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GREENHOUSE GAS FLUXES AND CARBON LOSSES FROM SOIL IN DECIDUOUS FORESTS WITH NATURALLY WET AND DRAINED MINERAL SOILS

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The scope of the study is to evaluate soil greenhouse gas (GHG) fluxes from drained and naturally wet (pristine) nutrient rich mineral forest soils representing *Mercurialosa mel.* (drained) and *Myrtillosoi-polytrichosa* and *Drypteriosa* (wet soil) forest stand types with dominant species (aspen, birch and black alder). GHG were monitored during 12 months period using opaque chamber method. Gas samples were collected once per month and carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) concentration was determined using gas chromatography. The calculated GHG fluxes were evaluated in conjunction with temperature, soil moisture and groundwater level measurement results. We did not found difference of the soil GHG fluxes in drained and pristine wet mineral soils. The N_2O and CH_4 emissions from soil are negligible; however, periodic extreme increase of CH_4 is characteristic for pristine wet soils, pointing out that wet mineral soils can be significant source of GHG emissions, just like organic soils. CO_2 emissions are correlating with air and soil temperature, while CH_4 and N_2O emissions are not correlating with any of the monitored environmental variables.

Keywords: *greenhouse gases; emissions; drained forest; mineral soil*

INTRODUCTION

Soil is the second largest carbon pool on Earth after the ocean. The soil carbon pool is approximately 3.1 times larger than the atmospheric pool of 800 GT (Scharlemann et al., 2014). Carbon storage in forest soil refers to the process of sequestering or storing carbon in the soil of forest ecosystems. Forest soils contain plant roots, foliar litter, and other dissolved organic material, which can store carbon (Menyailo, 2022). The amount of carbon soil can sequester is dependent on many local factors like local geology, soil type, vegetation and moisture regime. Soils with more organic material can store more carbon because organic material easily binds loose carbon molecules and the organic material itself is containing carbon (Baveye et al., 2020). Organic soils is significant source of GHG emissions; drainage can increase CO_2 emissions, but wet or rewetted organic soils produces more CH_4 emissions due to different patterns of decomposition of organic matter (Chapman & Thurlow, 1996). Recent studies in Latvia demonstrated that drainage of organic nutrient-rich forest soils is increasing CO_2 emissions from soil; however, negative effect due to the increase of emissions of CH_4 from soil and reduction of carbon stock in the living biomass is exceeding this effect, actually turning forest drainage into climate friendly measure, if GHG emissions from pristine wet organic soils in forest lands are accounted (Butlers, Lazdiņš, et al., 2022; Butlers et al., 2023; Samariks et al., 2023; Vanags-Duka et al., 2022).

Pristine wet mineral soils in forest lands can also contribute to GHG emissions. Although these soils are not drained, they can still emit GHG such as CO_2 and CH_4 due to natural processes (Escobar et al., 2022). However, number of studies addressing GHG emissions from wet mineral soils is limited and usually is associated with evaluation of the emissions from organic soils and drainage. Similarly, there is limited number of studies addressing effect of drainage of mineral forest soils on the GHG emissions. Modelling approaches usually ignores soil moisture regime assuming that mineral soils are well aerated and the same assumptions are used for wet and dry or drained mineral soils (Bārdulis et al., 2017; Liski et al., 2005; Peltoniemi et al., 2006). However, there are evidences that the drainage of wet mineral soils can

increase GHG emissions from forest soils and drainage ditches on mineral soils in boreal forests can emit significant amounts of CH_4 and CO_2 (Peacock et al., 2021). Soil CO_2 emissions can increase especially in sites with high nitrogen concentrations in soil, while sites with low nitrogen concentrations in soil can act as a CO_2 sink (Mäkipää et al., 2022).

