CASE STUDY ON GHG FLUX CONTRASTS BETWEEN NON-DRAINED AND DRAINED PEATLAND FORESTS BEFORE AND AFTER REGENERATIVE FELLING

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Abstract. Greenhouse gas (GHG) flux responses to regenerative felling are strongly mediated by peatland hydrology, yet empirical contrasts between non-drained peatland forests and drained peatland forests remain underrepresented in operational forestry decision-making. This case study quantifies soil carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) fluxes in naturally wet peatland forests and drained peatland forests in Latvia, comparing mature stands with adjacent clear-felled areas (regenerative felling). Flux measurements were collected during 2021-2024, with regenerative felling implemented in 2022 at the studied sites. Mean soil GHG fluxes (as CO_2 equivalents, abbreviated as CO_2e) increased after felling in both site types, but the magnitude and gas structure differed markedly. In drained peatland forests, CO_2e increased by 32% from 232 to 307 mg $CO_2eq \cdot m^{-2} \cdot h^{-1}$ (20.3 to 26.9 t $CO_2eq \cdot ha^{-1} \cdot yr^{-1}$), whereas in non-drained peatland forests it increased by 120% from 234 to 514 mg $CO_2eq \cdot m^{-2} \cdot h^{-1}$ (20.5 to 45.0 t $CO_2eq \cdot ha^{-1} \cdot yr^{-1}$). The stronger response in non-drained peatland forests was primarily driven by CH_4, rising from 0.95 to 5.22 mg $CH_4 \cdot m^{-2} \cdot h^{-1}$, consistent with post-harvest water-table rise and enhanced anaerobic microsites reported in other temperate/boreal clear-fell studies. In contrast, the drained peatland forest response was comparatively moderate and more closely associated with CO_2-dominated decomposition dynamics typical of drained organic soils. These results indicate that regenerative felling can generate substantially higher short-term climate forcing on naturally wet peat soils than on drained peat soils, implying that harvest planning on peatlands should explicitly account for site hydrology and the CH_4-sensitive post-harvest period.

Keywords: greenhouse gas, non-drained, drained, organic soil, forest, harvesting.

Introduction

Peatland forests represent a globally significant carbon store because long-term peat accumulation is sustained by waterlogged conditions that suppress aerobic decomposition. Disturbances that deepen the aerated layer, particularly drainage for forestry, modify redox conditions, temperature sensitivity of decomposition, and plant-mediated gas transport, thereby altering the balance among CO_2 production, CH_4 oxidation and production, and N_2O formation pathways [1; 2]. In boreal and temperate regions, forestry drainage typically reduces CH_4 emissions by lowering the water table and enhancing CH_4 oxidation, while simultaneously increasing CO_2 emissions through accelerated peat mineralisation; N_2O responses are more variable and tend to be contingent on nutrient status and nitrogen availability [3-5].

Clear-felling (regenerative felling) introduces an additional perturbation by abruptly reducing canopy interception and evapotranspiration, increasing ground-level radiation, and modifying soil temperature and moisture regimes. These shifts can rapidly change the water-table position and the relative contribution of autotrophic versus heterotrophic respiration, while simultaneously reshaping microsite mosaics (hummocks, hollows, wheel ruts, ditches) that govern CH_4 and N_2O "hot spots" and "hot moments" [6; 7]. Eddy-covariance and chamber-based studies from Fennoscandian peatland forests consistently indicate that recently clear-felled drained peatlands can become strong short-term GHG sources, often dominated by CO_2, with CH_4 and N_2O contributions depending on post-harvest hydrology and surface-type distribution [6; 8].

Despite this growing evidence base, operational guidance remains limited for hemiboreal peatland forests where both naturally wet (non-drained) peatland forest types and drained peatland forests occur within the same management landscape, and where harvest scheduling and site preparation may interact with high interannual variability in precipitation and water-table dynamics. Moreover, synthesis efforts that support greenhouse-gas accounting (including IPCC Wetlands Supplement defaults) still acknowledge substantial uncertainty and site-type heterogeneity for organic forest soils, motivating case studies that explicitly contrast hydrological states and management transitions [1; 5].

