SOIL CARBON TURNOVER OF DRAINED AND NATURALLY WET MINERAL FOREST SOILS IN LATVIA

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Abstract. Assessment of changes in carbon (C) stocks in mineral soils typically relies on the steady-state C stock values, which are influenced by various long-term land-use and management scenarios. This conventional approach limits understanding of the short-term soil C balance, including in lands not subject to land-use or management changes. Additionally, the role of the soil moisture condition impact on the mineral soil C balance is not broadly studied. To enhance our understanding of the effects of the soil moisture on C balances of mineral soils, this research conducted soil CO_2 emission monitoring in forests with both drained and naturally wet mineral soils. The study was implemented across 18 forest sites with dominant species of aspen (*Populus tremula L*), birch (*Betula pendula Roth, Betula pubescens Ehrh.*), black alder (*Alnus glutinosa (L.) Gärtner*) and Scots pine (*Pinus sylvestris L.*). Emission monitoring was performed using the closed static opaque chamber method. Concurrent measurements of the soil temperature and the groundwater level depth were also conducted. Our research revealed that CO_2 emissions resulting from soil respiration in both naturally wet and drained soils showed no notable differences, indicating that the mineral soil moisture regime has a minimal impact on C outflows from these soils. This finding implies that the C balance in mineral soils is largely dictated by the influx of C from vegetation residues and litter. Thus, for the conservation or enhancement of C stocks in mineral soils, maintaining the soil moisture regime that optimizes the decomposition and accumulation of vegetation litter is essential.

Keywords: mineral soil, drained, naturally wet, CO_2 emissions.

Introduction

Soil carbon balance plays a key role in the global carbon (C) cycle in terrestrial ecosystems [1], influencing atmospheric CO_2 levels and thus, climate change dynamics. Forest ecosystems, covering a substantial portion of the earth's land surface, are significant C sinks, with their soil acting as a major pool of organic C. The balance between C input through litter and C output via soil respiration, determines the net soil C stock changes. In forests, main soil C input sources are litterfall, ground vegetation and root turnover [2], and soil C loss through CO_2 emissions is driven by soil organic matter decomposition mainly due to microbial activity [3].

Extensive research has found that organic soils can be significant emission sources [4], yet the emissions from mineral soils have received less attention, particularly through direct measurements. The dynamics of the C balance in mineral soils remains less explored, partly because assessments of the mineral soil C stock changes generally rely on measured steady state C stocks in mineral soil depending on land-use and management practices [5]. This approach provides limited understanding of short-term C turnover in mineral soils, including in areas with no land use changes. Moreover, the impact of the soil moisture regime on the mineral soil C balance is still poorly understood.

Of Latvia's entire forested land, around 2 million hectares, which constitute 60% of the total forest coverage, are situated on mineral soils. Within these territories, 16% are with naturally wet mineral soils which are either constantly or periodically saturated. In the rest of forest areas with mineral soil, the depth of the groundwater level (GWL) does not influence soil aeration.

Although it is expected that the soil moisture regime influences both its CO_2 respiration, which depends on soil aeration, and C input into the soil, affected by various types of vegetation, it is commonly assumed that in such lands, regardless of the soil moisture regime, the soil C stock remains constant - in equilibrium [5; 6]. However, meteorological conditions vary between different years, and the GWL level fluctuates depending on the air temperature and precipitation. Therefore, it can be anticipated that the C balance should also vary.

To gain a broader understanding of the impact of the soil moisture regime on its C balance, in this study, we conducted monitoring of CO_2 emissions by soil respiration in forest types with drained and naturally wet mineral soil. The acquired results on soil CO_2 emissions serve as an indicator of the expected soil C balance.

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Materials and methods

The study was conducted in 18 research sites across Latvia, from May 2022 to October 2023. The sites were in forest stands classified according to the national forest type typology as stands with drained nutrient-poor (*Callunosa mel., Vacciniosa mel.*) and nutrient-rich (*Myrtillosa mel., Mercurialiosa mel.*) mineral soil, as well as stands with naturally wet nutrient-poor (*Vaccinioso–sphagnosa, Myrtilloso–sphagnosa*) and nutrient-rich (*Myrtilloso–polytrichosa, Dryopteriosa*) mineral soil. Selected sites were dominated by aspen (*Populus tremula L*), birch (*Betula pendula Roth, Betula pubescens Ehrh*.), black alder (*Alnus glutinosa (L.) Gärtner*) or Scots pine (*Pinus sylvestris L.*).

