Soil & Tillage Research 260 (2026) 107143

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Grassland renewal dominates multi-year nitrous oxide emissions in boreal legume grassland: Insights from eddy-covariance measurements

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ARTICLE INFO

Keywords:
Boreal grassland
Emission factors
Eddy covariance
Nitrous oxide
Grassland renewal

ABSTRACT

Nitrous oxide (N_2O) emissions from agricultural soils represent the dominant source of this potent greenhouse gas, yet the interactions between management practices and environmental drivers governing these emissions remain poorly quantified, particularly across the entire grassland rotation cycle including renovation phases. We conducted three-year eddy covariance measurements of N_2O fluxes from a legume-based grassland in eastern Finland, comparing mineral nitrogen (N_{min}) and cattle-slurry digestate (N_{org}) fertilization strategies across the first (R_1) and second grass production years (R_2), and the renovation year (R_3). Annual N_2O emissions increased through the rotation and ranged from 1.9 to 3.4 kg N_2O-N ha^{-1} under N_{min} and 2.6–5.4 kg N_2O-N ha^{-1} under N_{org} treatments. Emission factors ranged from 1.79 % to 7.56 % (N_{min}) and 2.65–3.06 % (N_{org}). Grassland renewal increased emissions by 55 % (N_{min}) and 80 % (N_{org}) relative to grass production years (R_2). Environmental controls diverged between treatments: ecosystem respiration as the primary driver of N_2O emissions under N_{min}, while soil temperature dominated under N_{org}. N_2O emissions during non-growing season contributed 22–35 % of annual budgets. Grassland renovation represents the critical emission hotspot within boreal grassland rotation cycles, overriding fertilizer type effects. N_{org} produced 37–59 % higher cumulative emissions. These findings highlight the critical importance of grassland management event and fertilizer type in N_2O emission mitigation strategies and warrant eddy-covariance measurements for more accurate N_2O emission inventories from boreal grasslands.

1. Introduction

Nitrous oxide (N_2O) is a critical climate forcing agent with a 100-year global warming potential 273 times that of carbon dioxide, contributing approximately 6 % of total anthropogenic radiative forcing (Lee et al., 2023). Agricultural soils constitute the dominant source, with nitrogen additions to managed lands resulting in 2.7–4.8 Tg N yr^{-1}, accounting for 56 % of global anthropogenic N_2O emissions (Tian et al., 2024). Despite grasslands occupying approximately one-third of European agricultural area and forming the foundation of ruminant livestock systems (Soussana et al., 2007), their contribution to national N_2O inventories remains poorly constrained, particularly in high-latitude regions where unique environmental conditions fundamentally affect nitrogen dynamics (Norderhaug et al., 2023; Soussana et al., 2007).

Boreal grasslands present specific challenges for emission quantification. Extended snow cover, multiple freeze-thaw cycles, and short growing seasons result in the nitrogen cycling being different from temperate systems (Norderhaug et al., 2023; Soussana et al., 2007). Previous studies have showed that winter and spring thaw periods may contribute 40–70 % of annual N_2O emissions from northern grasslands (Sturite et al., 2021; Wagner-Riddle et al., 2017), and winter emissions can be up to 78 % of the annual emissions (Virkajärvi et al., 2010). Yet most emission factor development has focused on growing season measurements. In Finland, where grassland-based livestock production supports rural economies and 80 % of beef production is integrated with dairy operations (Niemi and Väre, 2019), intensive grass-legume grasslands undergo renewal every 3–4 years (Li et al., 2023; Semberg et al., 2026; Thentu et al., 2025). This renovation process, involving herbicide application, ploughing, and reseeding, decomposes accumulated organic nitrogen and can induce emission peaks that increase

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https://doi.org/10.1016/j.still.2026.107143
Received 22 September 2025; Received in revised form 17 February 2026; Accepted 19 February 2026
Available online 21 February 2026

annual N_2O budgets by 200–500 % relative to established swards (Hörtnagl et al., 2018; Merbold et al., 2014). However, continuous measurements capturing these dynamics in boreal systems remain rare.

The integration of forage legumes, particularly white clover (*Trifolium repens*) and red clover (*Trifolium pratense*), has been widely promoted as a sustainable intensification strategy to reduce dependence on mineral nitrogen fertilizers through biological nitrogen fixation (Lüscher et al., 2014). In Nordic conditions, legume-grass mixtures can fix 50–300 kg N ha^{-1} yr^{-1}, substantially reducing fertilizer requirements while maintaining yields (Gylfadóttir et al., 2007). Legumes increase soil nitrogen availability through root exudation, nodule senescence, and incorporation of nitrogen-rich residues, creating complex feedbacks that may either mitigate or induce N_2O emissions depending on environmental conditions and management practices (Böldt et al., 2024; Rochette and Janzen, 2005). These feedbacks are further regulated by fertilizer type: while slow-release organic amendments such as digestate typically show lower emission magnitudes than mineral fertilizers in temperate studies, contrasting results have emerged from cold, coarse-textured soils where denitrification may be carbon-limited rather than nitrogen-limited (Charles et al., 2017; Meng et al., 2023; Wang et al., 2024). The effect of fertilizer type on N_2O emissions in boreal systems remains contentious. While IPCC default emission factors assume comparable emissions from mineral and organic nitrogen sources (Hergoualc'h et al., 2021), emerging evidence from Nordic agricultural systems challenges this assumption. Wallman et al. (2022) reported that biogas digestate and pig slurry applications on Swedish clay soils induced N_2O emissions equivalent to mineral fertilizer applications at 50 % above recommended rates, with approximately 75 % of annual emissions occurring during freeze-thaw cycles between harvest and sowing. Similarly, Virkajärvi et al. (2010) reported that unfertilized grass-clover grasslands in Finnish conditions emitted 6.4–7.6 kg N_2O-N ha^{-1} yr^{-1}, exceeding emissions from mineral-fertilized grassland (3.2–4.1 kg N_2O-N ha^{-1} yr^{-1}). Recent Danish field trials across 28 experimental sites (2022–2024) further indicated that organic fertilizers (cattle slurry, pig slurry, digestate) consistently produced higher average N_2O emissions than mineral fertilizers (Petersen et al., 2023). These contrasting results from boreal systems highlight the need for region-specific comparisons of fertilizer type effects on N_2O emissions.