The aim of this study was to quantify the contrast in soil-atmosphere GHG fluxes (CO_2, CH_4 and N_2O, expressed also as CO_2 equivalents) between non-drained peatland forests and drained peatland forests before and after regenerative felling, and to identify whether post-harvest responses differ in magnitude and gas composition in relation to the underlying hydrological regime.

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Materials and methods

The study was implemented in hemiboreal peatland forests in Latvia and included five permanent monitoring sites: three non-drained peatland forest sites and two drained peatland forest sites (Table 1). Repeated closed-chamber measurements were carried out from January 2021 to July 2024, covering both the pre-felling and post-felling phases. Regenerative felling was implemented in spring 2022, depending on site, which enabled a before-after comparison within each hydrological class. Post-felling management practices differed among sites and included soil preparation and subsequent planting. In the monitored sites, soil preparation was carried out in summer 2022, followed by planting in autumn 2022 or spring 2023, depending on site conditions and species selection. To avoid overextending the main text a site-level chronology of monitoring period, felling date, soil preparation and planting is provided in Supplementary Table S1. The design therefore represents a paired before-after case study of the short-term effect of regenerative felling under contrasting peatland hydrological conditions. The sites were revisited monthly during the monitoring period. The design represents a paired, management-transition case study in which fluxes are interpreted as responses to canopy removal superimposed on background variability driven by meteorology and site hydrology, consistent with established interpretations for post-harvest peatland-forest GHG dynamics [6].

Table 1

Study sites in hemiboreal peatland forests in Latvia

Identifier	Peat-forest class	Forest compartment	X coordinate	Y coordinate
LVMCA_R1	Non-drained	MPS Mežole, 218/4	57.27887	25.85441
LVMCA_R2	Non-drained	MPS Mežole, 108/4	57.311643	25.936089
LVMCA_R3	Non-drained	MPS Mežole, 218/4	57.311643	25.936089
LVMCA_R4	Drained	MPS Mežole, 193/27	57.268896	25.992854
LVMCA_R5	Drained	MPS Mežole, 51/11	57.337311	26.026355

Soil-atmosphere exchange of CO_2, CH_4 and N_2O was quantified in drained and non-drained peatland forests using the same non-steady-state closed-chamber method [9; 10]. Chambers were placed on permanently installed collars and closed for 30 min. Gas samples were collected immediately after chamber placement and subsequently every 10 min, resulting in four headspace samples per chamber closure (0, 10, 20 and 30 min). Samples were transferred into vacuumised 50 mL vials and analysed using a Shimadzu Nexis GC-230 gas chromatograph (Shimadzu USA Manufacturing, Inc., Canby, USA) equipped with an electron capture detector (ECD) and flame ionisation detector (FID). Thus, fluxes were determined from the slope of the concentration-time relationship in the chamber headspace rather than from single-point concentration measurements. This approach captures net soil-atmosphere exchange under field conditions and is widely used in peatland and forest GHG studies [10; 11].

For each chamber closure, instantaneous flux (mass per area per time) was calculated from the temporal change in gas concentration in the chamber headspace, scaled by chamber geometry and corrected for air temperature and pressure using the ideal gas law. Because four headspace samples were collected during each 30 min closure, flux estimation was based on the concentration-time slope derived from repeated measurements rather than on a simple start-end difference. A linear regression of concentration against time was used when concentration change was approximately linear, and the same calculation procedure was applied to all monitored sites. The resulting flux calculation is shown in Eq. (1). Where non-linearity is evident, Hutchinson-Mosier type approaches are recognised as preferable for bias reduction at high fluxes [11; 12].

The mass flux of gas i was calculated as:

$$F_i = \frac{dC_i}{dt} \cdot \frac{V}{A} \cdot \frac{P}{R \cdot T} \cdot M_i , \tag{1}$$

where dC_i/dt is the rate of concentration change in the chamber headspace, mol·mol^{-1}·s^{-1} or ppm·s^{-1}, converted consistently;
V – the chamber volume, m^3;
A – soil surface area covered, m^2;

P – air pressure, Pa;
T – air temperature, K;
R – the universal gas constant, 8.314 J·mol^{-1}·K^{-1};
M_i – molar mass of the gas; g·mol^{-1}.

Resulting fluxes F_i were expressed as mg·m^{-2}·h^{-1}.

