RESULTS OF PILOT STUDY COMPARING GREENHOUSE GAS FLUXES FROM FORWARDING RUTS AND CONTROL AREA IN MOIST MINERAL SOIL AFTER CLEARFELLING

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Abstract. Forest operations involving heavy machinery often result in soil compaction and rut formation, significantly affecting soil physical properties, greenhouse gas (GHG) emissions, and forest productivity. This pilot study evaluates the impact of rut formation on the emissions of methane (CH_4-C), nitrous oxide (N_2O-N), and carbon dioxide (CO_2-C) from forest soils in managed ecosystems. Gas flux measurements were conducted at two types of sites: undisturbed control plots and ruts affected areas created by forestry machinery. Measurements were done during summer and autumn 2024 in two spruce felling sites in the central part of Latvia, 16 measurement points in total (8 points in ruts and 8 points in control area). Gas samples were collected from opaque 60 L chambers and analysed using gas chromatography. CO_2 flux was determined in the field using EGM5 analyser. Statistical analyses compared gas emission rates between these sites to assess the influence of soil disturbance on GHG dynamics. The results showed that CH_4-C emissions were substantially higher in ruts affected areas due to anaerobic conditions induced by soil compaction and water retention. Conversely, N_2O-N emissions were higher in control plots, likely due to better aeration promoting nitrification and denitrification processes. CO_2-C emissions showed minor differences, suggesting limited microbial respiration in compacted soils. These findings highlight the significant environmental impact of rut formation, emphasizing the need for sustainable forest management practices that mitigate soil disturbances, reduce GHG emissions, and enhance ecosystem resilience. This study also highlights the necessity of comprehensive study to evaluate long term effect of rut formation in moist mineral soils and to elaborate activity data for a stand- and national-wise assessment of GHG outflow due to ruts formation.

Keywords: ruts; greenhouse gas; moist mineral soil; forest; harvesting.

Introduction

Ruts and soil compaction are significant concerns in forest operations due to their detrimental effects on soil health, water dynamics, and forest productivity. The formation of ruts – depressions created by the repeated passage of heavy machinery – leads to soil compaction, which in turn alters the soil physical and biological properties [1; 2]. The formation of ruts is influenced by several factors, including soil moisture content, soil type, and the frequency of machine passes. Uusitalo et al. (2020) found that in fine-grained boreal soils, rut depth caused by an 8-wheeled forwarder was best predicted by soil moisture content, cumulative mass of machine passes, bulk density, and thickness of the humus layer [3]. Their study emphasizes the importance of soil moisture, especially when it exceeds 80% saturation, in increasing the risk of rutting. Similarly, Marra et al. (2021) assessed rutting and soil compaction caused by skidding and forwarding operations [4]. They observed that the direction of extraction did not significantly affect soil damage severity during forwarding on a 25% slope. However, downhill skidding was preferable to uphill skidding to reduce soil compaction. Their findings highlight the role of operational techniques in mitigating soil disturbances.

Soil compaction resulting from rut formation leads to reduced pore space, limiting air and water infiltration. This can adversely affect root growth, microbial activity, and overall soil health. Nawaz et al. (2012) reviewed the impact of soil compaction on chemical properties, soil fauna, and plant growth, noting that compaction affects both topsoil and subsoil layers, leading to decreased aeration and increased soil strength [5].

Forest logging operations can significantly affect soil greenhouse gas (GHG) emissions. Rut formation due to use of heavy machinery compacts soil, reducing CO_2 efflux and increasing CH_4 emissions [6; 7]. Soil type, moisture conditions and traffic intensity are key factors in rut formation [8; 9]. Compaction reduces macropore volume and increases water-filled pore space, leading to elevated N_2O emissions and decreased CH_4 consumption [10]. Long-term logging and harvesting cycles result in a decrease in soil organic carbon (SOC) in the mineral soil [11].

The primary aim of this study is to assess whether rut formation in moist mineral soils significantly alters GHG fluxes, particularly emissions of CH_4, N_2O, and CO_2. Given that moist mineral soils are generally considered minor sources of GHGs, our study provides empirical evidence on how soil

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disturbance from forestry operations may modify emission dynamics. While previous studies have explored the effects of soil compaction on GHG fluxes, limited research has quantified the specific impact of rut formation in moist mineral soils. This study addresses this gap by providing statistical evidence of these effects.

