SHORT TERM EFFECT OF CLEAR-FELLING ON GREENHOUSE GAS EMISSIONS FROM NATURALLY WET ORGANIC AND MINERAL SOILS

Emils Martins Upenieks, Martins Vanags Duka, Aldis Butlers, Andis Lazdins
Latvian State Forest Research Institute "Silava", Latvia
emilsmartinsupenieks@gmail.com, martinsvanagsduka@gmail.com,
aldis.butlers@silava.lv, andis.lazdins@silava.lv

Abstract. Clear-felling, a predominant method for forest regeneration in areas with wet soils, has profound implications for greenhouse gas (GHG) emissions. This technique, by removing the forest cover, exposes the soil to increased sunlight, which can raise soil temperatures and enhance decomposition rates. Consequently, this process can significantly boost the emissions of carbon dioxide (CO_2) and nitrous oxide (N_2O). The absence of canopy cover also impacts soil moisture due to the decrease in plant transpiration, potentially leading to conditions that promote anaerobic processes in wet soils, thereby increasing methane (CH_4) emissions. We monitored soil GHG (CO_2, CH_4, N_2O) emissions in clear-felling sites before and after the harvesting. The study findings reveal a notable increase in CO_2 emissions following the harvest, with an average rise of 226 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$, representing a 120% increase. The CO_2 emissions from mineral and organic soils did not significantly differ. While clear-felling had minimal impact on CH_4 emissions from mineral soils, emissions from organic soils saw approximately a sixfold increase. Meanwhile, N_2O emissions remained largely unchanged in both soil types post-clear-felling. When converted to CO_2 equivalents, the emission results reveal a significant elevation in GHG emissions post-clear-felling, particularly from organic soils which witnessed a near threefold increase, whereas emissions from mineral soils roughly doubled. The study results highlight the implications of even-aged forest management strategies on wet soil GHG emissions.

Keywords: mineral soil, organic soil, wet soil, greenhouse gas emissions.

Introduction

Forests play a crucial role in the global carbon cycle, acting as significant carbon sinks that mitigate the effects of greenhouse gases (GHGs) on climate change. However, not all forests contribute equally to carbon sink and GHG emissions. Forests established on organic soils, are known to be a substantial source of GHGs, primarily due to the high organic matter content that, under certain conditions, can lead to increased emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions. Research has primarily focused on drained organic soils [1]; however, it is known that naturally wet organic soils, characterized by the peat depths exceeding 30 cm, can also be a significant source of GHG emissions [2; 3]. Similarly, albeit to a less extent, wet mineral soils also contribute to GHG emissions [4], yet emissions from these soils have been even less frequently studied. Recent data from Latvia highlight the importance of understanding the GHG emission dynamics in these forest ecosystems to develop effective mitigation strategies.

Clear-felling (CF), is a prevalent forestry practice for regenerating forests, particularly those on wet soils. The removal of the forest canopy effects on the microclimate in soil and, subsequently, on GHG emissions. The exposure of soil to direct sunlight after CF raises the soil temperature and may accelerate organic matter decomposition, thereby enhancing CO_2 and N_2O emission. Additionally, the reduction in plant transpiration after CF alters the soil moisture content, creating waterlogged conditions that favour anaerobic processes, emitting more CH_4. Despite the recognized impact of CF on GHG emissions from forest soils [5], there is limited information for quantitative assessment and comparison of the GHG patterns in mineral and organic soil, as well as GHG mitigation potential of measures aimed at diminishing the negative effect of CF.

Addressing this knowledge gap, our study monitored GHG fluxes from naturally wet mineral and organic forest soil in Latvia around a year before and after clear felling.

Materials and methods

The research was carried out at 5 study sites across Latvia, from January to October 2023. The sites were in forest stands dominated by birch (*Betula pendula Roth, Betula pubescens Ehrh*.), Scots pine (*Pinus sylvestris L.*) or Norway spruce (*Picea abies (L.) H.Karst*.). Forest stands were recognized for their naturally wet soils, categorized under the national forest typology [6] into: nutrient-poor soils, both mineral (*Vaccinioso–sphagnosa, Myrtilloso–sphagnosa*) and organic (*Sphagnosa*); and nutrient-rich

soils, including mineral soil (*Myrtilloso–polytrichosa, Dryopteriosa*) and organic soil (*Caricoso–phragmitosa*).