Traditional static chamber methodologies, while providing valuable spatial resolution, inadequately capture the temporal dynamics of N_2O emissions and frequently miss episodic emission events that may dominate annual budgets (Hicks and Baldocchi, 2020). The advent of quantum cascade laser spectroscopy has enabled continuous eddy covariance measurements of N_2O fluxes, providing ecosystem-scale integration with sub-hourly temporal resolution (Nemitz et al., 2018). Previous eddy covariance studies have suggested grassland emission factors ranging from 0.13 % to 5.71 % of applied nitrogen (Cowan et al., 2020; Fuchs et al., 2020; Regina et al., 2013), substantially exceeding the IPCC Tier 1 default value of 1 % and highlighting critical uncertainties in current inventory methodologies (Hergoualc'h et al., 2021). Despite these technological advances, multi-year eddy covariance datasets from boreal grassland systems remain absent (Shurpali et al., 2025; Thentu et al., 2025), forcing inventory compilers to rely on emission factors derived from temperate regions with fundamentally different environmental controls.

With three years of continuous eddy covariance measurements of N_2O fluxes from a red clover-timothy (*Phleum pratense* L.) grassland in eastern Finland, encompassing a complete rotation cycle including establishment, production, and renewal phases. This study aimed to compare two contrasting fertilization strategies: mineral nitrogen (N_{min}) and cattle-slurry digestate (N_{org}), representing dominant nutrient management approaches in Nordic livestock systems. Specific objectives were to: (1) quantify annual N_2O emission budgets and derive emission factors under contrasting fertilization managements across all rotation periods; (2) calculate yield-scaled emission intensities to evaluate the agronomic efficiency of different management strategies; and (3) identify the dominant environmental and management drivers of temporal emission variability. We hypothesized that: (i) N_{org} would reduce N_2O emissions compared to N_{min} due to slower nitrogen mineralization rates; (ii) grassland renewal would dominate the three-year cumulative emission budget regardless of fertilizer type, contributing more cumulative emissions; and (iii) emission peaks would be primarily controlled by the interaction of nitrogen availability with soil moisture and temperature, with spring thaw and post-fertilization periods representing critical emission windows.

2. Materials and methods

2.1. Site description and experimental design

The study was conducted at an agricultural field (6.3 ha; 280 m × 220 m) located in Maaninka, eastern Finland (63°09'N, 27°14'E, 89 m a.s.l.). The region experiences a continental boreal climate with 30-year (1981–2010) mean annual temperature of 3.2°C and precipitation of 612 mm. The soil is classified as a Haplic Cambisol/Regosol (Hypereutric, Siltic), with silt loam texture (25 % ± 6 % clay, 53 % ± 9 % silt, 22 % ± 8 % sand). Soil properties include pH 5.8 ± 0.2, organic carbon 3.0 ± 0.5 %, total nitrogen 0.2 ± 0.03 %, C:N ratio 15 ± 0.4, and bulk density 1.1 ± 0.1 g cm^{-3}.

The experimental grassland was established in 2015 with timothy (cv. Nuutti; 15 kg ha^{-1}), red clover (cv. Ilte; 5 kg ha^{-1}), and barley (*Hordeum vulgare* L. cv. Kaarle; 160 kg ha^{-1}) as cover crop. It was reseeded with red clover (cv. Ilte; 3 kg ha^{-1}) in May 2017, and underwent complete renewal in spring 2019. The experimental design comprised two treatment plots with contrasting nitrogen management: mineral nitrogen fertilizer (N_{min}) and organic nitrogen as biogas digestate slurry (N_{org}). The study spanned three years covering an entire grassland rotation cycle: R_1 (May 2017 - May 2018), R_2 (June 2018 - May 2019), and R_3 (June 2019 - May 2020).

2.2. Field management

During R_1 and R_2, the N_{min} plot received an average annual fertilization of 106 kg soluble N, 28 kg P, and 50 kg K ha^{-1}, applied in two splits (May and July, Table 1). The mineral fertilizer used was a compound NPK fertilizer (YaraMila Y3, Yara International ASA, Oslo, Norway) with formulation 23–3–8 (23 % N as ammonium nitrate, 3 % P_2O_5, 8 % K_2O), supplemented with potassium chloride (Yara) for additional K requirements. The N_{org} plot received a single application after the first

Table 1
Information of management, fertilization (kg ha^{-1}) and harvest event for grassland added with mineral nitrogen (N_{min}) or biogas digestate slurry (N_{org}) during the study period. The renewal was carried out on 4 June 2019, Timothy 'Nuutti' 15 kg ha^{-1} and red clover 'Ilte' 3 kg ha^{-1} were sown, and cover crop barley 160 kg ha^{-1}. Second over-seeding was carried out on 16 August 2019, Timothy 'Nuutti' 10 kg ha^{-1} and red clover 'Ilte' 2.5 kg ha^{-1}. Glyphosate was applied against weeds to both treatments before ploughing.

