis GC-230). Quality control of the GC results was conducted by evaluating conformity of the changes in CH_4 and N_2O concentrations with time to the linear regression (results of four consecutive gas samples were examined separately). CH_4 and N_2O fluxes (µg m$^{-2}\cdot$h^{-1}) were calculated according to the Ideal Gas Law using slope of the constructed linear regressions describing changes in CH_4 and N_2O concentrations with time as described by Petaja et al. in previous study conducted in Latvia [25].

Simultaneously with gas sampling, the soil water-table level (WTL) and air temperature were measured in each study site. Soil WTL was determined by measuring the water level in a groundwater well (a PVC pipe inserted vertically into the soil). The air temperature was measured using COMET temperature data logger and Pt1000 probe, soil temperature was detected with Yieryi YY-1000 soil temperature meter (at 5 cm depth) .

The software environment R (version 4.3.2) was used for statistical analysis and graph preparation (package ggplot2). The datasets of CH_4 and N_2O fluxes were not normally distributed (Shapiro-Wilk normality test, $p < 0.001$). To evaluate the statistical differences between independent variables, the Wilcoxon rank sum exact test was used, Spearman’s correlation coefficient (ρ) was estimated to assess the degree of dependence between pairs of variables. All statistical analyses were carried out with a significance level of 95% ($\alpha = 0.05$).

Results and discussion

Mean soil water-table level among the study sites (Fig. 1) during the study period (May-November 2022 and April-October 2023) ranged from 100 to 125 cm below the soil surface in drained study sites (mean 115 ± 1 cm) and from 46 to 93 cm below the soil surface in naturally wet study sites (mean 68 ± 2 cm). Furthermore, statistically significant difference in the mean soil water-table level between drained and naturally wet study sites was observed ($p < 0.001$). The air temperature during the study period ranged from -0.6 to 28.4 ºC, while the mean air temperature in the study period among the study sites varied in a narrow range from 14 to 19 ºC. Soil temperature at 5 cm depth ranged from 3.4 to 29.1 ºC, while the mean soil temperature in the study period among the study sites varied from 10 to 17 ºC.