Visits to each site occurred every four weeks, where CO_2, CH_4, and N_2O emission measurements were conducted in three to five replicates. In scope of each measurement, four gas samples were collected at intervals of 10 minutes utilizing the closed static opaque chamber technique [7] and subsequently analysed via gas chromatography [8]. The analysis of gas concentration and sampling time allowed for a linear regression analysis to determine the change in gas concentration over time, expressed through the regression slope. This slope, combined with the chamber specific area (0.1995 m^2) and volume (0.0655 m^3), facilitated the calculation of soil GHG emissions using the ideal gas law. These measurements were taken without disturbing the soil or vegetation, therefore CO_2 measurement results represent total soil respiration, including both heterotrophic and autotrophic respiration from the soil and autotrophic respiration vegetation within the chamber airspace. During GHG measurements, we measured the soil temperature at 10 cm depth using a ProCheck data logger with RT-1 temperature sensor, air temperature using a non-branded temperature logger, which was left in shade during the measurement campaign and the average temperature during gas sampling was used in calculation, and the groundwater level depth, which was measured using perforated tubes positioned vertically to a depth of 2 meters. Soil and air temperature sensors are factory calibrated.

Significance of emission differences was evaluated using the pairwise Wilcoxon rank sum test, setting a p-value of 0.05 as the threshold for statistical significance. Differences between regression models were examined through analysis of variance. CH_4 and N_2O emissions were converted to CO_2 equivalents using the global warming potentials of 28 and 265, respectively, as stated in the IPCC Fifth Assessment Report.

Results and discussion

Before CF, soil CO_2 emissions were 187 ± 38 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$ and did not significantly differ depending on the soil type or the dominant tree species (Fig. 1). After CF, CO_2 emissions significantly increased by 120% to 413 ± 127 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$. After CF, the largest increase in emissions was observed in birch stands with mineral soil. However, after CF, the assessed emissions from mineral soils (443 ± 268 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$) and organic soils (386 ± 137 mg $CO_2 \cdot m^{-2} \cdot h^{-1}$) did not significantly differ from each other. Typically, it is expected that after CF, due to the removal of the canopy, the soil is exposed to direct sunlight and, accordingly, warms up more than in sites with forest cover [9]. Since soil CO_2 emissions are primarily determined by soil temperature [10], higher soil emissions are also expected. However, this study did not identify soil warming as the reason for the significant increase in CO_2 emissions, as no significant difference was found between relationships of the atmospheric and soil temperature at a depth of 5 cm in sites before and after CF. The likely reason of such observation is that during the vegetation season, when temperature has the most impact on soil CO_2 emissions, soil warming in clear-cut sites is delayed by abundant vegetation. As it is estimated that ground vegetation biomass is significantly larger in clear-cuts than in forest stands [2].

The impact of CF on soil CH_4 emissions was ambiguous. Emissions from mineral soils before and after CF did not differ and averaged 34 ± 77 μg $CH_4 \cdot m^{-2} \cdot h^{-1}$ (Table 1). In contrast, emissions from organic soils increased due to CF, from 1.35 ± 2.26 to 61.86 ± 0.80 mg $CH_4 \cdot m^{-2} \cdot h^{-1}$. No reason was found for this increase in emissions. CH_4 emissions are primarily determined by the groundwater level, which correlates with the soil moisture [3]; however, the study did not observe an increase in groundwater levels after CF. The mean groundwater level in sites with mineral soil was 37 ± 26 cm, and with organic soil 14 ± 15 cm. Typically, the critical threshold for significant emission increase is a groundwater level of 30 cm [3; 4]. Interestingly, although the mean groundwater level depth in sites with organic soil before CF was 26 ± 24 cm, soil CH_4 emissions were insignificant.

It is generally assumed that soil N_2O emissions in sites with elevated groundwater levels are insignificant [11], and this was also the case in this study. The soil both emitted and ensured atmospheric N_2O removals. The mean measured emissions were characterized by high uncertainty, which did not allow for the identification of either soil type or CF impact on emission changes. The mean soil N_2O emissions in the study sites were 16 ± 12 μg $N_2O \cdot m^{-2} \cdot h^{-1}$.

