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N_2O AND CH_4 EMISSIONS FROM NATURALLY WET AND DRAINED NUTRIENT-RICH ORGANIC FOREST SOILS

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According to general knowledge rewetting of drained organic soils is a measure that can reduce net greenhouse gas emissions from ecosystem, however there is lack of evidence that approves such an assumption in hemiboreal forests. The aim of the study was to quantify N_2O and CH_4 flux from nutrient-rich organic soils in naturally wet (NWS) and drained (DS) hemiboreal forest sites in Latvia.
In central Latvia, 26 NWS (*Dryopterioso–caricosa* and *Filipendulosa*) and DS (*Oxalidosa turf. mel.*) were selected to evaluate annual N_2O and CH_4 soil flux by manual chamber method. Gas sampling was performed once a month in five replicates in every sampling plot for period of one year covering all seasons from October of 2019 till November of 2020. During gas sampling soil temperature and groundwater level were measured. In addition, soil and groundwater was sampled and tested.
Study results show that soil CH_4 flux has strong correlation with groundwater level and weak correlation with soil temperature in booth DS and NWS. Moderate correlation between soil temperature and N_2O flux were found in DS, however in rest of the study sites significant impact of soil temperature and groundwater level on N_2O flux was not found. Estimated annual average soil CH_4 flux is average -3.5±1.0 kg C-CH_4 ha^{-1} yr^{-1} in DS and average 100.6±101.0 kg C-CH_4 ha^{-1} yr^{-1} in NWS. While estimated annual average soil N_2O flux is average 1.1±0.4 kg N-N_2O ha^{-1} yr^{-1} in DS and 2.6±0.9 kg N-N_2O ha^{-1} yr^{-1} in NWS.

Keywords: drained organic soil, naturally wet organic soil, CH_4 flux, N_2O flux

INTRODUCTION

Paris agreement signed by 195 parties worldwide, in enhancing the implementation of the United Nations Framework Convention on Climate Change (Convention), aims to hold the increase in the global average temperature to well below 2 °C above pre-industrial levels (United Nations..., 2015). Despite the efforts dedicated for reaching climate mitigation goals greenhouse gas (GHG), including nitrous oxide (N_2O) and methane (CH_4), concentration in atmosphere continues to increase. According to data of National Oceanic and Atmospheric Administration and Advanced Global Atmospheric Gas experiment, since the Convention took into force on 1994 till 2018, total GHG concentration in atmosphere has been consistently increasing by 17.2 %, from 389.6 to 456.8 ppm CO_2 eq. (Prinn et al., 2021). It is estimated if GHG concentration in atmosphere persists between 430 and 480 ppm CO_2 eq. in 2100, probability of exceeding atmospheric temperature increase threshold of 1.5 °C is 49 to 86 % (Clareke et al., 2014). During period from 1994 till 2016, CH_4 and N_2O emissions in atmosphere have increased by 6 % from 1742 to 1842 ppb and from 311 to 329 pbb accordingly (Prinn et al., 2021) and continues to increase. Although GHG emissions, including emissions of land use, land use change and forestry (LULUCF), from European Union have been reduced by 27 % and reduction of N_2O and CH_4 is as high as 37 % since 1990 till 2018, N_2O and CH_4 emissions still constituted 18 % of total GHG emissions (in CO2 eq.) in 2018 (Mandl Nicole (EEA) et al., 2020). Neither N_2O and CH_4 emissions are a key source of LULUCF in EU level, however these emission from drained organic soils are a key source of LULUCF sector in national GHG inventory of Latvia (Latvia's National..., 2021; Mandl, Pinterits, 2020). Total area of forest organic soils in Latvia is 696.5 kha or 10.8 % of total state area, furthermore 54.8 % of organic forest soils are drained. CH_4 and N_2O emissions from drained and rewetted organic soils in forest lands accounted for 7.3 % of total national GHG emissions in CO_2 equivalents in 2019 (Latvia's National..., 2021).