Each site was visited every four weeks to conduct soil CO_2 emission measurements in three replicates. During a single measurement, four gas samples were collected at 10-minute intervals using the closed static opaque chamber method [7] and analyzed with a gas chromatograph Nexis GC-2030 (Shimadzu Corporation, Japan) [8]. Using the results of the gas concentration analyses and information about the sampling time, linear regression analysis was performed for each emission measurement to determine the regression slope, which characterizes the change in gas concentration over time in the chamber. The obtained slope, relative to the chamber area (0.1995 m^2) and volume (0.0655 m^3) information, was used to calculate the soil emissions (mg CO_2 C m^2 h^{-1}) using the ideal gas law equation. During measurements, vegetation and the soil surface were kept undisturbed, thus the measurements reflect the total soil respiration (R_{tot}), including soil heterotrophic and autotrophic respiration, and the autotrophic respiration of vegetation contained in the chamber head-space during the measurement.

To characterize R_{tot} affecting factors, the soil temperature at 10 cm depth and GWL depth measurements were simultaneously taken using perforated tubes installed vertically to a depth of 2 m in the soil. Before starting R_{tot} monitoring, soil samples were also collected from layers 0-10, 10-20, 20-40, and 40-70 cm in two replicates according to the international forest monitoring methodology [9]. Samples were tested in an ISO 17025 accredited laboratory for bulk density, pH, organic C, N, K, Ca and Mg content, using ISO standard methods [9].

Pearson correlation and third-order polynomial regression analysis were used to evaluate the relationships between R_{tot} and influencing factors. The significance of R_{tot} differences was assessed using a pairwise Wilcoxon rank sum test with $p = 0.05$ as the threshold for statistical significance. In the boxplots, the edges of the box represent the 25th and 75th percentiles, encapsulating the interquartile range (IQR). Traditionally, the whiskers extend to the smallest and the largest values within 1.5 * IQR from the 25th and 75th percentiles, respectively. Black dots mark outliers. Red dots and a solid horizontal line indicate the average values of the data represented – mean and median, respectively.

Results and discussion

The variation in GWL depth across study sites with naturally wet and drained soils has been distinct, as indicated by the observation in Fig. 1 that the interquartile range of GWL variations in naturally wet and drained soils mostly does not overlap.

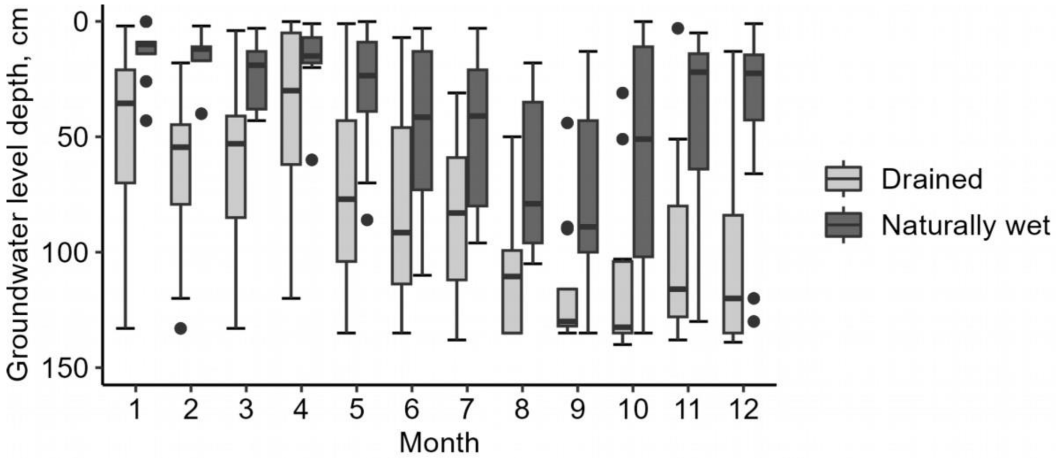

Fig. 1. **Groundwater level depth in the study sites**

In naturally wet soil sites, the GWL was considerably elevated only from January to April, a period when the soil temperature is low and, consequently, microbial activity is reduced as well as soil respiration. In drained soil sites, the average GWL depth was 101 ± 22 cm, compared to 46 ± 17 cm in naturally wet soil sites. Thus, GWL in sites with naturally wet soil was considerably lower compared to previous study observations in areas with undrained organic soil where the mean GWL was often higher than 20 cm [10].