To facilitate comparison among gases and with reporting conventions, fluxes were expressed as CO_2 equivalents (CO_2e) using 100-year global warming potentials (GWP100). In line with current practice, GWP100 values based on IPCC AR6 were applied ($CH_4 = 28$; $N_2O = 265$; mass-based), following the tabulated compilation used in GHG accounting frameworks [13]. CO_2e flux was computed as:

$$F_{CO_{2e}} = F_{CO_2} + GWP_{100,CH_4} \cdot F_{CH_4} + GWP_{100,N_2O} \cdot F_{N_2O}. \quad (2)$$

For indicative comparison with area-based annual reporting metrics, CO_2e fluxes (mg·m^{-2}·h^{-1}) were also annualised to emission factors (t CO_2eq·ha^{-1}·yr^{-1}) by:

$$EF_{ann} = F_{CO_{2e}} \cdot 8760 \cdot 10^4 \cdot 10^{-9}, \quad (3)$$

where 8760 – number of hours per year;
10^4 – converts m^2 to ha;
10^{-9} –converts mg to tonnes.

This annualisation provides a transparent scaling for comparative interpretation but does not replace seasonally resolved integration; post-harvest peatland fluxes can exhibit pronounced seasonality and short-lived peaks that bias annual estimates if sampling is sparse [6].

Fluxes were first calculated for each chamber closure and then aggregated by peatland forest class (non-drained or drained) and management status (before felling or after felling). CO_2, CH_4 and N_2O fluxes were subsequently converted to CO_2 equivalents and annualised according to Eq. (2) and Eq. (3). Site-specific monitoring chronology and the approximate number of monthly measurement campaigns are summarised in Supplementary Table S1. The article therefore includes mathematical processing at three levels: chamber-based flux determination from concentration-time slopes, conversion of gas-specific fluxes to CO_2 equivalents, and aggregation of repeated measurements into class-level descriptive means. Because the present contribution is a case study based on a limited number of monitored site objects with temporally dependent repeated observations, the results are presented as descriptive means rather than inferential statistics. Reliability is mainly affected by chamber deployment effects, regression model choice, spatial heterogeneity of peat microsites, and temporal representativeness of discrete measurements [10; 11]. Quantitative propagated error estimates were not available in the aggregated source dataset and are therefore not shown as numerical error bars.

Results and discussion

Across both peat-forest classes, regenerative felling shifted the soil GHG balance towards higher climate forcing, but the post-harvest response was strongly contingent on drainage state. When expressed as instantaneous flux rates (mg CO_2eq·m^{-2}·h^{-1}), the drained peatland forest increased from 232 to 307 mg CO_2eq·m^{-2}·h^{-1} after felling, whereas the non-drained peatland forest increased from 234 to 514 mg CO_2eq·m^{-2}·h^{-1}. The annualised emission-factor scaling yields the same pattern: from 20.3 to 26.9 t CO_2eq·ha^{-1}·yr^{-1} in drained peatland forest and from 20.5 to 45.0 t CO_2eq·ha^{-1}·yr^{-1} in non-drained peatland forest. In relative terms, this corresponds to a moderate increase (+32%) for drained sites, but a very strong increase (+119%) for non-drained sites, indicating that canopy removal triggered a substantially larger net forcing where the peat profile remained naturally wet. These contrasts are presented as descriptive case-study means and should therefore be interpreted as robust directional differences rather than formal tests of statistical significance.

The main contributor to total soil GHG emissions is CO_2, followed by CH_4 emissions, especially after felling in non-drained peat forests. A key scientific insight from the gas-specific data is that the post-harvest divergence between peat-forest classes is consistent with an amplification of methane-sensitive pathways in non-drained conditions. CH_4 flux increased only slightly in the drained peatland forest (from 0.12 to 0.67 mg CH_4m^{-2} h^{-1}), while it increased markedly in the non-drained peatland forest (from 0.95 to 5.22 mg $CH_4 \cdot m^{-2} \cdot h^{-1}$) following felling. N_2O fluxes remained low in both classes (≤ 0.06 mg $N_2O \cdot m^{-2} \cdot h^{-1}$), with no indication of a large post-harvest N_2O pulse at the class-mean level. Because CH_4 has a much higher GWP100 than CO_2, the increase in CH_4 emissions in non-drained peatland forests explains a large share of the observed increase in CO_2 equivalents. Fig. 1 presents the annualised CO_2-equivalent emissions as clustered stacked columns, allowing direct comparison of the total response and gas-specific contributions before and after regenerative felling in each peatland forest class.