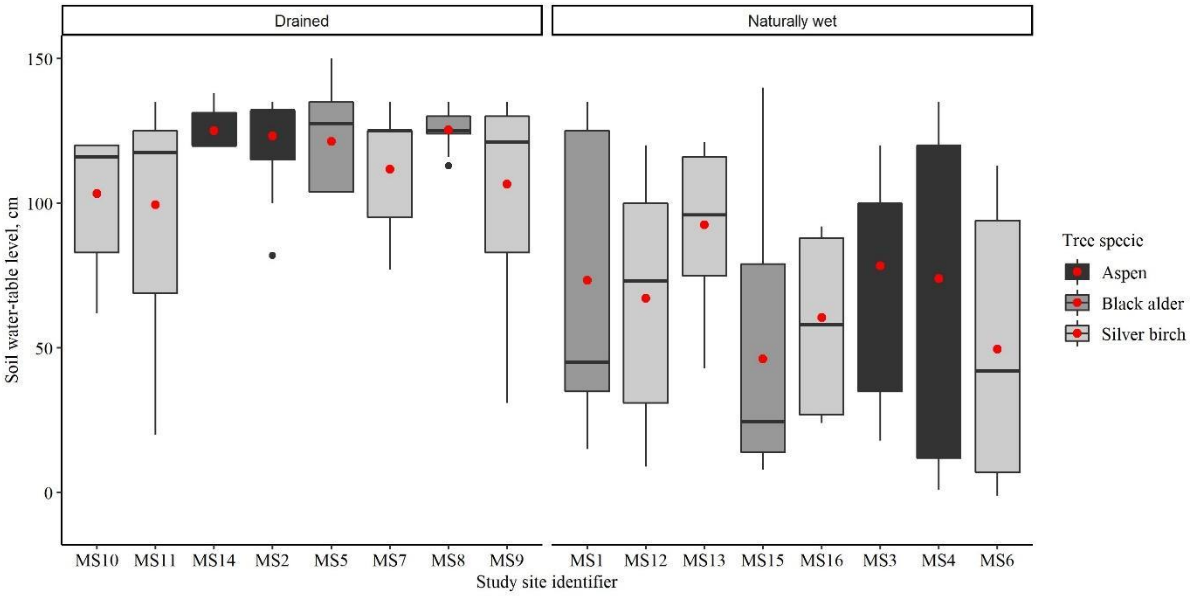

Fig. 1. **Variation of the soil water-table level below the soil surface among the study sites with drained and naturally wet mineral soil** (the medians are bold horizontal lines in the boxes, the mean values are red dots, and the black dots are outliers of the datasets)

In the forest stands with drained mineral soil, the mean CH_4 fluxes from the surface of tree stems were 10.2 ± 3.2 µg CH_4-C·m^{-2}·h^{-1} for aspen, 1.3 ± 2.6 µg CH_4-C·m^{-2}·h^{-1} for black alder and 4.5 ± 2.9 µg CH_4-C·m^{-2}·h^{-1} for silver birch. In the forest stands with naturally wet mineral soil, CH_4 fluxes from the tree stems were higher for all studied tree species (21.1 ± 5.5 µg CH_4-C·m^{-2}·h^{-1} for aspen, 6.3 ± 2.4 µg CH_4-C·m^{-2}·h^{-1} for black alder and 10.3 ± 2.3 µg CH_4-C·m^{-2}·h^{-1} for silver birch) than in the forest stands with drained mineral soil. However, no statistically significant differences in mean CH_4 fluxes from the surface of tree stems between the forest stands with drained and naturally wet mineral soil were found ($p = 0.083$) when study site mean values were compared. Comparing the CH_4 fluxes between the studied tree species, both in the forest stands with drained and naturally wet mineral soil, the highest mean CH_4 fluxes from the tree stems were found for aspen. Also among the individual study sites the highest mean CH_4 fluxes (24.6 ± 5.9 µg CH_4-C·m^{-2}·h^{-1}) were detected for aspen in the study site with naturally wet mineral soil (MS3).

No correlations between instantaneous CH_4 fluxes from the surface of tree stems and the soil water-table level ($\rho = -0.03$), air temperature ($\rho = -0.02$) or soil temperature at 5 cm depth ($\rho = -0.05$) were found. Also no correlation between mean CH_4 fluxes from tree stems and the mean soil water-table level in study sites was found ($\rho = -0.11$).

In the forest stands with drained mineral soil, the mean N_2O fluxes from the surface of tree stems were -0.8 ± 1.4 µg N_2O-N·m^{-2}·h^{-1} for aspen, 3.8 ± 1.3 µg N_2O-N·m^{-2}·h^{-1} for black alder and 1.9 ± 1.5 µg N_2O-N·m^{-2}·h^{-1} for silver birch. In the forest stands with naturally wet mineral soil, N_2O fluxes from the tree stems were similar for black alder (3.6 ± 1.3 µg N_2O-N·m^{-2}·h^{-1}) and higher for aspen and silver birch (4.1 ± 1.5 µg N_2O-N·m^{-2}·h^{-1} and 4.0 ± 1.5 µg N_2O-N·m^{-2}·h^{-1}, respectively). No statistically significant differences in mean N_2O fluxes from the surface of tree stems between the forest stands with drained and naturally wet mineral soil were found ($\rho = 0.105$) when the study site mean values were compared. Among the individual study sites the highest mean N_2O fluxes (6.9 ± 3.7 µg $N_2O\text{-}N{\cdot}m^{-2}{\cdot}h^{-1}$) were detected for silver birch in the study site with naturally wet mineral soil (MS6). No correlations between instantaneous N_2O fluxes from the surface of tree stems and the soil water-table level ($\rho = -0.03$), air temperature ($\rho = 0.08$) or soil temperature at 5 cm depth ($\rho = 0.10$) were found. Also only weak negative correlation between mean N_2O fluxes from tree stems and the mean soil water-table level in the study sites was found ($\rho = -0.35$).