Year	2017		2018		2019	
	N_{min}	N_{org}	N_{min}	N_{org}	N_{min}	N_{org}
Cultivation					3 Jun	
Establishment					4 Jun	
Rolling					5 Jun	
Over-seeding	18 May					
Mineral fertilization	22 May		22 May			
Grass cuts	29 Jun		26 Jun		6 Aug	
Mineral fertilization	3 Jul		2 Jul			
Digestate application		1 Jul	-	28 Jun		
Grass Cuts	16 Aug		7 Aug			
Reseeding					16 Aug	
Mineral fertilization			9 Aug			
Glyphosate treatment			25 Sep			
Ploughing			29–31 Oct			

cut, with an average annual rate of 98 kg N total (53 kg soluble N), 13 kg P, and 83 kg K ha^{-1}. In R_3, only the N_{min} plot was fertilized (45 kg N, 20 kg P, and 38 kg K ha^{-1}), while the N_{org} plot received no fertilizers.

Grass harvesting occurred twice annually in R_1 and R_2 (late June and mid-August) and once in re-establishing year R_3 (early August), using farm-scale machinery cutting the grass to 8-cm stubble height. Grassland renewal in autumn 2018 involved glyphosate application, plowing, and winter bare fallow. Re-establishment in June 2019 (R_3) included seeding with timothy (15 kg ha^{-1}), red clover (3 kg ha^{-1}), and barley (160 kg ha^{-1}) as a cover crop.

2.3. N_2O flux measurements using the eddy covariance technique

An eddy covariance tower was centrally positioned at the boundary between N_{min} and N_{org} plots (Fig. 1). The system comprised: (1) a sonic anemometer (R3–50, Gill Instruments Ltd., UK) at 2.5 m height measuring three-dimensional wind velocity and sonic temperature; (2) a pulsed quantum cascade laser spectrometer (APR QC-TILDAS-76-CS, Aerodyne Research Inc., USA) for continuous N_2O, carbon dioxide (CO_2), and water vapor flux measurements at 10 Hz. The EC instrumentation also included an infrared gas analyzer (LI-7000, Li-Cor Inc., USA) for measuring CO_2 and water vapor concentrations. Air samples were drawn through an 8-m heated PTFE intake tube (6 mm inner diameter) with dual 1.0 µm PTFE filters at 10 L min^{-1} flow rate (Li et al., 2023; Shurpali et al., 2025).

The spectrometer underwent monthly calibration during growing seasons using standard gases (299 and 342 N_2O, AGA Oy, Finland). Frequency response corrections accounted for high-frequency attenuation in the sampling line (Nemitz et al., 2018), with empirical transfer functions calculated (Rebmann et al., 2018). Storage flux corrections were applied using single-point concentration measurements scaled by canopy height changes.

2.4. Flux processing and quality control

Raw EC data were collected at 10 Hz using a data logger (CR3000, Campbell Scientific Inc., Logan, UT, USA). The 30-minute EC flux values were calculated based on the covariance between scalar variables (e.g., N_2O concentrations) and vertical wind velocity. Data processing was conducted using the EddyUH software package (Mammarella et al., 2016) and involved the following steps: (1) despiking, outliers in the data were identified and removed to reduce noise; (2) coordinate rotation, a two-dimensional rotation was applied to align the wind components with the mean wind direction; (3) block averaging, detrending was performed by averaging over 30-minute intervals; (4) lag time correction, the lag time due to the gas sampling line was calculated and adjusted by maximizing the covariance between N_2O concentrations and vertical wind velocity; (5) spectral corrections, low-frequency and high-frequency spectral losses were corrected using established methodologies (Rannik and Vesala, 1999); (6) quality control, data were filtered based on criteria such as stationarity and developed turbulence, with fluxes measured during unfavorable wind directions (85° to 130°), rain events, and maintenance periods being discarded.

2.5. Footprint analysis and flux partitioning

To attribute measured N_2O fluxes to the respective treatments (N_{min} and N_{org}), we employed the two-dimensional Flux Footprint Prediction (FFP) model to calculate 30-minute footprint climatologies (Kljun et al., 2015). The FFP model parameterization included measurement height (2.5 m), displacement height (estimated as 0.67 × canopy height), surface roughness length (estimated as 0.1 × canopy height), friction velocity, Obukhov length, and standard deviation of lateral velocity fluctuations derived from sonic anemometer measurements.

Flux data were assigned to treatment plots based on the 80 % cumulative footprint contribution area for heterogeneous agricultural landscapes (Barczyk et al., 2024; Chu et al., 2021). Fluxes were classified as N_{min} when > 70 % of the footprint area fell within the N_{min} plot, and as N_{org} when > 70 % fell within the N_{org} plot. Flux measurements with footprint contributions spanning both plots below this threshold were excluded from treatment-specific analyses. Wind direction predominantly originated from the southwest (210–240°) and northeast (30–60°) sectors during the study period, resulting in well-separated source areas for the two treatments (Li et al., 2023; Shurpali et al., 2025). The sample sizes for N_{min} and N_{org} classifications were 8247 and 7892 valid 30-minute periods, respectively, representing a group ratio of 1.04:1.

