EFFECT OF DEEP FURROWING ON METHANE FLUXES IN NON-DRAINED PEATLAND FOREST CLEARCUTS

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Abstract. This case study quantifies greenhouse gas (GHG) flux responses of nutrient-rich peatland forest soils to regenerative felling followed by excavator-based site preparation that created deep furrows (local drainage lines) intended to modify the post-harvest water regime. The study was implemented in three over-wet peatland forest sites (non-drained), where gas-exchange measurements were continued before and after felling and furrow installation using an established experimental layout with sampling points distributed at different distances from the furrow. Fluxes of soil carbon dioxide (CO_2) representing both heterotrophic and total respiration, methane (CH_4), and nitrous oxide (N_2O) were measured alongside controlling environmental variables (air/soil temperature and groundwater level), enabling attribution of observed changes to hydroclimatic and disturbance drivers. In plots where deep furrows were installed, mean soil GHG emissions increased by a factor of 1.7, from 242 ± 40 to 401 ± 110 mg CO_2-eq $m^{-2} \cdot h^{-1}$; the magnitude of increase scaled with the achieved drawdown of groundwater level, ranging from modest lowering (15 to 23 cm) associated with a smaller increase (220 ± 17 to 339 ± 33 mg CO_2-eq $m^{-2} \cdot h^{-1}$) to strong drawdown (≈10 ± 15 to 42 ± 26 cm) associated with an increase of 240 mg CO_2-eq $m^{-2} \cdot h^{-1}$, corresponding to emissions that were 1.8 times higher than before treatment. Despite CO_2 dominating the overall balance, CH_4 decreased markedly after furrow installation, with an average reduction of approximately eleven-fold, whereas N_2O increased by approximately 88%, yielding a net post-harvest increase in the integrated balance (1.42 to 1.74 t CO_2-eq ha^{-1}). The temporal pattern suggested that short-term emission elevations may be driven substantially by fresh harvest residues and rapidly responding ground vegetation, rather than groundwater change alone, highlighting the need for longer monitoring to separate transient disturbance pulses from persistent drainage effects. These results provide empirical constraints for improving national-scale emission factor development and for evaluating trade-offs between mitigating CH_4 via aeration and stimulating CO_2/N_2O following regenerative harvesting on peat soils.

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

Introduction

Greenhouse gas (GHG) exchange in peatland forest soils is highly sensitive to management actions that modify substrate aeration, labile carbon inputs, and hydrological controls, particularly in nutrient-rich, over-wet peatland forest types where groundwater is close to the surface for substantial parts of the year. In such systems, forest regeneration practices after clearcutting can shift the dominant biogeochemical pathways that govern CO_2 production, CH_4 formation and oxidation, and N_2O generation, thereby altering the net climate forcing of the site. From a GHG inventory and reporting perspective, these process-level responses are directly relevant because improved emission factors and their temporal dynamics are required for robust national GHG accounting; the 2019 Refinement to the 2006 IPCC (the Intergovernmental Panel on Climate Change) Guidelines explicitly emphasises the need for better characterisation of land-use management drivers and associated emissions in the Agriculture, Forestry and Other Land Use (AFOLU) systems [1].

After regenerative felling in peatland forests, a short-term increase in soil CO_2 efflux is commonly attributed to the combined effect of higher soil temperature, altered moisture conditions, and the rapid decomposition of harvest residues and disturbed organic layers. In peatland forests, post-harvest site preparation may include hydrological interventions such as deep furrows intended to improve surface drainage and regulate groundwater conditions during stand regeneration. The underlying management rationale is a trade-off: increasing aeration can suppress CH_4 production by reducing anoxic volume, yet enhanced oxygen availability can stimulate heterotrophic respiration and potentially promote nitrification – denitrification sequences that raise N_2O emissions. Empirical evidence indicates that CH_4 contributions to the overall GHG balance may decline after deep-furrow establishment, while N_2O may increase, with CO_2 typically remaining the dominant component of total CO_2-equivalent fluxes [2; 3].

A persistent challenge is separating transient disturbance pulses from longer-lasting hydrological effects. Apparent emission increases can be strongly influenced by fresh organic matter inputs from harvest residues and by changes in ground vegetation activity that are captured in gross soil respiration measurements; both mechanisms can confound attribution to groundwater drawdown alone [4; 5].