Climate change mitigation targets set at global, European Union as well as at national levels has increased scientific focus on ecosystem GHG emission studies. Furthermore, Regulation of the European Parliament and of Council on the inclusion of greenhouse gas emissions and removals from LULUCF into the 2030 climate and energy framework

promotes role of LULUCF sector in achieving climate change mitigation goals by setting a binding commitment to ensure that accounted emissions from land use are entirely compensated by CO_2 removals in LULUCF sector. Regulation aims to fully offset the country's total GHG emissions by CO_2 removals in the LULUCF sector in the second half of the 21st century. Furthermore, Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) 2018/841 on the inclusion of GHG emissions and removals from LULUCF in the 2030 climate and energy framework aims to set a target of GHG removal of the LULUCF sector in 2030 thus making the sector even more crucial in reaching overall EU climate targets.

In the national GHG inventory of 2019 Latvia used default Tier 1 CH_4 (2.5 kg CH_4 ha^{-1} yr^{-1}) and N_2O (2.8 kg N_2O-N ha^{-1} yr^{-1}) emission factors (EF) from 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2013 Wetlands Supplement). To improve accuracy of Latvia's national GHG inventory and to support policy makers this study aims to elaborate national CH_4 and N_2O emissions factors for drained and naturally wet nutrient-rich organic soils.

RESEARCH METHODS

The study was conducted in 31 forest sites with nutrient-rich drained and naturally wet organic soils located in central Latvia from October of 2019 till November of 2021 (**Klaida! Nerastas nuorodos šaltinis.**). Annual average air temperature within the study period according to 5 closest meteorological stations within range of 30 km from atleast 1 study site was 9.2±0.8 ºC (min 8.0±0.7, max 31.4±0.1), while annual precipitation ranged from 472 mm to 860 mm (average 668±136 mm).

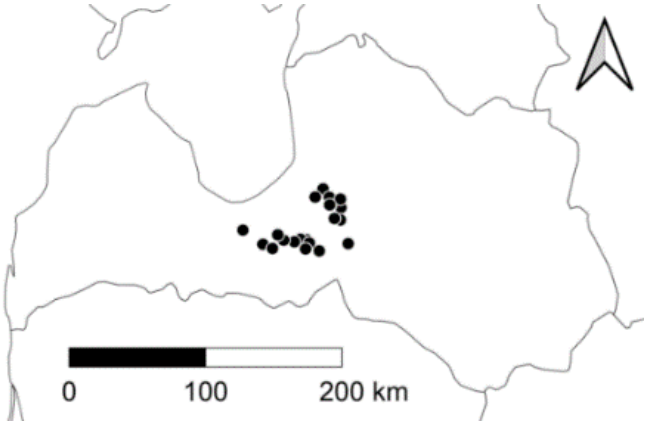

Figure 1. Location of study sites in Latvia

Selection of study sites

Primary study sites selection was based on site soil moisture regime and fertility characteristics according to the national forest site type classification system (Bušs, 1981). For further evaluation from 4 soil fertility classes forest stands characterized as compliant to 2 most fertile forest stands classes with drained (*Myrtillosa turf.mel.* and *Oxalidosa turf. mel.)* and naturally wet (*Dryopterioso–caricosa and Filipendulosa*) organic soils were selected. Sample plots were established in naturally wet and drained sites with peat layer atleast 30 cm and 20 cm accordingly (checked at atleast 5 places within sample plots). During the study period soil GHG monitoring was conducted for 12 consecutive months in each of the study sites. In each of the study site 1 round (500 m^2) sample plot was established atleast 20 m from forest stand or clearcut border. Soil GHG fluxes measurements were done by closed opaque manual chamber method (Pavelka et al., 2018). 5 chamber collars were installed evenly within sample plot with distance between individual collars at least 3 m. Collars were installed in soil depth aproximately 5 cm at least one month prior to first GHG measurements. Root damages were avoided as far as possible and ground vegetation was left intact during collar installation and field surveys. Sample plots were visited once per month and 4 soil flux samples were taken from chambers in each of collar positions within 30 minutes (10 minutes between each sampling) after positioning chamber on collar. Samples were collected in 100 mL vials with 0.3 mbar underpressure and transported to the laboratory to be tested by gas chromatograph. During gas sampling soil temperature at 5 cm depth as well as groundwater level was measured, in addition groundwater samples were collected from groundwater level monitoring wells for further tests in laboratory. For site fertility characterisation soil samples were collected from each sample plot in depth up to 80 cm (within step of 10 cm) (Cools and De Vos, 2016).