2.6. Gap-filling of N_2O fluxes

Gap-filling of N_2O fluxes was performed using a look-up table (LUT)

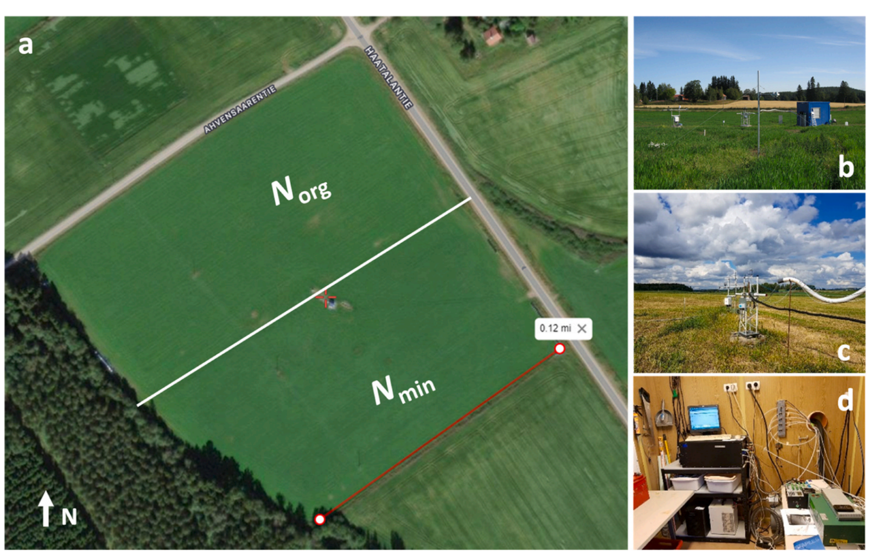

Fig. 1. Site location at Anttila (Maaninka, Finland) and experimental set-up. (a) Aerial view showing treatment layout with mineral nitrogen application (N_{min}) and biogas digestate slurry application (N_{org}) plots separated by a white line; (b-c) ground-level view of the flux measurement system in the field eddy covariance tower, and (d) ancillary measurement equipment including data acquisition system and gas analyzers housed in the instrument shelter.

approach with environmental conditions (soil temperature and moisture) and management period, following methodology validated for N_2O flux data (Mishurov and Kiely, 2011). Given the episodic nature of N_2O emissions and the recognized limitations of mean diurnal variation (MDV) for trace gas fluxes (Nemitz et al., 2018), MDV was applied only to short gaps (<4 h). Longer gaps were filled using the LUT approach, which has been shown to produce stable results for annual N_2O budget calculations (Mishurov and Kiely, 2011). Data coverage after quality control averaged 29.4 % for N_{min} and 43.6 % for N_{org} across the three-year period (Table S1), with interannual variation ranging from 24.9 % to 34.8 % (N_{min}) and 37.2–47.2 % (N_{org}). These coverage rates are consistent with other eddy covariance N_2O studies, where data recovery of 20–50 % is typical due to the stringent quality control requirements for trace gas fluxes (Cowan et al., 2020; Nemitz et al., 2018; Wecking et al., 2020). The continuous time series (Fig. 3a) indicates that the major emission events, including post-fertilization peaks and spring thaw pulses that dominate annual budgets, were well-captured within the retained dataset.

2.7. Environmental measurements

Environmental measurements were collected continuously throughout the study period. The variables measured included: net radiation (Rn, CNR1, Kipp & Zonen B.V., Delft, Netherlands), air temperature and relative humidity (HMP45C, Vaisala Inc., Vantaa, Finland), photosynthetically active radiation (PAR, SKP215, Skye Instruments Ltd., Llandrindod Wells, UK), soil temperature and volumetric water content at 5 and 20 cm depths (107 and CS616, Campbell Scientific Inc., Logan, UT, USA), and air pressure (CS106 Vaisala PTB110 Barometer, Vantaa, Finland).

All supporting meteorological and soil climate data were collected as 30-min mean values. Missing meteorological data were gap-filled using data from the nearby Maaninka weather station (Finnish Meteorological Institute), located approximately 6 km southeast of the experimental site.

2.8. Statistical analyses

All data analyses were conducted using R (version 4.3.3). A non-parametric method-Random Forest Model (Liaw and Wiener, 2002) was used to rank the importance of climate (air temperature), ecosystem CO_2 component (NEE, R_{eco}), and soil properties (e.g., temperature and water content) on changes in the N_2O fluxes, using the mean decrease accuracy (IncMSE %). A linear regression model was then used to analyze the overall effect of identified main drivers on N_2O fluxes using the "*lme4*" package (Bates et al., 2015). Figures were created using the "*ggplot2*" package (Villanueva and Chen, 2019). All statistical tests were conducted at a significance level of $p < 0.05$.

To contextualize emissions, we calculated the annual emission factor (EF%), which represents the percentage of applied nitrogen emitted as N_2O (Eq. 1) (Cowan et al., 2020; Hergoualc'h et al., 2021), and the yield-scaled N_2O emission ($Y_{N2O\text{-}N}$), which expresses emissions per unit of dry matter yield (Eq. 2) (Meng et al., 2023). These metrics provide insight into nitrogen use efficiency and the environmental cost of production.

Annual emission factors (EF) were calculated as (Eq. 1):

$$EF\ (\%) = (\text{Annual } N_2O\text{-N emissions} \ / \ \text{N fertilizer applied}) \times 100 \quad (1)$$

$$Y_{N2O\text{-}N} = \text{Annual } N_2O\text{-N emissions (g ha}^{-1}) \ / \ \text{Dry matter yield (kg ha}^{-1}) \quad (2)$$

3. Results

3.1. Climate and soil conditions

Meteorological conditions showed interannual variability across the rotation cycle (Fig. 2). Growing seasons commenced on 19 May (R_1), 1 May (R_2), and 1 May (R_3), with durations of 136, 155, and 142 days, respectively. Mean annual temperatures exceeded the 30-year average (3.2°C) by 0.9°C (R_1), 1.6°C (R_2), and 1.8°C (R_3) (Fig. 2a). Mean annual precipitation totaled 624 mm (R_1), 542 mm (R_2), and 509 mm (R_3), with R_2 and R_3 experiencing deficits of 11.4 % and 16.8 % relative to long-term means (612 mm, Fig. 2c).