Total area of forests with drained and pristine wet mineral soils in Latvia in 2020 was 810 kha (thousands ha), including 527 kha of drained mineral soils (Ministry of Environmental Protection and Regional Development, 2022). Area of wet mineral forest soils corresponds to 9% of the total forest area in Latvia and area of drained mineral forest soils – 17% of the total forest area in Latvia. According to the national forest stand type classification forest soils are accounted as mineral if peat and litter layer depth is less than 30 cm under pristine conditions and less than 20 cm after drainage (Bušs, 1981). According to the fourth cycle of the National forest inventory area of nutrient-rich drained mineral forest soils (stand types *Myrtillosa mel.* and *Mercurialosa mel.*) in Latvia is 439 kha, and area of nutrient-rich pristine wet mineral forest soils (stand types *Myrtillosoi-polytrichosa* and *Drypteriosa*) is 118 kha. Deciduous trees are dominating in 261 kha area of the drained nutrient rich mineral soils and in the most of the pristine nutrient rich wet mineral soils (109 kha). Birch is is the most common species in the both forest categories, respectively, 127 kha and 46 kha in drained and pristine soils (LSFRI Silava, 2023).

Studies in agricultural lands proves that even shallow peat layer (e.g. in Gleysol wih 3-6% of carbon content in topsoil layer) increases the GHG emissions from soil. In studies in Germany it was found that carbon losses in shallow peat soil reach 7-9 tons CO_2-C ha^{-1} yr^{-1} (Leiber-Sauheitl et al., 2014). Similar results, proving that shallow peat soils can be source of emissions are acquired in Finland (Ojanen & Minkkinen, 2019). Study in Denmark demonstrated that rewetted grasslands with shallow peat layer can emit CH_4 (Petersen et al., 2012; Schäfer et al., 2012). Other study in Denmark demonstrated that carbon losses from shallow soils can reach 11.5 tons C ha^{-1} yr^{-1} (Elsgaard et al., 2012). The study in Latvia demonstrated correlation between peat depth and carbon losses from soil; even areas with 10 cm deep peat layer in grasslands was source of emissions (Purvina et al., 2023).

Considering significant area of the wet and drained mineral soils in Latvia and knowledge gathered in shallow peat soils in non-forest lands it is important to investigate if the GHG emissions in the national GHG inventory are not underestimated. It is also important to investigate the effect of forest drainage and rewetting on the emissions to avoid reckless implementation of insufficiently substantiated climate change mitigation measures.

RESEARCH METHODS

The study sites were selected in young and middle age stands of the selected species (birch (*Betula* spp.), aspen (*Populus* spp.) and black alder (*Alnus glutinosa* (L.) Gaertn.)), which are common for wet and drained forest stand types. In total 15 study sites were selected, including 4 aspen dominant, 6 birch dominant and 5 black alder dominant stands. Seven stands have wet soils and 8 stands – drained mineral soils (Table **1**). Stand characteristics are encoded in the ID number of a study site; first letter is dominant species (A – aspen, B – birch, M – black alder), second letter is age group (J – young and M – mature stand), third letter is soil (M – mineral soil), fourth letter is nutritional conditions (R – nutrient-rich soil), fifth letter is moisture conditions (D – drained, W – wet).

Table 1. Characterization of the study sites.

ID	Dominant species	Stand type	Coordinates of plot B (LKS92)		Age, years	Height, m	Basal area, m^2 ha^{-1}	Growing stock, m^3 ha^{-1}
			X	Y				
AJ-MRD	Aspen	*Myrtillosa mel.*	624140	284193	23	8	7	33
AJ-MRW	Aspen	*Myrtillosoi-polytrichosa*	423057	253759	22	7	8	39
AM-MRD	Aspen	*Mercurialosa mel.*	434983	257787	68	27	23	293
AM-MRW	Aspen	*Myrtillosoi-polytrichosa*	438656	257963	63	26	32	392
BJ-MRD	Birch	*Myrtillosa mel.*	618249	282649	21	8	11	51
BJ-MPW	Birch	*Myrtillosa mel.*	482364	286081	65	24	32	357
BJ-MRW	Birch	*Myrtillosoi-polytrichosa*	623986	279234	28	13	15	96
BM-MRD	Birch	*Mercurialosa mel.*	617470	285130	79	23	18	197
MM-MRD	Black alder	*Mercurialosa mel.*	617385	285156	79	23	18	197
BM-MRD	Birch	*Mercurialosa mel.*	617470	285130	79	23	18	197
MM-MRD	Black alder	*Mercurialosa mel.*	617385	285156	79	23	18	197
BM-MRW	Birch	*Myrtillosoi-polytrichosa*	615183	352030	80	24	18	193
MJ-MRD	Black alder	*Myrtillosa mel.*	487873	281249	16	6	0	20
MJ-MRW	Black alder	*Drypteriosa*	426857	254366	18	11	10	59
MM-MRW	Black alder	*Myrtillosoi-polytrichosa*	617726	351163	86	29	16	227