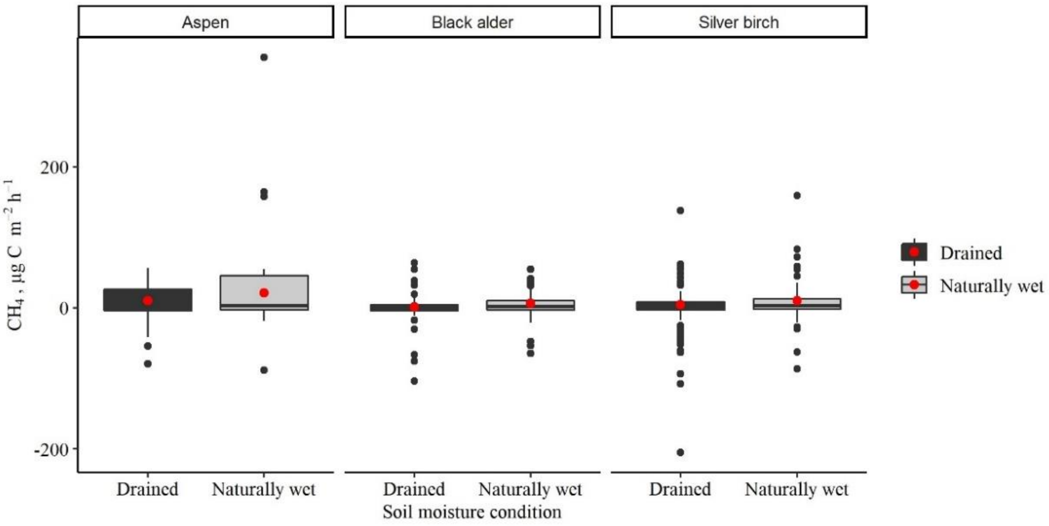

Fig. 2. **Variation of CH_4 fluxes from the surface of deciduous tree stems depending on tree species and soil moisture conditions** (the medians are bold horizontal lines in the boxes, the mean values are red dots, and the black dots are outliers of the datasets)

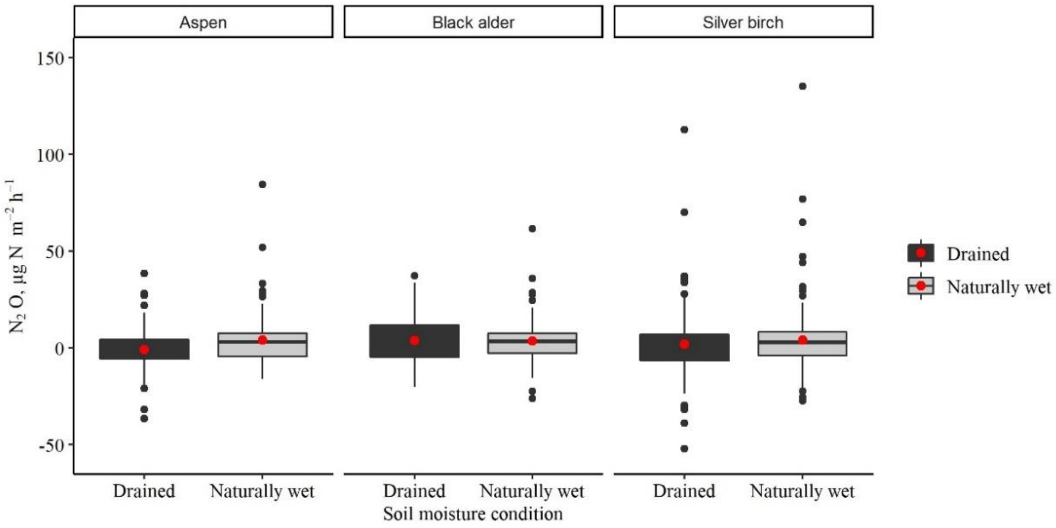

Fig. 3. **Variation of N_2O fluxes from the surface of deciduous tree stems depending on tree species and soil moisture conditions** (the medians are bold horizontal lines in the boxes, the mean values are red dots, and the black dots are outliers of the datasets)