Materials and methods

The study was implemented in two mature spruce stands (Table 1) harvested as clear-fellings in summer 2023. Measurement points were set up in areas with continuous deep (20 cm or more) ruts. Control measurement points were set up in the area between strip roads, 4-5 m from the measurement points in ruts. Soil type in all areas is Podzolic Gley (Pzg). From time to time the area suffered from exceeding surface water inflow due to precipitation.

Table 1

Location of study sites

Plot ID	Type	Subplot	Unique ID	WGS84 coordinates	
				X	Y
LVMCA_R5	Control	A	80-09-07-610-260 11-0	56.72704	24.08938
LVMCA_R5	Control	B	80-09-07-610-260 10-0	56.7274	24.08985
LVMCA_R5	Ruts	A	80-09-07-610-260 11-0	56.72704	24.08938
LVMCA_R5	Ruts	B	80-09-07-610-260 10-0	56.7274	24.08985
LVMCA_R6	Control	A	80-09-07-610-260 11-0	56.72779	24.09095
LVMCA_R6	Control	B	80-09-07-610-260 10-0	56.72813	24.09089
LVMCA_R6	Ruts	A	80-09-07-610-260 11-0	56.72779	24.09095
LVMCA_R6	Ruts	B	80-09-07-610-260 10-0	56.72813	24.09089

Several measurement programs were implemented in all plots, including: (1) manual measurement of groundwater level; (2) greenhouse gas (CH_4 and N_2O) sampling for gas chromatography (GC) analyses (2 permanent collars in every location) and heterotrophic respiration measurements using EGM5 analyser (3 measurement points in every location); (3) soil temperature measurements at 10 cm depth during site visits; (4) periodic air temperature measurement; (5) topsoil moisture around the measurement sites. In addition, pH, electric conductivity – EC (μS cm^{-1}), redoks potential – ORP (mV), O_2 content (%) was determined in water collected from ground wells.

Measurement plots were visited once per month for 5 months period, from 24.07.2024 to 22.10.2024. Soil heterotrophic respiration was measurement with EGM5 spectrometer using a non-transparent chamber with above-ground volume of 0.023 m^3 (diameter 31.5 cm, height 30.0 cm). Measurement of heterotrophic respiration continued for 180 seconds, 3 repetitions in every location, chambers were flushed before every measurement. CH_4 and N_2O measurements were continued during the whole measurement period (5 sample sets per sites were acquired). After arrival to the plot, chambers were flushed and located over permanently installed collars (2 collars per measurement point). A 100 cm^3 air samples were collected in grass bottles every 10 min. during the 30 min. period (4 samples in a series), representing change of gas content in the chamber. Volume of the chamber is 0.0655 m^3 (bottom diameter 50 cm, top diameter 42.5 cm, height 39,5 cm). CH_4, N_2O and CO_2 were determined in collected samples in the laboratory using GC technology. Water wells were emptied before collection of water samples to acquire fresh samples for analyses. *Gasfluxes* module from CRAN package of R software suite [12] was used to calculate heterotrophic respiration, beginning of the measurement period was automatically trimmed to reach the highest coefficient of correlation (usually 30 sec. at the beginning of the measurement period).

Spreadsheet application and following formula were used to calculated GHG fluxes in GC data. Only CO_2 concentration change measurements that exhibited a coefficient of determination (R^2) ≥ 0.95 in the linear regression analysis were included in the GHG flux calculations. This threshold was applied to ensure data quality and to exclude measurements with poor linearity, which could introduce errors in flux estimation. No other outliers, e.g. in case of very high CH_4 outputs, were excluded following to recommendation in the IPCC guidelines [13]. The applied CO_2 equivalent of CH_4 is 28 and of N_2O – 265 [14].

$$CO_2 - C(N_2O - N, CH_4 - C)[\mu gC(N)m^{-2}h^{-1}] = \frac{M[gmol^{-1}] * P[Pa] * V[m^3] * \delta v[ppm(v)]}{R[m^3PaK^{-1}mol^{-1}] * T[K] * A[m^2] * ppm} \quad (1)$$

P – 101300 Pa;
R – 8.3143 m^3 Pa K^{-1} mol^{-1};
V – 0.0655 m^3 and 0.023 m^3;
A – 0.19625 m^2 and 0,076 m^2;
M CO_2 – 44.01 g mol^{-1}; M CH_4 – 16.04 g mol^{-1}; M N_2O – 44.01 g mol^{-1}.