Measurement site consists of three plots established as a transect characterizing diversity of the moisture regime in the site. Stand characteristics, environmental parameters and GHG flux measurements were done in every plot, including soil and litter sampling at the beginning of the study. Two types of GHG measurement plots were established in each site – for heterotrophic respiration (HR) and CH_4 and N_2O fluxes (GC) – three points for measurement of HR and

two points – for measurement of GC (Figure **1**). A, B and C in Figure **1** are forest stand measurement plots – trees with diameter at breast height >14 cm are measured in plot A, trees with diameter >6 cm – in plot B, and the rest of trees with diameter >2 cm – in plot C.

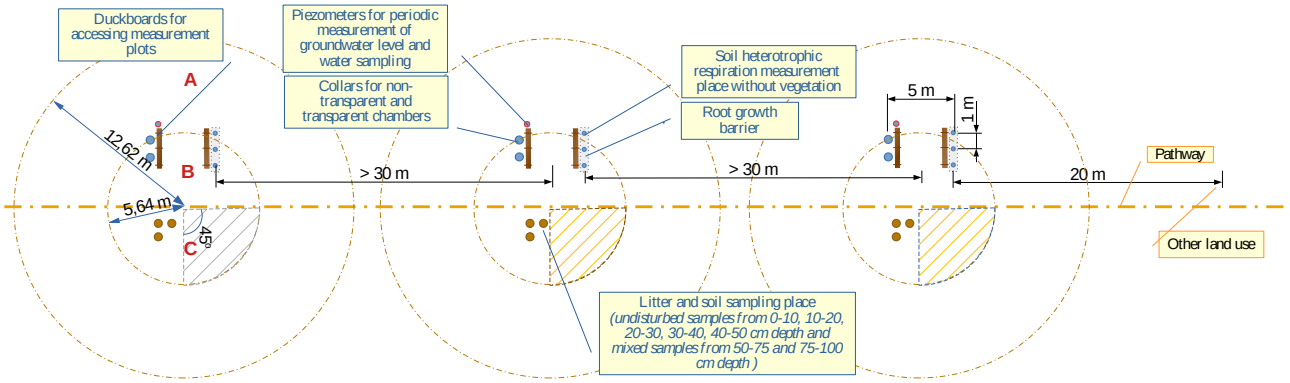

Figure 1. Design of the study site.

HR points are prepared by trenching and removing all vegetation to avoid root ingrowth, while retaining water and air exchange with the environment. HR includes emissions due to organic matter decomposition only (i.e. exclude autotrophic respiration emissions from alive vegetation aboveground parts and roots). Measurements are started six months after trenching (Hermans et al., 2022; Ojanen et al., 2012). Environmental variables (soil temperature and moisture) are measured besides the HR measurement points, every time in the same place. In the GC monitoring point vegetation is kept as intact as possible in these monitoring points. In every measurement point collars with 15 cm height and 50 cm diameters are permanently installed about 1 month before measurement. Volume of collars user for determination of HR is 20 L and volume of chambers used for determination of GC is 65 L. Such a big volume ensures that concentration of gases do not reach saturation point and doesn't dilute soil atmosphere (Salm et al., 2012).

HR is measured in the field using EGM5. Duration of the measurement 150 sec, flow rate 350 mL min^{-1}. Data processing and analysis was done using R *flux-package* (Flux Rate Calculation from Dynamic Closed Chamber Measurements). GC samples are collected with 50 ml glass bottles, which are vacuumed before sampling. Samples are collected directly after putting chamber on a collar and then after 10, 20 and 30 min. The concentration of CO_2, CH_4 and N_2O in the collected air is determined using the Shimadzu GC-2030 gas chromatographic system (equipped with an electron capture detector (ECD), a flame ionization detector and an autosampler built following to principles implemented in a Loftfield autosampler (Loftfield et al., 1997) in the Forest environment laboratory of the Latvian Forest Research Institute "Silava". The emission rate of trace gas is calculated using the linear increase of gas concentration within time, corrected for the area and volume of the chamber (Formula 1, example for CO_2 flux calculation).