Volumetric water content at 5 cm depth ranged from 0.09 to 0.54 m^3 m^{-3}, with significantly higher mean values during R_1 (0.34 m^3 m^{-3}) compared to R_2 and R_3 (0.27 m^3 m^{-3}; $p < 0.01$) (Fig. 2b). Soil temperature at 5 cm closely followed air temperature patterns, reaching highest of 20.9°C (July 2018) and 19.1°C (July 2019), while the winter lowest was −7.5°C.

3.2. N_2O fluxes measured by eddy covariance

N_2O fluxes showed varying patterns throughout the three-year rotation (Fig. 3a). The daily N_2O fluxes ranged from −0.5 to 0.5 nmol m^{-2} s^{-1} during periods without management disturbances (R_1-R_2), with N_2O uptake events observed predominantly during active vegetation growth phases.

The magnitude and frequency of emission events were strongly influenced by management practices and environmental conditions. Emission peaks occurred following specific management events, particularly fertilizer applications, with maximum flux rates of 11.7 nmol m^{-2} s^{-1} for N_{min} and 13.4 nmol m^{-2} s^{-1} for N_{org} treatments. These emission pulses typically lasted for 7–14 days. The timing of these emission events differed between treatments, with N_{min} showing bimodal emission patterns corresponding to the split fertilizer applications, while N_{org} showed single, more intense emission events following the digestate application.

Daily flux distributions (Fig. 3b) showed significant differences between rotation years ($p < 0.001$) but not between treatments during R_1 and R_2 ($p = 0.16$ and $p = 0.09$, respectively). During R_3, however, the N_{org} treatment showed significantly higher mean daily fluxes (7.1 ± 1.3 nmol m^{-2} s^{-1}) compared to N_{min} (5.9 ± 0.8 nmol m^{-2} s^{-1}; $p < 0.05$), despite receiving no fertilizer input.

3.3. Seasonal and cumulative N_2O emissions

The cumulative N_2O emissions suggested seasonal patterns and treatment effects throughout the rotation cycle (Fig. 3c-d). Emissions were higher during the growing seasons compared to non-growing seasons across all rotation cycle, with growing season emissions accounting for 65–78 % of annual totals (Table 2, Fig. 4a-b). This seasonal distribution was more significant under the N_{min} treatment, where growing season emissions constituted 78 %, 72 %, and 75 % of annual emissions in R_1, R_2, and R_3, respectively, compared to 65 %, 68 %, and 70 % under the N_{org} treatment. Annual emission increased through the rotation cycle (Table 2). Under N_{min}, emissions increased from 1.9 kg N_2O-N ha^{-1} yr^{-1} in R_1 to 2.2 kg N_2O-N ha^{-1} yr^{-1} in R_2 and 3.4 N_2O-N ha^{-1} yr^{-1} in R_3. The N_{org} treatment showed a similar trend: 2.6, 3.0, and 5.4 kg N_2O-N ha^{-1} yr^{-1} for R_1, R_2, and R_3, respectively, while N_{org} resulted in 36.8 %, 36.4 %, and 58.8 % higher N_2O-N emissions than N_{min} during R_1, R_2, and R_3, respectively (Table 3).

3.4. Emission factors and yield-scaled intensities

Under N_{min}, emission factors were 1.8 % (R_1), 2.1 % (R_2), and 7.6 % (R_3) (Table 2). For N_{org}, emission factors were 2.7 % (R_1) and 3.1 % (R_2), with R_3 excluded due to absence of fertilizer application.