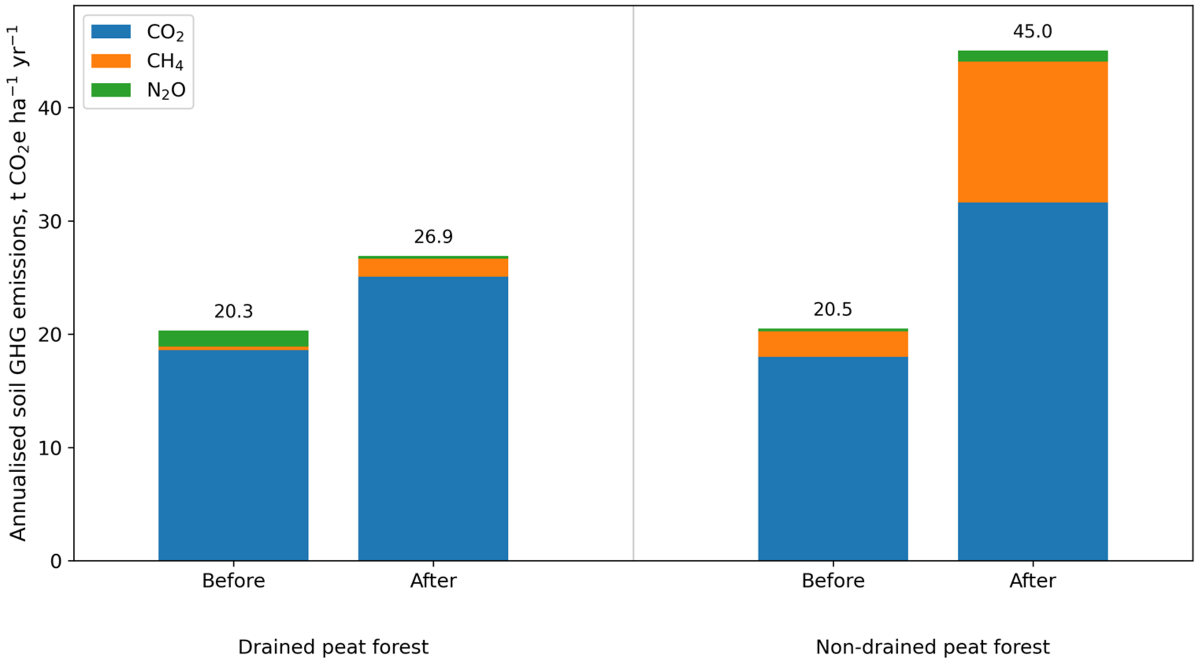

Fig. 1. **Annualised soil greenhouse gas emissions before and after regenerative felling in drained and non-drained peatland forests, expressed as CO_2 equivalents (GWP100) and shown as stacked contributions of CO_2, CH_4 and N_2O; data labels indicate total annualised emissions for each column**

The present analysis addresses only soil-atmosphere GHG exchange and therefore captures only one component of the post-felling carbon balance. Regenerative felling also causes an immediate reduction in live biomass carbon stock, interrupts ongoing biomass carbon sequestration, and initiates decomposition of harvest residues, roots and stumps left on site. Therefore, the increase in soil CO_2e emissions observed after felling should be interpreted together with concurrent biomass-related carbon losses when evaluating the overall short-term climate effect of harvesting. In practice, this means that the total ecosystem carbon balance immediately after felling is likely to be more negative than indicated by soil fluxes alone. Biomass pools and harvested wood product dynamics were outside the scope of the present case study and were therefore not quantified.