Consistent with this, emission estimates in organic soils can differ markedly among studies and may require targeted measurement campaigns to avoid systematic under- or overestimation [6; 7]. The need for longer observation series is therefore methodological as well as interpretative, because interannual hydroclimatic variability can modulate both CH_4 dynamics and N_2O peaks, especially in spring and early summer conditions.

Despite growing evidence that clearcutting alters soil greenhouse gas exchange in peatland forests, the specific short-term effect of post-harvest deep-furrow installation on the integrated CO_2, CH_4, and N_2O balance in non-drained nutrient-rich peatland forests remains insufficiently quantified. In particular, there is limited empirical evidence comparing post-felling greenhouse gas fluxes in areas with and without deep furrows and relating the magnitude of the response to changes in groundwater level. This knowledge gap limits both process-based interpretation of post-harvest greenhouse gas dynamics and the development of management-specific emission factors for greenhouse gas accounting [8; 9].

The aim of this study is to quantify the short-term effects of regenerative felling and subsequent deep-furrow installation on soil CO_2, CH_4, and N_2O fluxes in non-drained nutrient-rich peatland forests, and to compare post-harvest greenhouse gas responses in furrowed and non-furrowed areas in relation to groundwater regime.

Materials and methods

The case study follows the LIFE OrgBalt project monitoring concept [10] by establishing replicated chamber measurement points at different distances from deep furrows and repeating measurements across both pre-harvest and post-harvest periods. Gas-exchange measurements were carried out approximately once per month during the monitoring period. In each measurement campaign, fluxes were assessed in five replicated chamber positions per study plot. Soil heterotrophic and total CO_2 production and net soil-to-atmosphere fluxes of CH_4 and N_2O were measured, while air temperature, soil temperature, and groundwater table depth were recorded concurrently as explanatory environmental covariates.

Study sites and interventions are summarised in Table 1. For clarity, the experimental categories are hereafter referred to as furrowed and non-furrowed plots. Two plots underwent regenerative felling followed by site preparation with deep-furrow installation and are therefore referred to as furrowed plots. The comparison plot underwent regenerative felling but no deep-furrow installation and is therefore referred to as the non-furrowed plot. The non-furrowed plot was located in a pine stand with moderately rich peat soil in the vicinity of Smiltene, where gas-exchange measurements started on 31 May 2022 and regenerative felling was carried out on 8 February 2023.

Table 1

Sites, monitoring window, and management chronology

Site ID	Lat, lon (WGS84)	Period	Key operations
031-108-4 (LVC312), 4.05 ha; site index IV; birch-dominated; age 95 years	57.311643, 25.936089	20.01.2021-30.07.2024	Regenerative felling was carried out on 24 May 2022. Soil preparation and deep-furrow installation were completed in August 2022. In April 2023, Norway spruce was planted on elevated microsites, whereas black alder was planted in the wetter part of the area. Two deep furrows were created along the longest edges of the site and drained water towards a depression at the site margin.
012-218-4 (LVC309), 0.75 ha; site index II; spruce-dominated; age 80 years	57.278890, 25.853660	20.01.2021-19.12.2022	Regenerative felling was carried out on 22 March 2022. Soil preparation, deep-furrow installation, and renovation of the existing ditches were completed in June 2022. One deep furrow was created in the area, draining water towards the lower part of the site.

Measurements were continued for two years after harvesting in the furrowed plots and for one year after harvesting in the non-furrowed plot. The monitoring period covered 2021-2024, with reference data originating from the LIFE OrgBalt project and instrumentation renewed in July 2023 where indicated.

Overall, the study comprised three monitored plots, i.e. two furrowed plots and one non-furrowed plot. Based on the monitoring windows used in this study and an average sampling frequency of one campaign per month, the dataset comprised approximately 89 stand-level measurement campaigns in total. Assuming five replicated chamber measurements per plot in each campaign, this corresponds to approximately 445 individual chamber-based flux measurements or about 1335 flux observations in total for CO_2, CH_4 and N_2O combined. Thus, the dataset includes repeated observations before felling and during the first one to two years after felling, depending on plot.