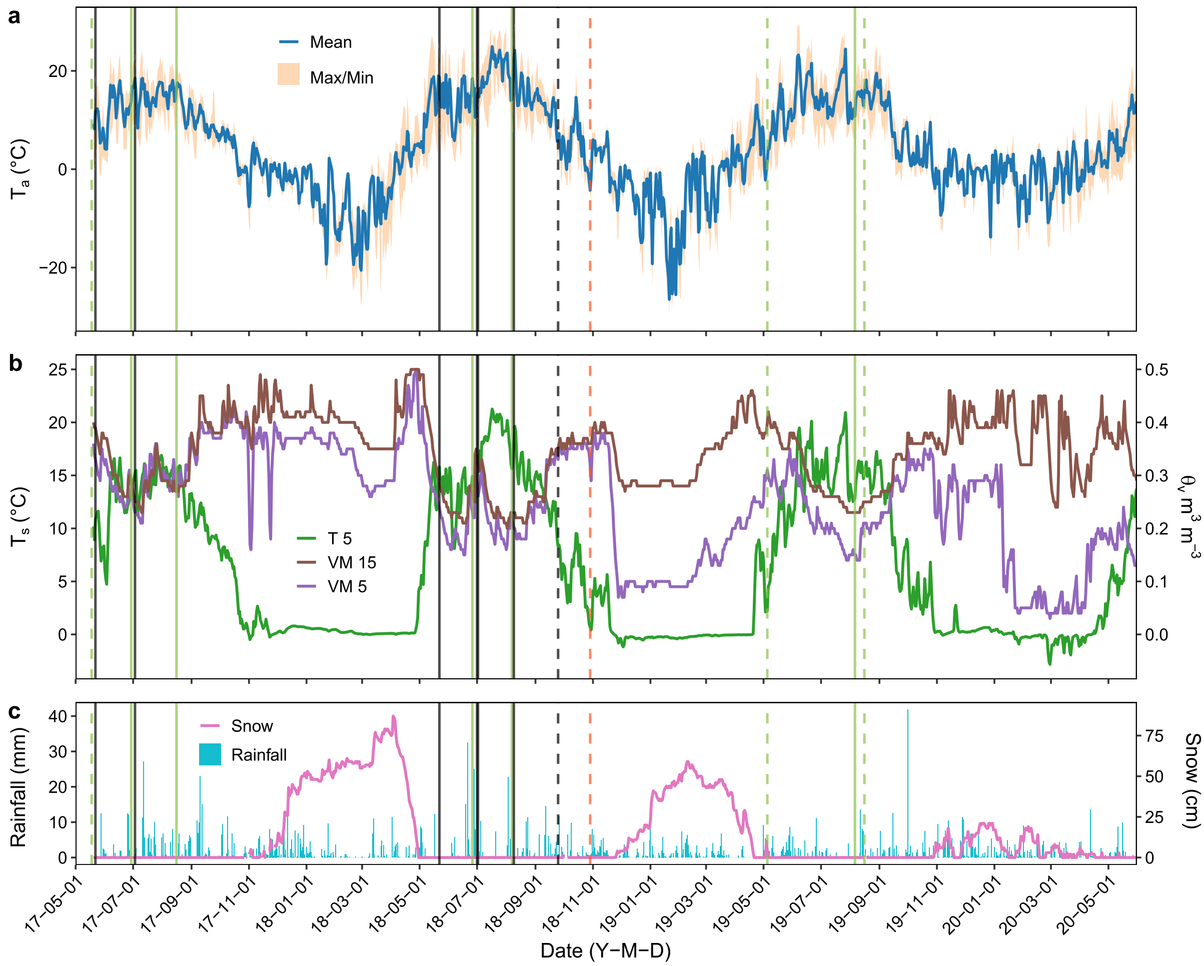

Fig. 2. Climatic conditions and management interventions during the three-year study period (2017–2020). (a) Daily mean air temperature (Ta, °C, blue line) with maximum and minimum values (orange shading); (b) soil temperature at 5 cm depth (Ts5, green line) and volumetric moisture content at 5 cm and 15 cm depths (VM5, purple line; VM15, brown line); (c) daily precipitation (blue bars) and snow depth (pink line). Vertical lines indicate management events: green = seeding, yellow = harvest, black = fertilization, blue = glyphosate, red = plowing. Detailed management information is provided in Table 1.

During grass production years (R_1 and R_2), yield-scaled emissions were relatively stable at 0.32–0.35 g N_2O-N kg^{-1} DM under N_{min} and 0.44–0.53 g N_2O-N kg^{-1} DM under N_{org} (Table 2). However, these values increased to 1.00 ± 0.15 and 1.57 ± 0.23 g N_2O-N kg^{-1} DM in R_3, respectively.

3.5. Environmental drivers of N_2O emissions

Multivariate analysis suggested different environmental controls between fertilization treatments (Fig. 5a). Under N_{min} treatment, ecosystem respiration was the dominant predictor, followed by net ecosystem exchange and soil temperature at 5 cm depth. Linear regression confirmed negative correlation between soil temperature and N_2O emissions ($R^2 = 0.013$, $p < 0.001$, Fig. 5b). Under N_{org} treatment, soil temperature at 5 cm depth showed the highest relative importance in the multivariate analysis. Its individual linear relationship with N_2O emissions was weak and negative ($R^2 = 0.009$, $p < 0.01$, Fig. 5c).

4. Discussions

4.1. Emission factors exceed current inventory defaults

The present multi-year eddy covariance measurements indicate emission factors ranging from 1.79 % to 7.56 % for N_{min} and 2.65–3.06 % for N_{org}, representing a 2- to 8-fold exceedance of the IPCC Tier 1 default value of 1 % for managed grasslands (Calvin et al., 2023; Hergoualc'h et al., 2021). This underestimation aligns with continuous flux measurements challenging the adequacy of current inventory methodologies (Hergoualc'h et al., 2021). Previous eddy covariance studies from intensively managed European grasslands support these findings, reporting emission factors of 0.87–1.69 % in Scotland (Cowan et al., 2020), 1.91–2.58 % in Switzerland (Hörtnagl et al., 2018), and 1.4–3.8 % in Irish systems (Murphy et al., 2022). The convergence of evidence across diverse pedoclimatic conditions suggests that chamber-based emission factors, which form the basis of current defaults, might fail to capture episodic emission events that can dominate annual N_2O budgets.

The exceptional emission factor of 7.56 % observed during the renovation year (R_3), despite reduced fertilizer application (45 kg N ha^{-1}), highlights the critical role of soil physical disturbance in regulating N_2O production pathways. The mechanistic basis for this enhancement likely involves the disruption of soil aggregate structure through plowing, which simultaneously exposes previously protected organic nitrogen pools to rapid mineralization and creates anaerobic microsites conducive to denitrification (Baggs et al., 2003; Ball et al., 2008). The magnitude of this renovation effect in our boreal system exceeds observations from temperate grasslands, where Merbold et al. (2014) reported 3.2-fold increases and Hörtnagl et al. (2018) observed 4.7-fold elevations relative to established grasslands.