Compared to naturally wet soils, it is observed that drained soil emissions tend to have greater variation (Fig. 2). Nonetheless, this difference is not significant, with the emission variation coefficient for drained soils being 78 ± 25%, and for naturally wet soils 74 ± 16%. The mean measured instantaneous R_{tot} emissions in sites with drained soils range from 62 to 94 mg CO_2-C·m^{-2}·h^{-1} (mean 75 ± 7 mg CO_2-C·m^{-2}·h^{-1}), while for naturally wet soils sites, they range from 47 to 104 mg CO_2-C·m^{-2}·h^{-1} (mean 75 ± 13 mg CO_2-C·m^{-2}·h^{-1}).

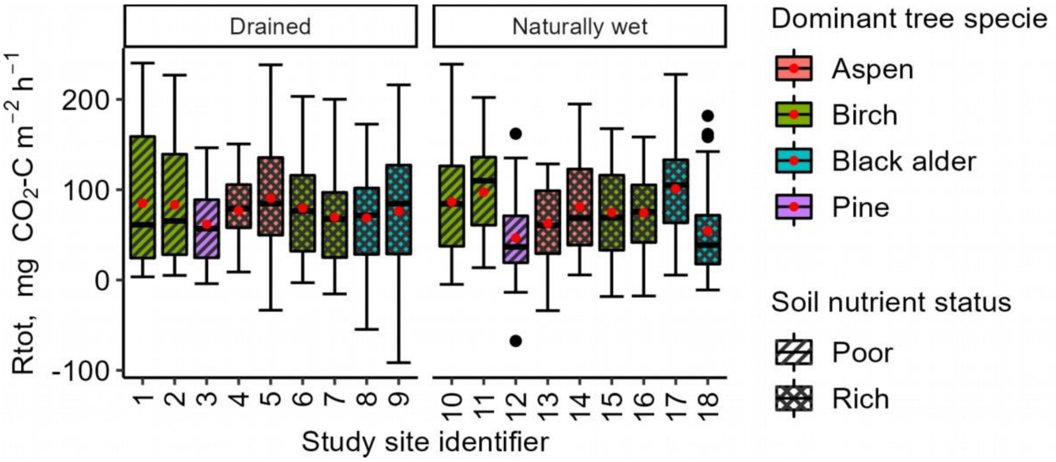

Fig. 2. **Variation of soil total respiration in the study sites**

When combining the R_{tot} measurement results based on the soil nutrient status categories or the dominant tree species, significant differences are mostly not observed (Table 1). Significant differences ($p < 0.05$) in R_{tot} were only observed in birch and pine stands with naturally wet soil, with mean emissions of 94 ± 12 and 47 ± 18 mg CO_2-C·m^{-2}·h^{-1}, respectively, and between pine stands with naturally wet soil and aspen stands with drained soil (86 ± 11 mg CO_2-C·m^{-2}·h^{-1}). Primarily, the observed similar R_{tot} emissions could be explained by the lack of a considerable correlation between the mean GWL depth and the mean R_{tot} in the study sites ($r = 0.20$). In addition, except for pine stands with naturally wet soil, the mean GWL level in the stands with naturally wet soil has mostly been below 30 cm, which is considered the threshold value for soil to be regarded as deeply drained [5]. Accordingly, the soils classified have been fairly aerated, hence, R_{tot} could have behaved similarly as in drained soils.

Table 1

Mean measured soil total respiration and groundwater level depth

Moisture regime	Soil nutrient status	Dominant tree species	R_{tot}, mg CO_2-C·m^{-2}·h^{-1}	Significance letters	Groundwater level depth, cm
Drained	Poor	Birch	83 ± 14	Ab	76 ± 36
		Pine	62 ± 11	ab	78 ± 50
	Rich	Aspen	86 ± 11	a	120 ± 21
		Birch	75 ± 10	ab	94 ± 33
		Black alder	66 ± 13	ab	125 ± 21
Naturally wet	Poor	Birch	94 ± 12	a	52 ± 41
		Pine	47 ± 18	b	21 ± 14
	Rich	Aspen	72 ± 9	ab	57 ± 49
		Birch	71 ± 15	ab	37 ± 31
		Black alder	80 ± 11	ab	42 ± 41