GHG flux samples were analysed in University of Tartu by gas chromatograph (Loftfield et al., 1997). Physio-chemical analysis of soil and water samples were done in Laboratory of Forest Environment of Latvian State Forest Research Institute "Silava". The soil samples were prepared for analyses according to the LVS ISO 11464 (2005) standard. Chemical parameters were determined to organic soil milled till fine powder and fine earth fraction (D < 2 mm) of mineral soil (prepared according to LVS ISO 11277) according to standard methods (Table 1). Organic carbon concentration (g kg^{-1}) in soil was calculated as the difference between total carbon concentration and inorganic carbon (carbonate) concentration. Water samples analysed by photometry and ion chromatography were filtered through 0.45 µm and 0.2 µm filters accordingly.

GHG flux calculation

GHG flux is calculated using slope of linear regression that represents hourly GHG concentration changes in chamber. Acquired slope data was discarded if $R^2<0.7$ except cases when difference between maximum and minimums concentration in chamber was less then gas chromatograph method uncertainty. Acquired slope information was further expressed as GHG flux from area of soil:

$$flux = \frac{M}{R}\frac{P}{T}\frac{V}{t}\frac{slope}{A}, \quad (1)$$

where *flux* – soil GHG flux, μg GHG m^2 h^{-1};
M – molar mass of GHG, g mol^{-1};
R – universal gas constant, m^3 Pa K^{-1} □mol^{-1};
P – assumption of air pressure inside the chamber, 101 300 Pa;
T – air temperature, K;
V – chamber volume, 0.063 m^3;
t – time period between first and last GHG flux sampling, 0.5 h;
slope – slope of the hourly GHG concentration changes inside of chamber;
A – collar area, 0.1995 m^2.

Table 1. Standard methods utilised for soil and groundwater sample analysis

Parameter	Unit	Method principle	Standard method
Soil samples			
Bulk density	kg m^{-3}	Gravimetry	LVS ISO 11272:2017
Total carbon	g kg^{-1}	Elementary analysis (dry combustion)	LVS ISO 10694:2006
Total nitrogen	g kg^{-1}	Elementary analysis (dry combustion)	LVS ISO 13878:1998
$CaCO_3$	g kg^{-1}	Volumetry	ISO 10693
HNO_3 extractable K, Ca, Mg and P	g kg^{-1}	ICP-OES	LVS EN ISO 11885:2009)
Groundwater samples			
pH	log unit	Potentiometry	LVS ISO 10523:2012
Conductivity (EC)	μS cm^{-1}	Conductometry	LVS EN 27888:1993
Total nitrogen (N)	mg L^{-1}	Catalytic oxidation	LVS EN 12260:2004
Nitrates (NO_3^-), phosphates (PO_4^{3-})	mg L^{-1}	Ion chromatography	ISO 10304-1:2007
Ammonium ion (NH_4^+)	mg L^{-1}	Photometry	LVS ISO 7150-1:1984

Statistical analysis

Data statistical analysis was carried out using RStudio (Rstudio Team, 2019). The compliance of the data distribution with the normal distribution was checked using the Kalmogorov-Smirnov test. Statistical differences of GHG fluxes between forest site groups with drained and naturally wet soils were evaluated by Wilcoxon signed-rank test. Correlation between GHG flux and affecting factors were determined by Pearson and Spearman correlation. Data uncertainty within this paper is expressed as confidence interval, significance level α=0.05 is applied.

RESEARCH RESULTS

Characteristics of study sites

Mean peat layer in study sites ranged from 25 cm to at least 100 cm (average 75±7 cm) and 23 cm to at least 100 cm (average 54±12cm) in DS and NWS respectively. Study site topsoil (upper 20 cm layer) characteristics are summarised in

Table 2.