It is important to note that emission factors derived from eddy

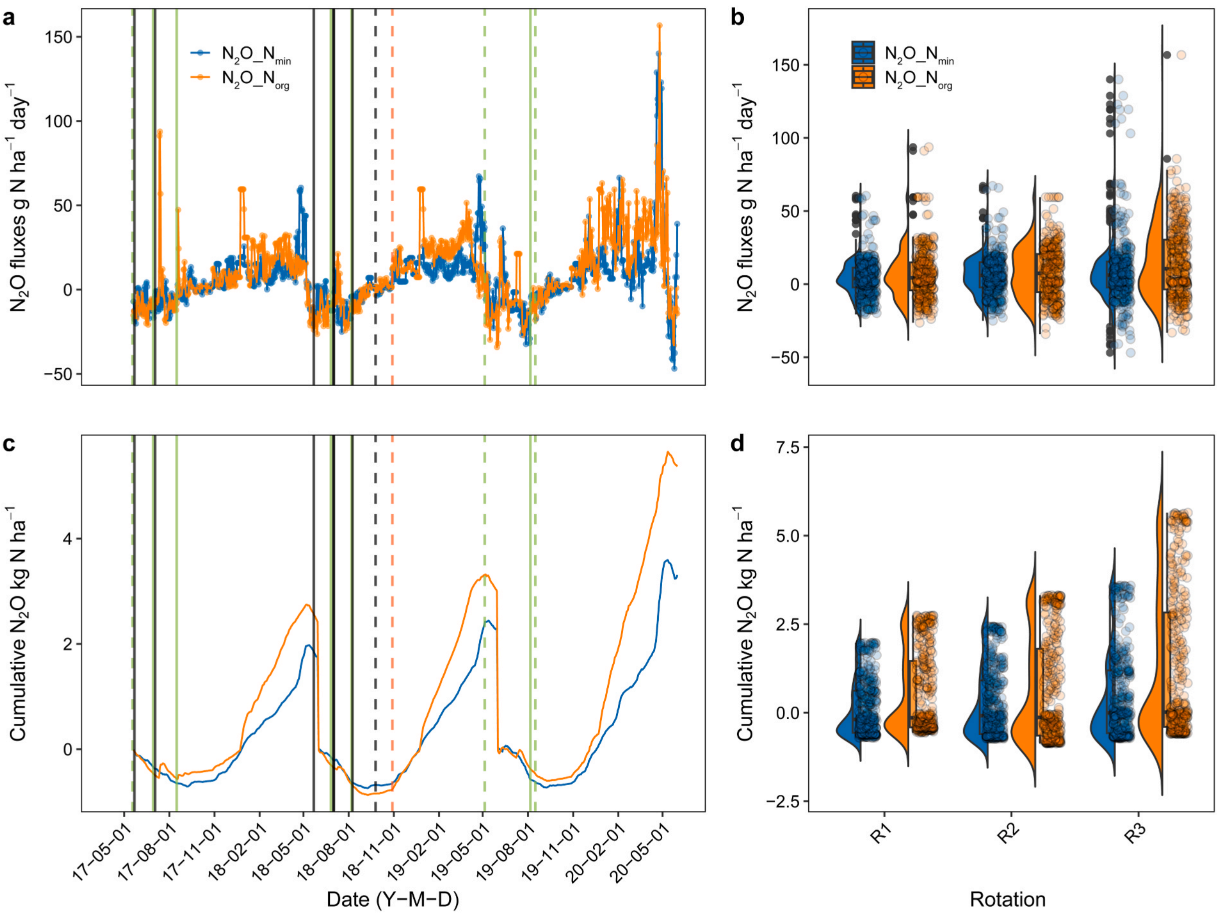

Fig. 3. Temporal patterns of nitrous oxide (N_2O) fluxes under mineral nitrogen (N_{min}) and biogas digestate slurry (N_{org}) treatments. (a) Daily N_2O fluxes (nmol m^{-2} s^{-1}) across the three-year rotation with management events indicated by vertical lines (color coding as in Fig. 2); (b) distribution of daily N_2O fluxes by rotation period; (c) cumulative N_2O emissions (kg N ha^{-1}) across the three-year rotation; and (d) distribution of running cumulative N_2O emissions by rotation period. The experiment spanned three rotation cycles: R_1 (May 2017 - May 2018), R_2 (June 2018 - May 2019), and R_3 (June 2019 - May 2020). Detailed management information is provided in Fig. 2 and Table 1.

Table 2
Annual nitrous oxide emissions, emission factors, and seasonal distribution under mineral (N_{min}) and organic (N_{org}) nitrogen management across the three-year rotation cycle.

Rotation	Treatment	Annual emissions (kg N ha^{-1})	Emission factor (%)	Growing season (% of annual)	Non-growing season (% of annual)
R_1	N_{min}	1.9 ± 0.2	1.8	78	22
	N_{org}	2.6 ± 0.3	2.7	65	35
R_2	N_{min}	2.2 ± 0.3	2.1	72	28
	N_{org}	3.0 ± 0.4	3.1	68	32
R_3	N_{min}	3.4 ± 0.4	7.6[a]	75	25
	N_{org}	5.4 ± 0.6	n.a.[b]	70	30

Note: [a] Based on 45 kg N ha^{-1} applied; [b] No fertilizer applied

covariance measurements are not directly comparable to chamber-derived IPCC default values due to fundamental methodological differences (Wecking et al., 2020). Chamber-based emission factors are calculated by subtracting background emissions (measured from unfertilized control plots) from fertilized plot emissions, thereby isolating the fertilizer-induced N_2O fraction. In contrast, EC-derived emission factors represent total ecosystem emissions including both fertilizer-derived and background N_2O from soil organic matter cycling, plant residue decomposition, and biological nitrogen fixation in legume systems. As indicated by Wecking et al. (2020), this methodological distinction can account for substantial differences in reported emission factors.