Although the mean measured R_{tot} in the study sites do not significantly differ from each other, a correlation between R_{tot} and the soil SOC content is observed. The correlation coefficient between SOC content and R_{tot} for different soil layers in drained soils is relatively consistent (mean $r = -0.45 \pm 0.12$), with the strongest correlation ($r = -0.61$) in the soil surface layer of 0-10 cm. The correlation in naturally wet soils is weak and ranges from negative in the top layers to positive in the deeper layers, likely indicating impact of measurement uncertainty. The higher correlation in the soil surface layer can be explained by the wide range of SOC concentrations in this layer represented by the study sites – from 42 to 544 g $C \cdot kg^{-1}$ in drained soils and from 61 to 492 g $C \cdot kg^{-1}$ in naturally wet soils. However, such correlations should be considered in a broader context, taking into account other soil parameters, as the soil bulk density ($r = 0.55$), pH ($r = 0.55$) and C:N ($r = -0.44$) content also show a weak to moderate correlation with R_{tot}. Therefore, it is possible that soil CO_2 emissions are determined more by the local conditions, such as vegetation, soil acidity, and the composition of organic matter, including its decomposition state, rather than merely the availability of SOC in the soil [11; 12].

The observation that the categories of drained and naturally wet soils did not affect R_{tot} is also indicated by the relationship between R_{tot} and the soil temperature depending on the moisture regime status – the regression curves overlap (Fig. 3). Although the overall relationship follows an exponential trend, the application of such a model for emission forecasting would risk overestimating emissions, as suggested by acquired polynomial models. As soil temperature approaches 20 ºC, emissions may even start to decrease. Likely because while the temperature determines microbial activity, soil moisture conditions like overly drained environment can be a limiting factor of soil CO_2 emission. Similar observations have been made in other studies [13].

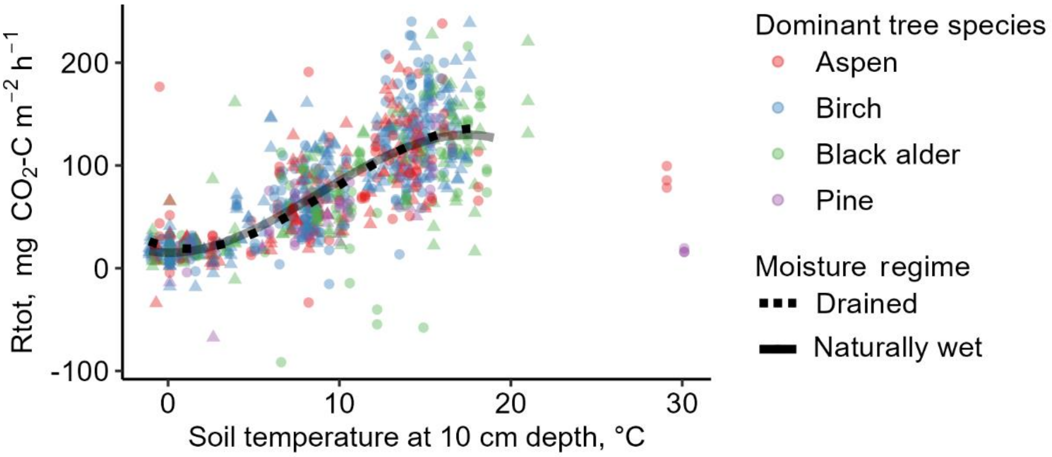

Fig. 3. **Relationship between the soil temperature and Rhet in drained and naturally wet sites:** triangle and round-shaped data points represent measurements in naturally wet and drained sites, respectively

Conclusions

1. The CO_2 emissions by soil total respiration in the study sites with both moist and drained soils did not significantly differ, indicating that the moisture regime of mineral soils did not impact the carbon losses from mineral soils. This suggests that the carbon balance in mineral soils is determined by the carbon input from vegetation litter, and to enhance the preservation or sink of mineral soil carbon stock, it is necessary to ensure soil moisture conditions that maximize the amount of vegetation litter.
2. Soil chemical and physical parameters have a weak to moderate correlation with the soil total respiration, but these relationships should be considered comprehensively. Although higher emissions may be observed from soils with lower SOC content, this is most likely explained by a complex interaction with other soil parameters that also correlate with soil emissions, such as the bulk density, pH, SOC, and N ratio.
3. In the study sites classified as moist according to the forest type classification, the mean groundwater level was mostly below 30 cm. Therefore, research should continue in sites where the mineral soil is more frequently saturated to gain a broader understanding of CO_2 emissions from naturally wet soils.

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Author contributions

Conceptualization, A.L.; methodology, A.L. and A.B.; software, A.B.; validation, D.P.; formal analysis, A.B..; investigation, Z.A.Z., R.N.M. and D.P.; data curation, D.P.; writing – original draft preparation, A.B.; writing – review and editing, A.B. and A.L.; visualization, A.B.; project administration, A.L.; funding acquisition, A.L. All authors have read and agreed to the published version of the manuscript.

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