$$CO_2 - C[\mu g C m^{-2} h^{-1}] = \frac{M[g mol^{-1}] * P[Pa] * V[m^3] * \delta v[ppm(v)] * f_1}{R[m^3 Pa K^{-1} mol^{-1}] * T[K] * A[m^2] * ppm} \quad (1)$$

where P – the assumption of air pressure inside the chamber, 101300 Pa;
R – the universal gas constant, 8.3143 m^3 Pa K^{-1} mol^{-1};
V – the chamber volume, 0.0655 m^3 and 0.023 m^3;
A – the collar area, 0.19625 m^2 and 0,076 m^2;
M CO_2 – the molar mass of CO_2, 44.01 g mol^{-1};
M CH_4 – the molar mass of CH_4, 16.04 g mol^{-1};
M N_2O – the molar mass of N_2O, 44.01 g mol^{-1}.

Environmental variables determined during field works are groundwater level, soil temperature and moisture, as well as air temperature. Stand characteristics were determined in every plot to identify dominant tree species and to use for calculation of carbon input in soil with litter. Correlation and regression analysis was done to identify factors affecting GHG fluxes. Uncertainty is expressed as standard error of mean.

RESEARCH RESULTS AND DISCUSSION

Measurements were done from April, 2022 to May, 2023, once per month in average, from 126 to 294 successful individual measurements for every variant (dominant species and water regime). In total 1114 successful individual measurements were carried out. Average hourly GC and HR fluxes are shown in Table **2**. Drained and wet soils are sources of CO_2 emissions and there are no significant difference depending from presence of drainage ditches. Average hourly CO_2 emissions are 28.41 ± 1.69 CO_2–C, mg m^{-2} h^{-1}, which corresponds to 9.1 tons CO_2 ha^{-1} yr^{-1}. Drained soils regardless of dominant species is small sink of CH_4 emissions and wet soils are small source of CH_4 emissions; however, the difference is not significant. Both groups of plots, with drained and wet soils, are small source of N_2O emissions.

There is no significant difference between them; therefore, the study is not approving assumption that drainage is increasing N_2O emissions in forest lands with mineral or shallow peat soils.

Table 2. Average GHG fluxes depending on moisture regime and dominant species.

Moisture regime	Dominant tree specie	CO_2–C, mg m^{-2} h^{-1} (HR)	CH_4-C, mg m^{-2} h^{-1} (GC)	N_2O-N, mg m^{-2} h^{-1} (GC)
Drained	Aspen	33.34 ± 2.73	-0.012 ± 0.015	0.021 ± 0.012
	Birch	31.22 ± 2.98	-0.032 ± 0.006	0.017 ± 0.004
	Black alder	22.62 ± 7.82	-0.022 ± 0.006	0.007 ± 0.004
	Average	28.96 ± 2.97	-0.022 ± 0.006	0.015 ± 0.004
Wet	Aspen	24.91 ± 2.09	0.016 ± 0.011	0.012 ± 0.007
	Birch	28.41 ± 3.41	0.009 ± 0.018	0.026 ± 0.01
	Black alder	30.27 ± 3.18	0.004 ± 0.007	0.013 ± 0.003
	Average	27.87 ± 1.69	0.009 ± 0.007	0.016 ± 0.004