Table 2. Study site characteristics

Parameter	Value	Naturally wet forest sites				Drained forest sites			
		Norway spruce	Silver birch	Black alder	Clearcut	Norway spruce	Silver birch	Black alder	Clearcut
Number of study sites	number	1	3	5	1	12	3	2	4
Forest stand characteristics									
Age of dominant tree species, years	average	67	56	43	-	55	39	40	-
	range (min...max)	-	21-77	10-80	-	14-86	18-60	26-53	-
Growing stock, m^3 ha^{-1}	average	446	225	170	-	269	135	189	-
	range (min...max)	-	78-365	35-325	-	7-521	38-210	123-254	-
Peat layer, cm	average		41	59	47	81	43	65	90
	range (min...max)	-	31-52	23-99	-	37-99	25-75	60-70	63-99
Topsoil (upper 20 cm layer) characteristics									
C_{org}, g kg^{-1}	average ±SE	490	463±26	344±96	447	483±37	316±97	430±53	546±17
N_{tot}, g kg^{-1}	average ±SE	32	25±4	19±5	28	23±8	23±2	27±4	27±8
P, g kg^{-1}	average ±SE	1.9	1.2±0.6	1.7±0	3.8	1.5±0.3	2.1±0.6	3.2±0.7	1.3±0.1
K, g kg^{-1}	average ±SE	19	21±4	18±2	16	21±1	14±0.5	16±1	15±1
Ca, mg kg^{-1}	average ±SE	0.3	0.4±0.02	0.5	0.6±0.1	0.3±0.03	0.7±0.3	1.0±4	0.6±0.01
Mg, g kg^{-1}	average ±SE	18	10±6	14±4	42	16±2	24±8	32±8	12±3

During the study period of 1 year depth of groundwater level in both drained and naturally wet forest sites ranged from atleast 140 cm to 0 cm. Mean distance from topsoil to groundwater level was 55±2 cm and 35±3 cm at drained and

naturally wet forest sites respectively. Monthly mean groundwater level was by 18±2 cm deeper in drained forest sites (Figure 2).

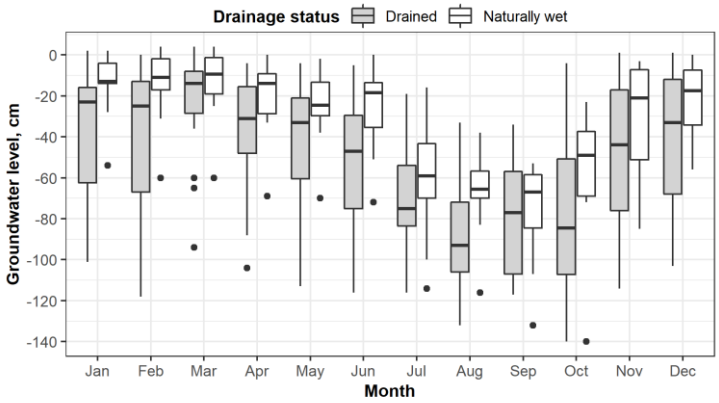

Figure 2. Monthly groundwater depth variation in study sites. In the boxplots, the median is shown by the bold line, the box corresponds to the lower and upper quartiles, whiskers show the minimal and maximal values (within 150% of the interquartile range from the median) and black dots represent outliers of the datasets.

Soil GHG flux and affecting factors

Study results shows that soil CH_4 flux is a subject of high uncertainty. Difference of estimated soil CH_4 flux within same survey of single study site reaches 2 and 4 orders of magnitude in DS and NWS accordingly, thereby spatial variability of soil CH_4 flux is considerable higher in NWS. During the study period estimated annual average soil CH_4 flux in DS ranged from -5.5±1.0 kg C-CH_4 ha^{-1} yr^{-1} in Norway spruce stands to 6.8±16.6 C-CH_4 ha^{-1} yr^{-1} in Black alder stands (average -3.5±1.0 kg C-CH_4 ha^{-1} yr^{-1}), while in NWS estimated soil CH_4 flux ranges from -3.7±2.8 kg C-CH_4 ha^{-1} yr^{-1} in Silver birch stands to 199.8±393.2 kg C-CH_4 ha^{-1} yr^{-1} in Black alder stands (average 100.6±101.0 kg C-CH_4 ha^{-1} yr^{-1}). Study results indicate that Black alder forest stands tend to have considerably higher average soil CH_4 flux compared to other tree species dominated forest stands included in this study, however also uncertainty of estimated annual soil CH_4 flux results for Black alder stands is considerable higher (Table 3). Pattern of exceedingly high emissions were found in 10 % of NWS.