The furrowed plots represented over-wet, non-drained peatland forest sites where deep furrows were installed to improve post-harvest drainage conditions, whereas the non-furrowed plot represented a harvested organic-soil pine stand without furrow installation.

Before harvesting, the furrowed plot 031-108-4 (LVC312) represented a 4.05 ha stand of site index IV, dominated by birch at 95 years of age. The pre-harvest species composition was 60% birch, 20% Norway spruce, and 20% black alder. Total growing stock was 222 $m^3 \cdot ha^{-1}$, with an average tree height of 20 m, an average diameter of 28 cm, and a basal area of 13 m^2 ha^{-1}. The second furrowed plot, 012-218-4 (LVC309), represented a 0.75 ha stand of site index II, dominated by Norway spruce at 80 years of age. The pre-harvest species composition was 90% Norway spruce and 10% birch. Total growing stock was 320 $m^3 \cdot ha^{-1}$, with an average tree height of 21 m, an average diameter of 21 cm, and a basal area of 27 m^2 ha^{-1}. The non-furrowed plot represented a 2.1 ha stand of site index IV, dominated by Scots pine at 138 years of age. The stand consisted entirely of pine before harvesting, with a total growing stock of 350 $m^3 \cdot ha^{-1}$, an average tree height of 22 m, an average diameter of 33 cm, and a basal area of 26 m^2 ha^{-1}.

In all study plots, regenerative felling was applied as the principal harvesting treatment, removing the mature overstorey and initiating stand regeneration. In the furrowed plots, harvesting was followed by site preparation with deep-furrow installation in order to improve post-harvest drainage conditions in over-wet organic soils. In plot 031-108-4 (LVC312), regenerative felling was carried out on 24 May 2022, followed by soil preparation and deep-furrow installation in August 2022; in April 2023, Norway spruce was planted on elevated microsites and black alder in the wetter part of the area. In plot 012-218-4 (LVC309), regenerative felling was carried out on 22 March 2022, followed by soil preparation and deep-furrow installation in June 2022. In the non-furrowed plot, gas-exchange monitoring started on 31 May 2022 and regenerative felling was carried out on 8 February 2023, but no deep furrows were installed after harvesting.

Because the treatment was regenerative felling, harvesting intensity was effectively stand replacing at the overstorey level, although the precise retained-tree volume was not analysed as a separate variable in this study.

Treatment effects were assessed by combining within-site before–after contrasts around the regenerative felling and deep-furrow implementation dates with contemporaneous contrasts between furrowed and non-furrowed stands. Within treated sites, the distance-to-furrow gradient provided an internal test of hydrological regulation on gas exchange, because plot positions capture microtopographic variation in water table and temperature regimes.

Statistical analyses were performed separately for CO_2, CH_4, N_2O, and CO_2-equivalent fluxes. Because the study design included repeated measurements through time, treatment effects were evaluated using linear mixed-effects models with treatment (furrowed vs non-furrowed), period (before vs after felling), and their interaction as fixed effects. Plot identity and measurement campaign were included as random effects to account for repeated observations within plots and temporal dependence. When necessary, flux data were log-transformed to improve residual normality and variance homogeneity. Pairwise contrasts between treatments and periods were evaluated using estimated marginal means with Tukey-adjusted comparisons. Differences were considered statistically significant at $p < 0.05$.

Instantaneous surface flux (F, mg·m^{-2}·h^{-1}) was derived from the linear change in chamber head-space mixing ratio d_C/d_t and chamber geometry:

$$F = \frac{d_C}{d_t} \cdot \frac{P \cdot V}{R \cdot T \cdot A} \cdot M \cdot 3.6 \cdot 10^3 \ , \tag{1}$$

where d_C/d_t – linear slope;
P – air pressure, Pa;
V – chamber volume, m^3;
A – enclosed soil area, m^2;
R – the universal gas constant;
T – head-space temperature, K;
M – molar mass, mg·mol^{-1}.

When element-based fluxes were used (CO_2-C, CH_4-C, N_2O-N), molecular fluxes were obtained by stoichiometry: CO_2 = CO_2-C·(44/12), CH_4 = CH_4-C·(16/12), N_2O = N_2O-N·(44/28).