The average fluxes were calculated for every measurement point and conditions (ruts or control). Further splitting of conditions is performed due to limited number of repetitions. To compare mean values between ruts and control plots, we used independent samples t-tests to determine whether the differences in CH_4-C, N_2O-N, and CO_2-C fluxes were statistically significant. Correlation analysis was performed using Pearson's correlation coefficient to evaluate relationships between GHG fluxes and environmental variables such as soil moisture, air temperature, and groundwater level. Additionally, linear regression models were applied to examine how CO_2 fluxes were influenced by the air temperature and groundwater level.

Results and discussion

The results of measurements of the environmental variables are summarized in Table 2, and grouped statistics of GHG and soil respiration measurements are provided in Table 3.

Table 2

Grouped statistics of environmental variable measurement results

Data	Average	Minimal	Maximal	Std
Groundwater level, cm	148	87	200	34.9
Air temperature, °C	19.5	12.2	26.5	4.5
Soil temperature, °C	14.2	8.7	18.3	3.3
Soil moisture, %	42	29	87	19
pH	5.42	4.73	6.39	0.57
EC, µS cm^{-1}	28	14	44	14
ORP, mV	195	17	333	138
O_2 conc., %	64	48	89	16

Table 3

Grouped statistics of GHG measurement results

Type	CH_4-C, µg m^{-2} h^{-1}				N_2O-N, µg m^{-2} h^{-1}				Soil respiration CO_2-C, mg m^{-2} h^{-1}			
	mean	std	max	count	mean	std	max	count	mean	std	max	count
Control	4.25	217.79	520.65	16	43.18	65.74	174.29	16	86.80	68.95	206.04	16
Ruts	495.78	511.81	1641.97	16	18.49	46.68	172.43	16	69.01	95.75	258.48	16

The statistical analysis reveals notable differences in GHG emissions between rut-affected and control areas. Methane emissions in rutted areas were significantly higher than in control areas ($t = -3.53$, $p = 0.002$), indicating that soil compaction and water retention create anaerobic conditions that promote methanogenesis. This finding aligns with earlier research showing increased CH_4 emissions from waterlogged organic soils in forestry sites. The CH_4 emissions are not correlating with the groundwater level, pointing out that the soil compaction creates anaerobic conditions in soil even if groundwater is at 2 m depth.

In contrast, nitrous oxide (N_2O) emissions showed no significant difference between the two types of sites ($t = 1.22$, $p = 0.231$). This result suggests that both soil types may experience variable oxygen availability, which affects N_2O production through nitrification and denitrification processes. Similar trends were reported by studies in peatland forests where fluctuating water tables led to inconsistent N_2O emissions.

The lack of significant difference in CO_2 emissions (heterotrophic respiration of HR in Figure 1) between rutted and control areas ($t = 0.60$, $p = 0.551$) suggests that soil compaction may suppress microbial respiration, counteracting the expected increase in decomposition from exposed organic material. However, CO_2 emissions correlated negatively with the soil moisture ($r = -0.56$, $p < 0.001$) and air temperature ($r = -0.49$, $p = 0.004$), showing that drier and warmer conditions promote greater respiration rates. Notably that harvesting residues are loaded into strip roads in the studied sites, therefore, the upper soil layer in ruts consists of mixture of litter, harvesting residues and soil. Normally in such conditions we should expect significant increase of CO_2 emissions due to decomposition of organic matter, but in this case anaerobic conditions hampered decomposition of organic matter.

Figure 1 presents the distribution of CH_4-C, N_2O-N, and CO_2-C fluxes in rutted and control areas, illustrating the variability and statistical differences between the two site conditions. The box plots reveal a substantial increase in CH_4-C emissions in rutted areas compared to control sites, with a wide range of values indicating the presence of localized anaerobic hotspots. The median CH_4 flux in rutted soils is significantly higher than in control areas, confirming that soil compaction and increased water retention create favourable conditions for methanogenesis. The variability in CH_4 emissions further suggests that methane production is not uniformly distributed but influenced by microsite-specific conditions such as small-scale variations in soil aeration and organic matter decomposition.

In contrast, N_2O-N emissions do not show a consistent increase in rutted areas, as reflected in the overlapping interquartile ranges between the site types. This suggests that oxygen availability and denitrification dynamics vary across locations, likely driven by differences in soil structure and moisture retention rather than a uniform effect of rut formation. The observed variability aligns with the lack of significant correlation between N_2O fluxes and environmental variables, indicating that localized factors, such as microbial community composition and nitrogen availability, may play a dominant role in controlling emissions.