Table 3. Annual soil CH_4 flux (kg C-CH_4 ha^{-1} yr^{-1}) in study sites

Dominant tree specie	Drained forest sites	Naturally wet forest sites
Silver birch	-1.7±2.0	-3.7±2.8
Norway spruce	-5.5±1.0	-2.4±1.2
Clearcut	-4.7±1.0	6.9±6.2
Black alder	6.8±16.6	199.8±393.2
Black alder (hotspot excl.)	-	-0.9±0.4
Black alder (hotspot)	-	10036.7±834.4
Average	-3.47±0.94	100.6±101.0

Estimated average soil CH_4 flux of Black alder stands ranges from -1.7±1.0 kg C-CH_4 ha^{-1} yr^{-1} to 15.5±12.7 kg C-CH_4 ha^{-1} yr^{-1} in DS (2 study sites) and from -1.9±1.1 kg C-CH_4 ha^{-1} yr^{-1} to 1036.7±834.4 kg C-CH_4 ha^{-1} yr^{-1} in NWS (5 study sites), furthermore if soil CH_4 flux hotspot site is excluded, average CH_4 flux from rest of 4 NWS

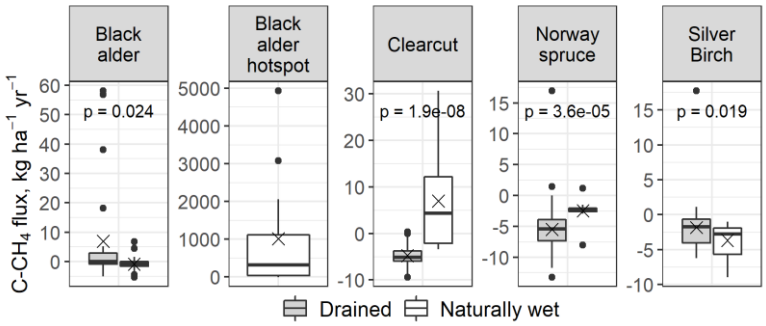

Figure 3. Intra-annual soil CH_4 flux variation. In the boxplots, the median is shown by the bold line, the mean is shown by "x", the box corresponds to the lower and upper quartiles, whiskers show the minimal and maximal values (within 150% of the interquartile range from the median) and black dots represent outliers of the datasets.

study sites ranges from -1.9±1.1 kg C-CH_4 ha^{-1} yr^{-1} to -0.2±0.7 kg C-CH_4 ha^{-1} yr^{-1} (Figure 3**Klaida! Nerastas nuorodos šaltinis.Klaida! Nerastas nuorodos šaltinis.**).

Acquired soil CH_4 flux data has weak correlation with soil temperature and groundwater chemical analysis result data but has strong nonlinear correlation with groundwater level data in both DS and NWS, however it was not possible to elaborate model with good fit to raw empirical data set due to high proportion of CH_4 flux data outliers with considerably high concentrations. If outliers are excluded relationship between groundwater level and soil CH_4 flux is characterised by exponential regression (Figure 4).