Integrated climate forcing was expressed as CO_2 equivalents (CO_2-eq, mg CO_2-eq·m^{-2}·h^{-1}) using GWP100 factors consistent with the monitoring summaries:

$$\mathrm{CO_{2-eq}} = \mathrm{CO_2} + 28 \cdot \mathrm{CH_4} + 265 \cdot \mathrm{N_2O}, \tag{2}$$

which reproduces the reported CO_2-eq totals in peat-forest before/after felling comparisons in the monitoring dataset with several environmental variables (Table 2).

Table 2

Variables used in the analysis

Category	Variable	Unit
Response	CO_2–C (heterotrophic respiration)	mg C·m^{-2}·h^{-1}
Response	CH_4 flux	mg·m^{-2}·h^{-1}
Response	N_2O flux	mg·m^{-2}·h^{-1} (converted if µg reported)
Covariate	Air temperature	°C
Covariate	Soil temperature	°C
Covariate	Groundwater table depth	cm

Flux summaries were calculated as arithmetic means with uncertainty reported as the arithmetic standard error; this uncertainty structure was retained after unit conversions and CO_2-eq aggregation.

Results and discussion

Following regenerative felling, soil greenhouse gas fluxes changed in both furrowed and non-furrowed organic-soil stands, but the direction and magnitude of the response differed between treatments. Mixed-effects analysis showed that the treatment × period interaction was statistically significant for CH_4 and total CO_2-equivalent fluxes ($p < 0.05$), indicating that post-harvest responses differed between furrowed and non-furrowed stands. In contrast, the interaction was not statistically significant for CO_2, whereas N_2O showed a positive post-harvest response in both treatments, with a stronger increase in furrowed stands. In the furrowed plots, mean soil greenhouse gas exchange expressed as CO_2 equivalents increased from 242 ± 40 to 401 ± 110 mg CO_2-eq m^{-2}·h^{-1}, corresponding to an approximately 1.7 times higher than under pre-harvest conditions. The magnitude of the increase covaried with groundwater drawdown, ranging from a smaller increase where the mean groundwater level decreased from 15 to 23 cm to a stronger response where groundwater declined from 10 ± 15 to 42 ± 26 cm. In the non-furrowed plot, post-harvest heterotrophic respiration and N_2O emissions also increased, but in contrast to the furrowed plots, CH_4 emissions increased rather than decreased, indicating the persistence of wetter and more anaerobic soil conditions after felling. Thus, the comparison between furrowed and non-furrowed stands suggests that deep furrows substantially modified the post-harvest gas balance primarily by suppressing CH_4 emissions.

“Gas-specific responses differed markedly between furrowed and non-furrowed stands, and this difference was statistically supported for CH_4 fluxes. In the furrowed plots, CH_4 emissions decreased after felling and furrow installation, whereas in the non-furrowed plot CH_4 emissions increased after felling, resulting in a significant treatment × period interaction. N_2O emissions increased after felling in both treatments; however, the magnitude of this response should be interpreted according to the corresponding model-based significance test. The contrasting responses show that furrow installation altered not only the magnitude but also the direction of the post-harvest CH_4 response.

At the scale of the broader monitoring dataset contrasting forest site types, mean fluxes in the non-drained peatland forest rose from 234 to 514 mg CO_2-eq·m^{-2}·h^{-1} after regenerative felling, i.e. approximately 2.2 times higher than before felling. In the drained peatland forest the increase was smaller, from 232 to 307 mg CO_2-eq m^{-2}·h^{-1}, i.e. approximately 1.3 times higher than before felling. In both site types, post-felling CH_4 increased 5.5 times (non-drained peatland forest: from 0.95 to 5.22 mg·m^{-2}·h^{-1}; drained peatland forest: from 0.12 to 0.67 mg·m^{-2}·h^{-1}), whereas N_2O responses diverged (non-drained peatland forest: from 0.01 to 0.04 mg·m^{-2}·h^{-1}; drained peatland forest: from 0.06 to 0.01 mg·m^{-2}·h^{-1}). The contrast implies that drainage status modulates the post-harvest partitioning among CO_2, CH_4 and N_2O and the resulting CO_2-eq balance (Fig. 1).