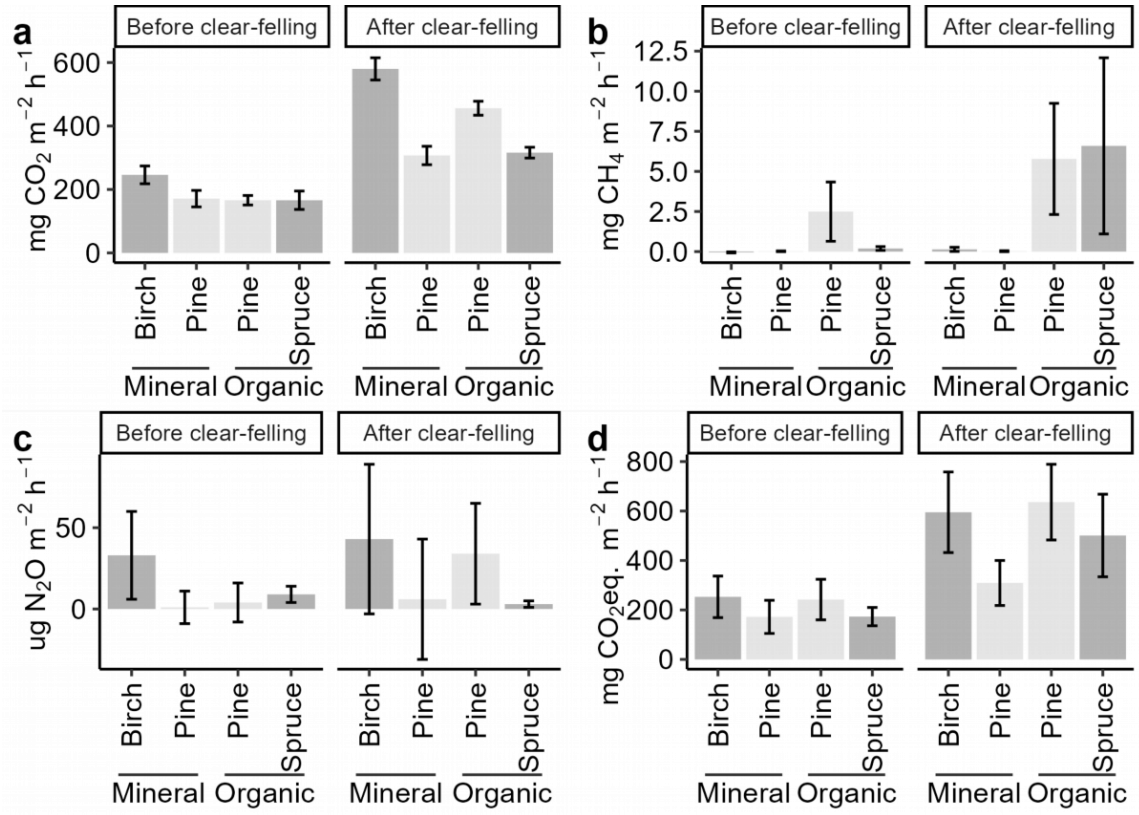

Fig. 1. **Mean measured soil GHG emissions:** a – CO_2 emissions; b – CH_4 emissions, c – N_2O emissions, d – GHG emissions in CO_2 equivalents; Dark grey bars – nutrient-rich soils; light grey bars – nutrient-poor soils

Comparing the measured GHG emissions expressed in CO_2 equivalents, a larger role of non-CO_2 emissions is evident in sites with organic soils. N_2O and CH_4 emissions from total GHG emissions constitute approximately 2%, while in the case of organic soils, the share is about 25%. As a result of CF, emissions from organic soils increased nearly threefold, rising from 208 ± 68 to 569 ± 131 mg CO_2 eq.$\cdot m^{-2} \cdot h^{-1}$. Meanwhile, the proportion of non-CO_2 emissions in the total GHG emissions due to CF doubled, increasing from 17 to 32%. GHG emissions from nutrient-poor organic soils were on average higher than those from nutrient-rich organic soils, but the differences were not significant. In the case of mineral soils, soil nutrient-status has a more pronounced impact on its GHG emissions, with nutrient-richer soils having emissions approximately 50 to 100% greater. Before CF, mineral soil mean emissions were 212 ± 80 mg CO_2 eq.$\cdot m^{-2} \cdot h^{-1}$, but after – mean 452 ± 131 mg CO_2 eq.$\cdot m^{-2} \cdot h^{-1}$. Consequently, GHG emissions from mineral soils approximately doubled after CF (Table 1).