Annualized gas fluxes based on the study results are summarized in Table **3**. CO_2 emissions from drained soils in average is 6.81 ± 11.22 tons CO_2 ha^{-1} yr^{-1} and from wet soils – 6.48 ± 5.45 tons CO_2 ha^{-1} yr^{-1}. The highest species related uncertainty, which is also affecting total uncertainty, is found in black alder stands with drained soils. The reason for that may be water regime and more extreme fluctuations of groundwater level, which could be catch by continuous measurements. The annual CH_4 emissions in drained soils in average are -2.38 ± 11.04 kg CH_4 ha^{-1} yr^{-1} (-59.6 ± 276.08 kg CH_4-CO_2 eq ha^{-1} yr^{-1}) and in wet soils 1.29 ± 14.07 kg CH_4 ha^{-1} yr^{-1} (32.35 ± 351.82kg CH_4-CO_2 eq ha^{-1} yr^{-1}). Although the uncertainty of the estimated annual CH_4 fluxes is high there is clear trend of reduction of the emissions in drained soils. The annual N_2O emissions in drained soils in average are 2.30 ± 9.31 kg N_2O ha^{-1} yr^{-1} (686.47 ± 2774.88 kg N_2O -CO_2 eq ha^{-1} yr^{-1}) and in wet soils 2.27 ± 9.54 kg CH_4 ha^{-1} yr^{-1} (677.68 ± 2842.31 kg N_2O -CO_2 eq ha^{-1} yr^{-1}). The study results point out that N_2O can be a considerable source of emissions in drained and wet mineral soils; however, further studies are necessary to reduce uncertainty and to identify factors promoting the emissions.

Table 3. Average annual GHG fluxes depending on moisture regime and dominant species.

Moisture regime	Dominant species	Total emissions per year per ha	Total emissions per year per ha in CO_2 equivalents
CO_2 emissions		tons CO_2 ha^{-1} yr^{-1}	
Drained	Aspen	7.86 ± 2.57	
	Birch	6.96 ± 1.89	
	Black alder	5.52 ± 10.75	
Wet	Aspen	6.03 ± 1.86	
	Birch	6.15 ± 3.05	
	Black alder	7.03 ± 4.05	
CH_4 emissions		kg CH_4 ha^{-1} yr^{-1}	kg CH_4-CO_2 eq ha^{-1} yr^{-1}
Drained	Aspen	-1.74 ± 9.46	-43.58 ± 236.38
	Birch	-3.36 ± 4.3	-83.97 ± 107.51
	Black alder	-2.87 ± 3.85	-71.68 ± 96.36
Wet	Aspen	1.82 ± 6.7	45.53 ± 167.41
	Birch	3.74 ± 10.88	93.41 ± 272.02
	Black alder	0.49 ± 4.68	12.24 ± 117.08
N_2O emissions		kg N_2O ha^{-1} yr^{-1}	kg N_2O-CO_2 eq ha^{-1} yr^{-1}
Drained	Aspen	2.68 ± 8.39	798.09 ± 2499.35
	Birch	2.71 ± 2.58	808.48 ± 767.96
	Black alder	0.85 ± 3.26	254.02 ± 971.75
Wet	Aspen	1.64 ± 4.8	488.05 ± 1429.9
	Birch	4.57 ± 6.21	1362.26 ± 1849.85
	Black alder	1.8 ± 2.55	537.48 ± 759.2

HR is increasing in summer months and drops down during autumn months. The pattern of the emission rate is similar in drained and wet soils; however, in wet soils the increase of the HR in spring falls behind the increase in drained soils (Figure **2**). CH_4 emissions are increasing in spring months, especially in wet soils, when groundwater level is high. During summer months CH_4 emissions are negative, except one month in wet sample plots. This is associated with CH_4 extremes in one of the black alder plots. Similarly, N_2O emissions are increasing during the first half of the year, and are negligible during summer month, which also means that N_2O emissions are not correlating with HR.