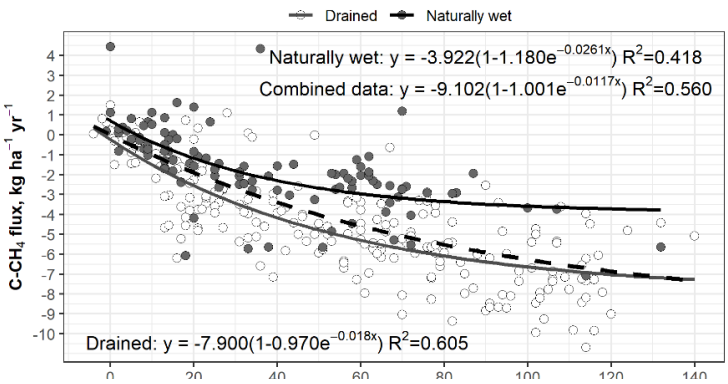

Figure 4. Relationship between groundwater level depth and soil CH_4 flux

These results indicate that during majority of measurements soil has not been a source of CH_4 emissions in booth DS and NWS, however as groundwater raised CH_4 removals decreased till gradually turned into CH_4 emissions as groundwater level reached topsoil and soil were saturated by water respectively. Similar observations are made if also statistical outliers are included in data evaluation. Regardless of drainage status soils become a source of CH_4 emissions when groundwater depth decreased below 20 to 30 cm. If whole dataset is considered average soil CH_4 flux from DS and NWS is significantly different in all groundwater depth ranges, except in depth between (0 to 9 cm) (p=0.27) (Table 4). Furthermore, if the one sample plot mentioned above with excessively high soil CH_4 flux at NWS is excluded from evaluation, average flux differences remain significant (p<0.05) in all groundwater depths except from 0-9 cm (p=0.95) and in conditions when GHG flux sampling ring is flooded (p=0.90).

Table 4. Average soil CH_4 flux by different groundwater level depths

Groundwater level, cm	Drained forest sites		Naturally wet forest sites					
	kg C-CH_4 ha y^{-1}	n	kg C-CH_4 ha y^{-1}	n	kg C-CH_4 ha y^{-1}	n	kg C-CH_4 ha y^{-1}	n
	Total data		Total data		Without hotspot site		Hotspot site	
Flooded	1.6±0.9	45	448.1±869.9	37	12.1±11.9	14	1025±1184.7	23
0-9	5.2±3.2	107	366.1±409.3	104	2.3±3.7	87	2233.5±2377.6	17
10-19	0.4±3.3	123	20.7±22.5	104	0.3±1.7	99	510.2±302.5	5
20-29	-2.8±0.4	105	-1.9±1	60	-1.9±1	60	-	0
30-39	-3.8±0.5	90	-2.7±1.1	60	-2.7±1.1	55	-2.1±1.6	5
40-49	-2.3±2.3	65	-2.4±0.6	25	-2.2±0.7	20	-3.3±1	5
50-59	-5±0.6	80	-2.1±1.2	65	-2.1±1.2	65	-	0
60-69	-5.1±0.5	105	-2.6±0.5	60	-2.6±0.5	55	-2.6±0.9	5
70-79	-5.6±0.5	115	-2.7±1.5	35	-2.7±1.5	35	-	0
80-89	-6.4±0.6	60	-3.9±1.2	20	-3.9±1.2	20	-	0
90-99	-7±0.6	70	-	0	-	0	-	0
100-119	-7.2±0.5	175	-5.6±1.1	20	-5.6±1.1	20	-	0
120-140	-5.8±1	20	-7.3±1.7	10	-7.3±1.7	10	-	0

According to the study results average annual soil N_2O flux in DS (1.1±0.4 kg N-N_2O ha^{-1} yr^{-1}) and NWS (2.6±0.9 kg N-N_2O ha^{-1} yr^{-1}) differ significantly (p=0.01). Average annual soil N_2O flux in DS ranged from 0.6±0.6 to 1.5±1.3 kg N-N_2O ha^{-1} yr^{-1} in Black alder dominated stands and clearcuts accordingly (Table 5). While in NWS highest average soil N_2O flux where found in Black alder dominated stands (3.3±4.0 N-N_2O ha^{-1} yr^{-1}) and lowest flux – in clearcut sample plot (0±0.1 kg N-N_2O ha^{-1} yr^{-1}). Furthermore, in case of Black alder dominated stands (p=0.001) and clearcuts (p<0.05) difference between DS and NWS soil N_2O flux is significant. According to data acquired, soil temperature had moderate (r = 0.48) impact on soil N_2O flux in DS only, while groundwater level had weak impact on N_2O flux in neither DS and NWS. From groundwater quality parameters monitored NO_3^- and N as well as Ca and Mg concentration had the most notable impact on soil N_2O flux. NO_3^- and N concentration had moderate linear correlation in DS (r = 0.54 and 0.52 accordingly) and weak linear correlation in NWS (r = 0.42 and 0.32 accordingly). While Ca and Mg concentration had