Table 1

Summary of GHG measurement results

Soil type	Nutrient status	Dominant tree specie	CO_2, mg$\cdot m^{-2} \cdot h^{-1}$	CH_4, ug$\cdot m^{-2} \cdot h^{-1}$	N_2O, ug$\cdot m^{-2} \cdot h^{-1}$	CO_2 eq., mg$\cdot m^{-2} \cdot h^{-1}$	GWL, cm
Before clear-felling							
Mineral	Poor	Pine	171 ± 26	20 ± 21	1 ± 10	172 ± 67	21 ± 5
Mineral	Rich	Birch	246 ± 28	-50 ± 32	33 ± 27	253 ± 84	54 ± 10
Organic	Poor	Pine	166 ± 15	2492 ± 1847	4 ± 12	242 ± 82	10 ± 3
Organic	Rich	Spruce	166 ± 29	192 ± 120	9 ± 5	173 ± 37	15 ± 3
After clear-felling							
Mineral	Poor	Pine	307 ± 29[a]	26 ± 29	6 ± 37	309 ± 91	41 ± 12
Mineral	Rich	Birch	580 ± 35	140 ± 128	43 ± 46	595 ± 163	31 ± 5
Organic	Poor	Pine	456 ± 22	5779 ± 3466	34 ± 31	636 ± 153	6 ± 4
Organic	Rich	Spruce	316 ± 17	6593 ± 5492	3 ± 2	501 ± 167	15 ± 3

The clear-felling was carried out around the turn of the year, and upon resuming GHG emission measurements at the beginning of the year after the clear-felling, it was observed that the increase in emissions during this period was relatively the largest, compared to the same months before the clear-felling (Fig. 2). This could be related to the initial impact of soil disturbances [12], which gradually diminishes. Conversely, during the warm season, there was a larger increase in absolute emissions, facilitated by more favorable temperature and moisture conditions for mineralization of soil organic matter.

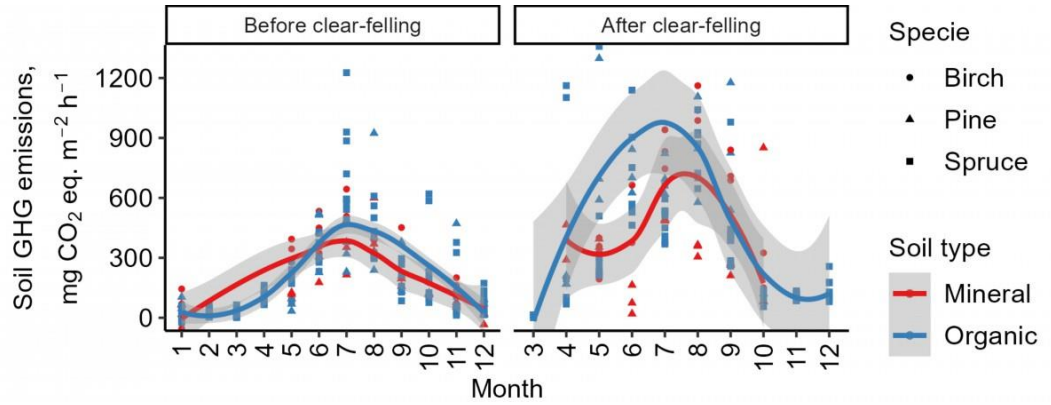

Fig. 2. **Soil GHG emission monthly dynamics before and after CF:** grey shading indicates 95% confidence intervals of the fitted lines