CO_2-C emissions exhibit a moderate difference between rutted and control areas, with control plots generally showing slightly higher median respiration rates. This pattern suggests that soil compaction in ruts may suppress microbial respiration by limiting oxygen diffusion and root activity, counteracting the expected increase in CO_2 emissions from organic matter decomposition. The negative correlation observed between CO_2 emissions and soil moisture further supports this interpretation, as drier conditions likely enhance aerobic microbial activity, whereas waterlogged conditions reduce oxygen availability and restrict CO_2 production.

The results depicted in Figure 1 highlight the differential impact of rut formation on GHG fluxes, with methane emissions showing the most pronounced response to soil disturbance. These findings underscore the importance of considering micro-scale soil conditions when assessing GHG emissions from forestry operations and emphasize the need for further research into the long-term effects of rut formation on soil carbon dynamics. Interestingly, CH_4 emissions showed no significant correlations with environmental variables like the soil moisture ($r = 0.04$, $p = 0.819$) or soil temperature ($r = 0.13$, $p = 0.495$), suggesting that CH_4 fluxes are likely driven by localized anaerobic hotspots rather than large-scale environmental gradients. This pattern supports findings from boreal forests, where methane-producing microbes thrive in isolated wet patches.

The results of this study prove the environmental impacts of rut formation caused by forest operations, with a focus on GHG emissions in organic soils. While methane emissions were notably higher in rut-affected soils, the response of nitrous oxide and carbon dioxide emissions appeared more complex. These findings align with prior research showing that soil compaction alters gas flux dynamics through changes in soil aeration, water retention, and microbial activity.

Previous studies have reported similar increases in CH_4 emissions in waterlogged and compacted organic soils due to restricted oxygen diffusion, creating anaerobic microsites that favour methanogenesis [15]. However, contrasting studies in agricultural soils suggest that methane oxidation can be suppressed in compacted soils, further amplifying CH_4 release. The lack of correlation between CH_4 emissions and environmental variables such as the soil temperature and moisture indicates that local-scale factors, such as microtopography and root decay, might be more critical in methane production regulation [16]. Nitrous oxide emissions showed no significant difference between rut-affected and control soils, contrasting with findings from managed peatlands where soil compaction consistently elevates N_2O emissions due to denitrification processes [17].