The direction of change – higher soil GHG emissions after regenerative felling – is consistent with the broader literature on peatland-forest clear-cutting, which reports substantial post-harvest perturbations to energy balance, evapotranspiration, and ground-layer development, with consequent impacts on CO_2, CH_4 and N_2O exchange [6]. The particularly strong increase observed in non-drained peatland forests is mechanistically plausible because these systems operate close to hydrological thresholds: canopy removal reduces transpiration demand and can shift the near-surface peat profile towards more persistent anoxia. Under such conditions, methanogenesis is favoured and the relative contribution of CH_4 to CO_2e can increase sharply, even if CO_2 fluxes also rise due to warmer soil and altered substrate inputs. This interpretation aligns with recent eddy-covariance evidence highlighting that CH_4 and N_2O fluxes after clear-cutting are strongly influenced by surface-type variation (e.g., hummocks vs hollows, wet depressions, disturbed patches), which can expand following harvest operations [14].

In drained peatland forests, the smaller post-harvest increment fits the established conceptual model for drained peatland forests, where deeper aeration typically suppresses CH_4 emissions through oxidation while enhancing CO_2 emissions via accelerated peat decomposition [3]. Clear-cutting can still increase CO_2 and sometimes induce episodic CH_4 and N_2O responses depending on post-harvest water-table dynamics and ground vegetation succession, but the magnitude is often moderated compared with naturally wet systems because drainage constrains the extent of sustained anoxic volume in the upper peat [6].

The low N_2O fluxes observed here are within the range commonly reported for many peatland forest floors, where N_2O remains small unless site fertility, nitrogen availability, and redox oscillations align to create strong nitrification–denitrification coupling [3]. As this study is framed as a case study and reports descriptive class means rather than inferential statistics, the results should be interpreted as indicating the likely direction and relative magnitude of responses under the observed site conditions, rather than as transferable national emission factors or formally tested universal responses. Nevertheless, the contrast between non-drained and drained classes directly supports the IPCC Wetlands Supplement logic that drainage state is a first-order stratification variable for organic soils, and it suggests that harvest-related pulses should be evaluated separately for naturally wet versus drained peatland forests in operational mitigation planning and in Tier 2/Tier 3 inventory improvements [1].

Conclusions

1. This case study demonstrates that regenerative felling increased soil greenhouse gas exchange (expressed as CO_2 equivalents) in both drained peatland forests and non-drained peatland forests, but the magnitude of the response was strongly conditioned by hydrological state. While pre-felling CO_2e levels were comparable between the two peat-forest classes, post-felling emissions diverged substantially, indicating that drainage state is a first-order stratification variable for anticipating short-term climate forcing after harvest operations. This finding is consistent with peatland biogeochemistry theory and with empirical evidence from boreal peatland forests showing that canopy removal modifies surface energy balance, evapotranspiration, and water-table dynamics, thereby reshaping the balance between aerobic decomposition and anaerobic methane production.
2. Quantitatively, regenerative felling increased annualised soil emissions from 20.3 to 26.9 t $CO_2eq \cdot ha^{-1} \cdot yr^{-1}$ in drained peatland forests, corresponding to an increase of 6.6 t $CO_2eq \cdot ha^{-1} \cdot yr^{-1}$ or 32%, whereas in non-drained peatland forests emissions increased from 20.5 to 45.0 t $CO_2eq \cdot ha^{-1} \cdot yr^{-1}$, corresponding to an increase of 24.5 t $CO_2eq \cdot ha^{-1} \cdot yr^{-1}$ or 119%. The disproportionate post-harvest increase in non-drained sites was associated with a strong rise in CH_4 fluxes, highlighting that methane-sensitive pathways can dominate the near-term climate response when peat remains naturally wet and harvest-induced reductions in evapotranspiration enhance anoxia in the upper peat.
3. N_2O fluxes were comparatively low across both peat-forest classes and did not dominate the CO_2eq response at the class-mean level. This is congruent with published evidence indicating that strong N_2O responses in peat soils are typically contingent on nutrient status, nitrogen availability, and redox oscillations, rather than being an inevitable outcome of canopy removal on its own.
4. From an applied perspective, the results support integrating hydrological classification into forest management on peatlands and into inventory-oriented emission-factor development. Specifically, regenerative felling on non-drained peatland forests appears to carry a substantially higher risk of short-term CO_2eq emission escalation than comparable operations on drained peatland forests. These outcomes reinforce current guidance that organic-soil GHG accounting should be stratified by drainage state and that post-harvest periods require targeted monitoring because short-lived hydrological shifts and microsite heterogeneity can strongly bias annual sums.

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Author contributions

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