Conclusions

1. CO_2 emissions from mineral and organic soils did not significantly differ, but in both cases, after the clear-felling emissions significantly increased by the same rate.
2. In areas with mineral soil CH_4 emissions before and after clear-felling did not significantly differ; but in organic soils, there were a notable increase in emissions due to the clear-felling.
3. No impact of clear-felling on soil N_2O emissions was observed, and emissions were insignificant in mineral and organic soils.
4. After clear-felling, greenhouse gas emissions from mineral soils doubled, while those from organic soils tripled. The role of CH_4 and N_2O in the total greenhouse gas emissions from mineral soils is negligible, but in the case of organic soils, their proportion in the total emissions increased from 17 to 32% because of the clear-felling.
5. Groundwater level and soil temperature were not determining factors for the increase in soil emissions after clear-felling, as no significant changes in the soil temperature dynamics and mean groundwater level conditions were observed.

Acknowledgements

This research was conducted as part of the project “Carbon Cycle in Forest Ecosystems”, (Contract No. 5_5.9.1_0081_101_21_87). Part of field measurement data were acquired within the scope of the project “Evaluation of factors affecting greenhouse gas (GHG) emissions from surface of tree stems in deciduous forests with drained and wet soils” (No. LZP-2021/1-0137).

Author contributions

Conceptualization, A.L.; methodology, A.L. and A.B.; software, A.B.; validation, A.B.; formal analysis, A.L. and M.V.D.; investigation, E.M.U. and M.V.D.; data curation, A.B.; 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.

References

[1] Jauhiainen J. et al. Reviews and syntheses: Greenhouse gas exchange data from drained organic forest soils; a review of current approaches and recommendations for future research, Biogeosciences Discuss., no. July, 2019, pp. 1-26, DOI: 10.5194/bg-2019-261

[2] Butlers A., Lazdiņš A., Kalēja S., Bārdule A. Carbon Budget of Undrained and Drained Nutrient-Rich Organic Forest Soil, Forests, vol. 13, no. 11, 2022, p. 1790, DOI: 10.3390/f13111790
[3] Butlers A. et al. CH4 and N2O Emissions of Undrained and Drained Nutrient-Rich Organic Forest Soil, Forests, vol. 14, no. 7, 2023, DOI: 10.3390/f14071390
[4] Hiraishi T. et al., Eds. 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Switzerland: IPCC, 2014.
[5] Yamulki S. et al. Effects of clear-fell harvesting on soil CO2, CH4, and N2O fluxes in an upland Sitka spruce stand in England, Biogeosciences, vol. 18, no. 13, 2021, pp. 4227-4241, DOI: 10.5194/bg-18-4227-2021
[6] Bušs K. Forest Ecology and Typology. Rīga, Latvija: Zinātne, 1981.
[7] Pumpanen J. et al. Comparison of different chamber techniques for measuring soil CO 2 efflux, Agric. For. Meteorol., vol. 123, no. 3-4, 2004, pp. 159-176, DOI: 10.1016/j.agrformet.2003.12.001
[8] Loftfield N., Flessa H., Augustin J., Beese F. Automated Gas Chromatographic System for Rapid Analysis of the Atmospheric Trace Gases Methane, Carbon Dioxide, and Nitrous Oxide, J. Environ. Qual., vol. 26, no. 2, 1997, p. 560, DOI: 10.2134/jeq1997.00472425002600020030x
[9] Hashimoto S., Suzuki M. The impact of forest clear-cutting on soil temperature: A comparison between before and after cutting, and between clear-cut and control sites, J. For. Res., vol. 9, no. 2, 2004, pp. 125-132, DOI: 10.1007/s10310-003-0063-x
[10] Lloyd J., Taylor J. A. On the Temperature Dependence of Soil Respiration, Funct. Ecol., vol. 8, no. 3, 1994, p. 315, DOI: 10.2307/2389824
[11] Eggleston H. S., Buendia L., Miwa K., Ngara T., Tanabe K. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Japan, 2006.
[12] Siira-Pietikäinen A., Pietikäinen J., Fritze H., Haimi J. Short-term responses of soil decomposer communities to forest management: Clear felling versus alternative forest harvesting methods, Can. J. For. Res., vol. 31, no. 1, 2001, pp. 88-99, DOI: 10.1139/x00-148