A complementary annualised comparison reported that deep furrows had little effect on CO_2 emissions, but were associated with a 59% increase in N_2O emissions and a 77% decrease in CH_4 emissions, resulting in an overall 14% decrease in total CO_2-eq relative to non-furrowed conditions after felling when comparing furrowed vs non-furrowed conditions; in the same context, CO_2 emissions increased from 4.5 ± 0.4 to 8.9 ± 0.1 t CO_2-C·ha^{-1}·yr^{-1} after felling, and N_2O rose to 2.7 ± 1.2 and 4.4 ± 1.1 kg N_2O·ha^{-1}·yr^{-1} in the non-furrowed and furrowed plots, respectively.

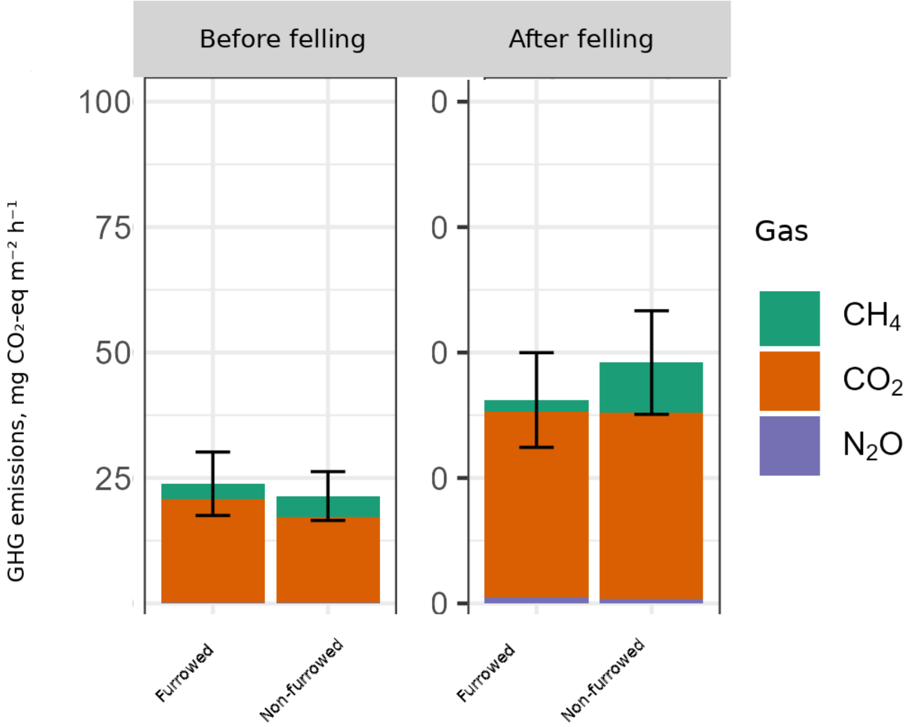

Fig. 1. **Soil GHG emissions before and after felling in furrowed and non-furrowed plots; panels are arranged from left to right in chronological order**

The observed post-harvest increase in CO_2-eq is mechanistically consistent with a disturbance-driven pulse of soil carbon mineralisation following canopy removal, coupled with altered soil thermal and hydrological regimes. In organic forest soils, clear-fell harvesting and associated site disturbance commonly increase soil temperature, reduce transpiration, modify near-surface aeration and moisture conditions, and increase the supply of labile substrates through root mortality and logging residues, thereby stimulating heterotrophic respiration and, under favourable redox conditions, also N_2O production [2; 3; 5; 13]. The results showed that elevated emissions were strongest in the first months after operations, supporting an interpretation driven not only by hydrological change but also by rapidly decomposing fresh organic matter and post-harvest disturbance effects, which is consistent with previously reported short-term post-harvest GHG responses in forest soils [2; 5]. This aligns with field evidence that CO_2, CH_4 and N_2O can respond in different directions after clear-felling, and that interannual variability can be large; in [5] clear-felling altered all three gases, with CO_2 often dominating the annual GHG budget while N_2O can contribute substantially in some years.