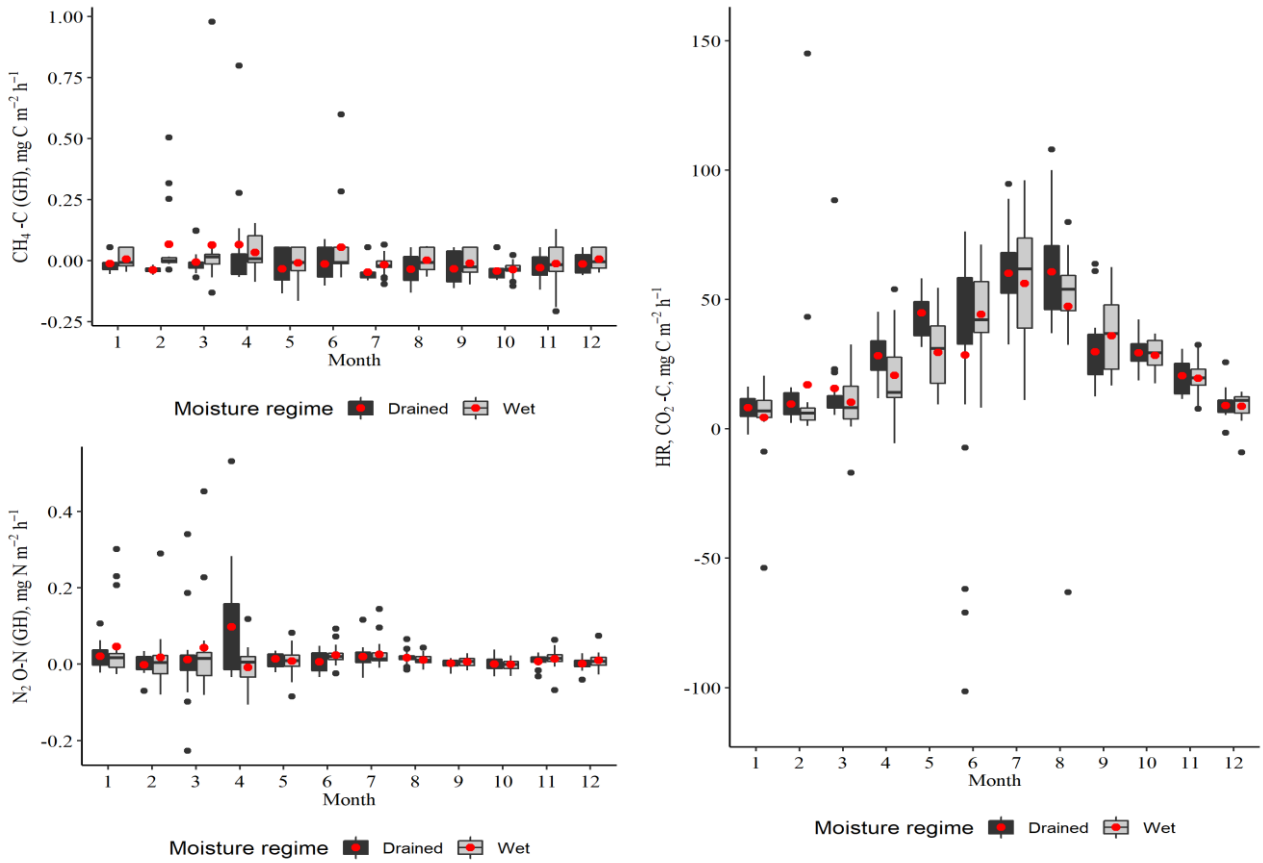

Figure 2. Monthly fluctuations of HR and CH_4 and N_2O fluxes in drained and wet sites. In the box plots, the medians are shown by bold lines, the mean values are shown by red point, the boxes correspond to the lower and upper quartiles, the whiskers show the minimal and maximal values (within 150% of the interquartile range from the median), and the black dots show outliers of the datasets.

Strong correlation was found between air temperature and HR, no significant difference in this trend was found between drained and wet soils (Figure **3**). No such correlation was found for CH_4 and N_2O emissions. Significant correlation was also found between CH_4 emissions and groundwater level, if groundwater level is above 70 cm (positive emissions if groundwater level is above 30 cm); R^2 of logarithmic regression is 0.32.