In general, the results of our study are in line with previous findings in the boreal, hemi-boreal and temperate region supporting that tree stems are a markable source of CH_4 and N_2O emissions even during the winter season and nighttime (e.g. [19; 23; 26-28]). GHG fluxes from tree stems in forest lands with mineral soil have been reported relatively rarely compared to forests with organic soils. In the study carried out in Estonia, CH_4 fluxes from grey alder (*Alnus incana* (L.) Moench) stems (forest stands on a former agricultural Gleysol) were in the range from slight removals (mean -0.40 ± 0.05 µg $CH_4\text{-}C{\cdot}m^{-2}{\cdot}h^{-1}$ during the very dry summer 2018, nighttime) to significant emissions with mean of 168.47 ± 33.59 µg $CH_4\text{-}C{\cdot}m^{-2}{\cdot}h^{-1}$ (May 2018, nighttime) [27]. Grey alder stems were net emitters of N_2O with maximum mean N_2O emissions detected in summer 2017 (14.93 ± 4.90 µg $N_2O\text{-}N \cdot m^{-2} \cdot h^{-1}$ at daytime), while slight N_2O removals were detected in other study periods (-0.04 ± 0.22 µg N $m^{-2} \cdot h^{-1}$, summer 2018, nighttime) [27]. Our study covered the frost-free period, thus, further research including measurements during all seasons is necessary to estimate annual emissions from tree stems and clear seasonal patterns. Exclusion of the winter season can underestimate overall CH_4 and N_2O emissions [23]. However, previous studies show that emissions peak during the vegetation season [19] which was covered within our study. Seasonal dynamics of CH_4 and N_2O fluxes can be explained by environmental variables such as the temperature and soil water content as well as by physiological activity of trees including sap fluxes [19; 29].

Although higher CH_4 and N_2O fluxes from the surface of tree stems were mostly observed in forest stands with naturally wet mineral soil than under drained conditions, no clear correlations between CH_4 and N_2O fluxes and the soil water-table level were found. It indicates the need for further research. For instance, Mander et al. within the long-term monitoring of dynamics of CH_4 fluxes in a riparian forest concluded that 83% of ecosystem CH_4 emission moves through the tree stems during the wet period [28]. Also Jeffrey et al. highlighted that contribution of CH_4 fluxes from tree stems to the total net CH_4 fluxes at ecosystem level was the highest during flooded conditions (up to 70.2%) but less important during dry periods (up to 28.2%) in transitional zones of coastal freshwater wetland [30]. Thus, tree-mediated GHG emissions through fluxes from tree stems cannot be neglected when the total GHG balance of forest ecosystems is estimated including estimates of the impact of forest drainage.

Conclusions

1. Stems of deciduous trees including silver birch, black alder and aspen were mostly the source of CH_4 and N_2O emissions and, thus, can contribute to the total GHG balance of forest ecosystems. The exception was aspen stems in forest stands with drained mineral soil which showed slight CH_4 removals in average.
2. Higher CH_4 and N_2O fluxes from the surface of tree stems were mostly observed in forest stands with naturally wet mineral soil than under drained conditions (although the difference was not statistically significant). Thus, forest drainage may potentially reduce CH_4 and N_2O fluxes from the surface of tree stems.
3. However, high variation in the CH_4 and N_2O fluxes from the surface of tree stems were observed and thus further research is necessary to increase accuracy of overall estimation and projections of the studied greenhouse gases.

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Author contributions

Conceptualization, A.B.; methodology, A.B.; software, G.P.; validation, D.P.; formal analysis, G.P. and D.P.; investigation, D.P. and Z.A.Z.; data curation, A.A., V.B. an J.I.; writing – original draft preparation, G.P. and D.P.; 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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