Deep furrows, as implemented here, act primarily by reshaping microtopography and enhancing lateral drainage, which tends to lower water tables locally and to reduce the extent and duration of anoxic conditions in surface peat. The pronounced 11-fold reduction in CH_4 in furrowed plots is therefore consistent with suppression of methanogenesis and/or increased CH_4 oxidation under more oxic conditions. Where supported by the mixed-effects analysis, this pattern indicates that furrow installation significantly altered the post-harvest methane response relative to the non-furrowed treatment. The results highlight as a plausible contributor to reduced CH_4, emphasising that the persistence of the CH_4 response should be tested with longer monitoring. Such climate sensitivity of soils is strongly controlled by water-table depth, temperature, and substrate supply [11].

At the same time, the furrow-induced shift toward more aerobic conditions can increase CO_2 production from peat decomposition, especially where the groundwater drawdown is strongest, as observed in the plot with drawdown to 42 ± 26 cm showing the greatest CO_2-eq increase. The net GHG response therefore reflects a trade-off between reduced CH_4 emissions and potentially higher CO_2 and N_2O emissions under more aerobic conditions. In the present study, furrowed plots showed a 77% decrease in CH_4 emissions and a 59% increase in N_2O emissions, whereas CO_2 changed little. Overall, this resulted in an approximately 14% decrease in CO_2-eq after felling relative to non-furrowed conditions. Although N_2O increased, its absolute contribution to the total GHG balance remained smaller than that of CO_2. From a mitigation perspective, this pattern is plausible because methane exerts a much stronger warming effect per unit mass than CO_2 over the standard 100-year accounting horizon; therefore, even modest absolute changes in CH_4 flux can materially affect CO_2-equivalent balances in wet non-drained peat soils, particularly immediately after canopy removal [10; 11].

The contrast between non-drained and drained peatland forests provides additional context for interpreting the furrow intervention. After regenerative felling, the non-drained site displayed a markedly larger increase in CO_2-eq, approximately 2.2 times higher than before felling, compared with the drained type, where emissions were approximately 1.3 times higher. In both types, CH_4 increased by approximately 5.5 times after felling, indicating that post-harvest hydrological changes and substrate inputs can stimulate methanogenesis even in drained settings, although absolute CH_4 fluxes remained much higher in non-drained site. The divergent N_2O trajectories suggest that nitrogen availability, redox fluctuations, and microbial community constraints differ between site types; this heterogeneity is consistent with synthesis work highlighting large variability of drained organic forest soil GHG fluxes and the need for site-specific or stratified emission factors rather than a single “one-size-fits-all” value [12].

When compared with other peatland-forest disturbance studies, the direction of change observed here is broadly consistent with published evidence. In boreal nutrient-rich peatland forests, clear-cutting has been shown to increase short-term CO_2 losses relative to less intensive harvesting, whereas the magnitude and, in some cases, the direction of CH_4 and N_2O responses depend strongly on drainage status, water-table position, site fertility, and year-to-year weather variability [2; 5; 11; 13]. The present case study provides additional evidence that a targeted temporary hydrological measure, namely deep-furrow installation, can substantially suppress CH_4 emissions during the vulnerable post-harvest phase, but that its climate benefit must be evaluated together with potential CO_2 and N_2O penalties, and with explicit treatment of uncertainty and inter-annual weather variability.

Conclusions

1. Deep furrows installed after regenerative felling in non-drained nutrient-rich peat forests appear to be a highly efficient hydrological measure that improves regeneration conditions by lowering excess water and increasing near-surface aeration, which is mechanistically consistent with improved early tree growth and survival.

2. Deep furrows substantially reduced soil CH_4 emissions under wet post-harvest conditions, indicating a strong shift away from anaerobic methane production and/or enhanced methane oxidation.
3. Although N_2O emissions increased after furrow installation, the net greenhouse gas balance expressed as CO_2-eq decreased relative to non-furrowed post-felling conditions, implying a potential overall climate-mitigation benefit dominated by CH_4 suppression.
4. The magnitude of the furrow effect was conditional on the achieved groundwater drawdown and post-harvest hydroclimatic conditions, highlighting hydrology as the primary regulator of the GHG response.
5. Multi-year monitoring remains necessary to confirm the persistence of both the growth-related benefits and the GHG reduction, and to separate transient disturbance pulses (e.g., residue-driven CO_2 increases) from longer-lasting hydrological effects.

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Author contributions

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