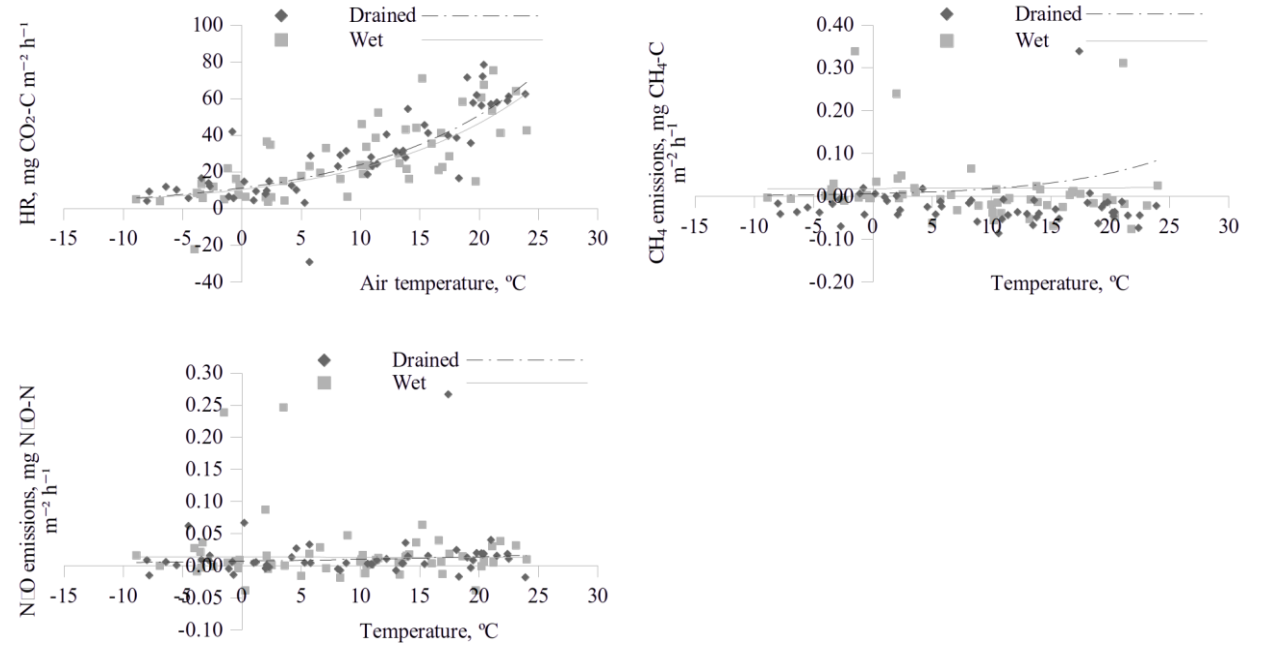

Figure 3. Relationships between HR, GC and air temperature.

According to recent studies implemented in Latvia HR values in nutrient rich birch and spruce stands equals to 13.48 ± 1.63 tons CO_2 ha^{-1} yr^{-1} in drained and to 12.87 ± 1.76 tons CO_2 ha^{-1} yr^{-1} (Butlers, Spalva, et al., 2022). This is about twice more

than the HR values in our study and close to the soil carbon input values reported in forest lands by other studies (Butlers, Lazdiņš, et al., 2022). Thus, the assumption applied in the national GHG inventory that drained and mineral soils are not a source of CO_2 may lead to underestimation of the emissions. Other study reported that the CH_4 emissions from nutrient-rich organic soils in Latvia are, respectively, -4.6 ± 1.3 and 134.1 ± 134.7 kg CH_4 ha^{-1} yr^{-1}, from drained and wet soils (Butlers et al., 2023). In our study we found values similar for mineral soils, however, no significant increase of the emissions are found in wet mineral soils. Further studies are necessary to identify the reasons of periodic extreme increase of CH_4 emissions, which is observed in wet organic, as well as in wet mineral soils. In our study we did not observed significantly higher N_2O emissions from wet soils, which were observed earlier by other study y (Butlers et al., 2023) in nutrient rich organic soils (respectively, 4.1 ± 1.4 kg and 1.7 ± 0.6 kg N_2O ha^{-1} yr^{-1}) from wet and drained soils). The estimated rate of N_2O emissions is relatively high and can be a significant source (0.55 mill. tons CO_2 eq if extrapolated to drained and wet mineral forest soils in Latvia); however, uncertainty of the estimate is high and further studies are necessary to increase accuracy of the N_2O emissions' projections.

CONCLUSIONS

The study results demonstrates that wet and drained nutrient-rich mineral forest soils in deciduous stands may be a source of CO_2 emissions at certain stand development stages, e.g., during the forest regeneration; however, carbon input with litter can compensate carbon losses. Increase of groundwater level above 30 cm is increasing CH_4 emissions to positive values; however, they are much smaller than the values reported for nutrient-rich wet organic forest soils. N_2O emissions from wet and drained mineral forest soils, despite small absolute values, can significantly increase the total GHG emissions (expressed as CO_2 equivalents) from forest lands. Further studies are necessary to reduce uncertainty of the N_2O and CH_4 emissions from mineral forest soils.

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