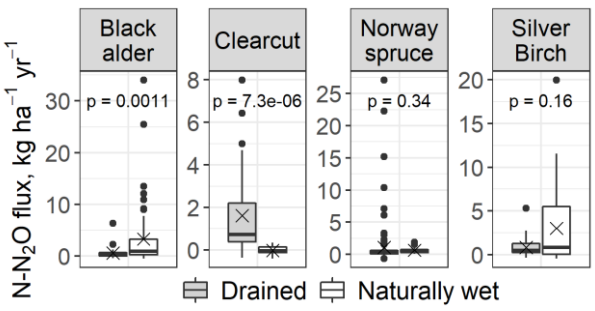

Figure 5. Intra-annual soil N_2O flux variation

weak nonlinear correlation in DS (r = 0.44 and 0.42 accordingly) and moderate correlation in NWS (r = 0.57 and 0.62 accordingly). Regarding pH and EC, weak linear correlation was found in NWS only (r = 0.42 and 0.43 accordingly).

Table 5. Annual soil N_2O flux (kg N-N_2O ha^{-1} yr^{-1}) in study sites

Dominant tree specie	Drained forest sites	Naturally wet forest sites
Silver birch	0.9±0.6	2.7±3.1
Norway spruce	1.0±0.9	0.6±0.3
Clearcut	1.5±1.3	0±0.1
Black alder	0.6±0.6	3.3±4.0
Average	1.1±0.4	2.6±0.9

CONCLUSIONS AND DISCUSSION

Study results show that groundwater level depth threshold found for nutrient-rich organic forest soils to become a source of CH_4 emissions around 20 to 30 cm complies with assumption of 2013 Wetlands Supplement guidelines regarding drainage class classification – threshold of groundwater level depth of 30 cm to distinguish between shallow or deep drained soils (IPCC, 2014). Estimated average soil CH_4 flux in NWS monitored in this study (100.6±101.0 kg C-CH_4 ha^{-1} yr^{-1}) is similar but with considerably less uncertainty if compared to default EF for CH_4 from rewetted nutrient-rich organic soils in boreal climate zone (0 to 493 kg C-CH_4 ha^{-1} yr^{-1}, average 137 kg C-CH_4 ha^{-1} yr^{-1}) and considerably lower compared to EF for CH_4 from nutrient-rich organic soils in temperate climate zone (0 to 856 kg C-CH_4 ha^{-1} yr^{-1}, average 216 kg C-CH_4 ha^{-1} yr^{-1}) provided by 2013 Wetlands Supplement indicating that. Lower uncertainty is achieved also for calculated annual average soil CH_4 flux in DS (-3.47±0.94 kg C-CH_4 ha^{-1} yr^{-1}) compared to default EF for drained organic soils in temperate (-0.6 to 5.7 kg C-CH_4 ha^{-1} yr^{-1}, average 2.5 kg C-CH_4 ha^{-1} yr^{-1}) and drained nutrient-rich organic soil boreal (-1.6 to 5.5 C-CH_4 ha^{-1} yr^{-1}, average 2.0 C-CH_4 ha^{-1} yr^{-1}) climate zones. Estimated annual soil N_2O flux in both DS (1.1±0.4 kg N-N_2O ha^{-1} yr^{-1}) and NWS (2.6±0.9 kg N-N_2O ha^{-1} yr^{-1}) is within uncertainty of default N_2O EF for drained organic soils in temperate climate zone (-0.57 to 6.1 kg N-N_2O ha^{-1} yr^{-1}, average 2.8 kg N-N_2O ha^{-1} yr^{-1}) and EF for nutrient-rich drained organic soils in boreal climate zone (1.9 to 4.5 kg N-N_2O ha^{-1} yr^{-1}, average 3.2 kg N-N_2O ha^{-1} yr^{-1}).

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