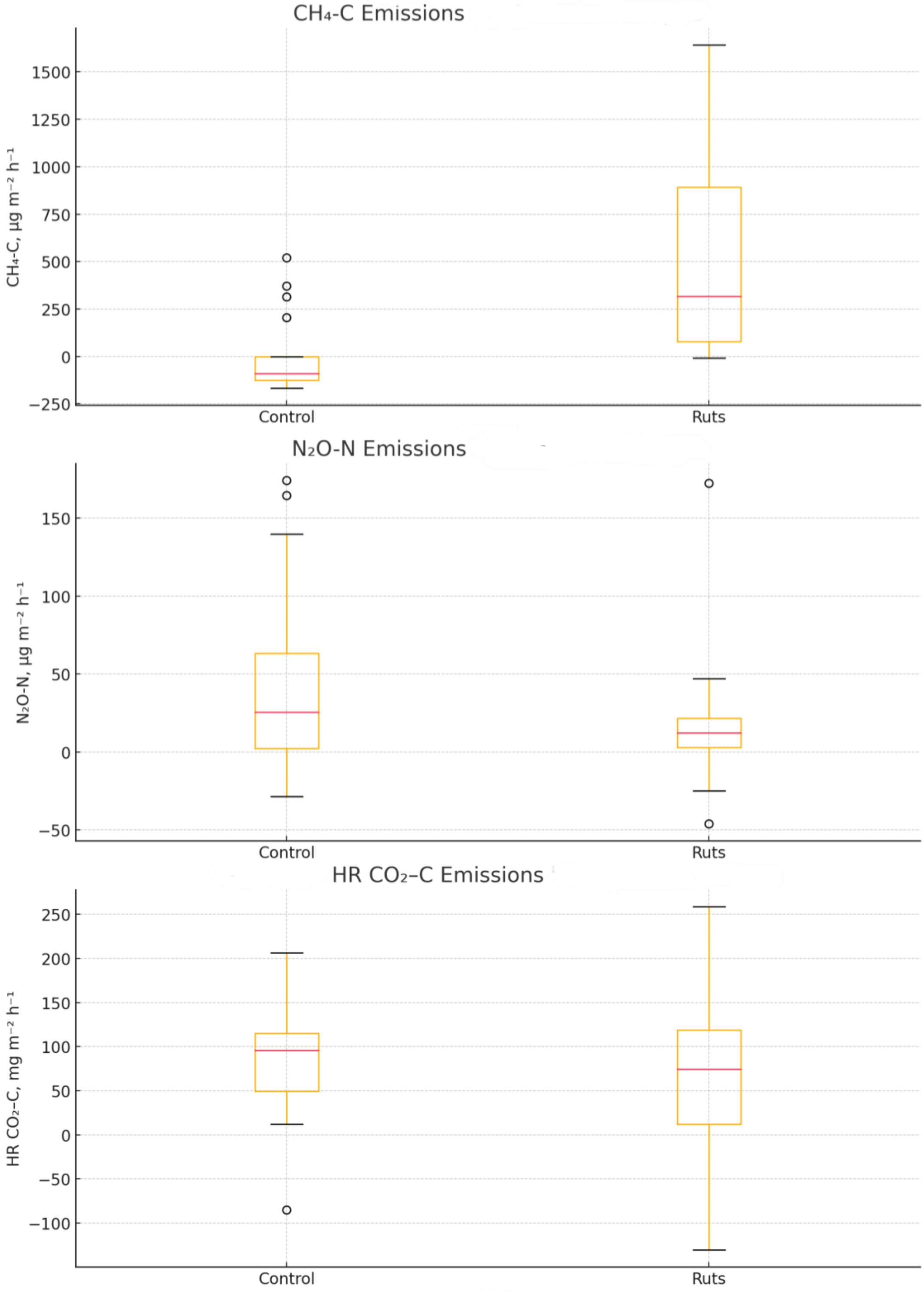

Fig. 1. **Comparison of greenhouse gas fluxes (CH4-C, N_2O-N, and CO_2-C) between rutted and control areas in moist mineral soils**

This discrepancy could stem from site-specific conditions, including the vegetation cover, which can influence nitrogen cycling through root exudation and microbial community shifts. The lack of significant differences in CO_2 emissions could result from two counteracting processes: reduced root respiration in compacted soils and enhanced organic matter decomposition from exposed soil layers.

This dual mechanism is supported by [18], who found that while compaction reduced respiration, carbon loss through surface litter decomposition persisted.

These findings underscore the need for high-resolution spatial and temporal data in national GHG inventories. The Intergovernmental Panel on Climate Change (IPCC) has emphasized that uncertainties in GHG emissions from forestry operations remain high due to limited data on rut formation and soil compaction effects [19]. The study emphasizes the necessity of incorporating the effect of logging operations into the National GHG inventory system, further elaboration on relationships between the GHG fluxes and elaboration of the system for gathering activity data for the GHG assessments. Comprehensive monitoring programs, including ground-based measurements and remote sensing, would improve the accuracy of national emission estimates and inform climate mitigation policies in forestry and land management sectors.

Conclusions

1. This study demonstrates that rut formation in moist mineral soils significantly increases CH4 emissions due to anaerobic conditions while having a more complex effect on CO2 fluxes. These findings highlight the need to incorporate soil disturbance effects into national GHG inventories.
2. N2O emissions exhibited high variability, indicating site-specific denitrification dynamics influenced by fluctuating oxygen availability. The lack of significant correlation with environmental variables suggests that localized soil conditions, rather than broader climatic factors, are the primary drivers of N2O fluxes in rutted and control areas.
3. The strong correlations between CO_2 emissions and the soil moisture and air temperature emphasize the crucial role of climatic conditions in regulating soil respiration. In contrast, methane emissions remained unaffected by these factors, indicating the dominance of localized anaerobic hotspots in rutted soils. This finding highlights the significant impact of rut formation on CH_4 fluxes, demonstrating that soil compaction can create persistent methane-emitting microsites, independent of broader environmental conditions.
4. This study underscores the need for high-resolution, site-specific activity data to accurately quantify rut-induced GHG emissions and ensure their proper integration into national greenhouse gas inventories, thereby improving the precision of forestry-related emission estimates.
5. Future research should investigate the long-term impacts of rut formation on carbon stock changes, seasonal variations in GHG flux dynamics, and the development of mitigation strategies to minimize the environmental footprint of forest harvesting operations.

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Author contributions

Conceptualization, A.L.; methodology, A.L. and A.B.; validation, A.B. and D.P.; formal analysis, A.L.; data curation, D.P.; writing – original draft preparation, A.L.; writing – review and editing, A.L. and A.B.; visualization, A.L.; 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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