4.2. Fertilizer type effects reveal contrasting biogeochemical pathways

The increased emissions from N_{org} (36.8 %, 36.4 %, and 58.8 % increases across R_1, R_2, and R_3, respectively) challenge assumptions regarding the greenhouse gas mitigation potential of organic amendments including the use of legumes as nitrogen source. From the clover material added in autumn to soil, 60–77 % is still in soil after the following growing season in Finnish conditions (Müller, 1988). Soil is thus accumulating plant-derived nitrogen across rotation cycles. It is noteworthy that most of the clover nitrogen added in autumn is liberated during winter, not during the following growing season (Müller and Sundman, 1988). This likely favors N_2O emissions during winter and spring time.

Our findings align with evidence from cold-climate agricultural systems suggesting that carbon-nitrogen stoichiometric interactions may have an impact when comparing mineral and organic fertilizers (Zaehle, 2013). Petersen et al. (2023) reported 6.8-fold higher emissions from cattle slurry relative to mineral fertilizer applications on Danish sandy soils. The more moderate increases observed in the present study likely reflect the higher clay content (25 %) and associated enhanced nitrogen retention capacity characteristic of silt loam soils (Lipiec et al., 2007).

The divergent environmental controls identified between

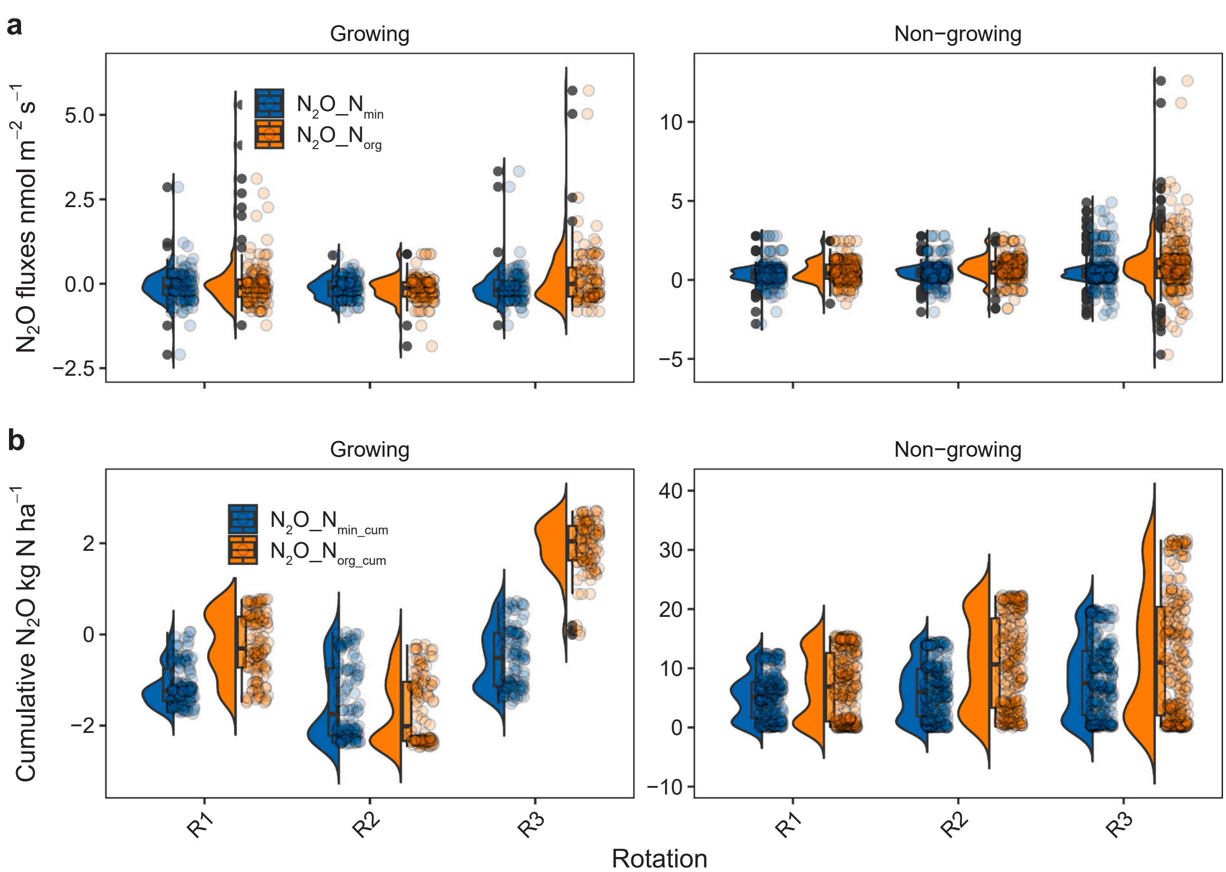

Fig. 4. Seasonal variability in nitrous oxide (N_2O) fluxes under mineral nitrogen (N_{min}) and biogas digestate slurry (N_{org}) treatments. (a) Distribution of daily N_2O fluxes (nmol m^{-2} s^{-1}) during growing and non-growing seasons for each rotation period; (b) distribution of running cumulative N_2O emissions (kg N ha^{-1}) during growing and non-growing seasons for each rotation period. Each point represents the cumulative sum up to that date within the season. Violin plots show data distribution with individual measurements represented by points. The experiment spanned three rotation cycles: R_1 (May 2017 - May 2018), R_2 (June 2018 - May 2019), and R_3 (June 2019 - May 2020).

Table 3
Biomass yields and yield-scaled nitrous oxide (N_2O) emission across rotation cycles.

Rotation	Yield (kg DM ha^{-1})		Yield-scaled emissions (g N_2O-N kg^{-1} DM)	
	N_{min}	N_{org}	N_{min}	N_{org}
R_1	5860 ± 123	4880 ± 605	0.32 ± 0.04	0.53 ± 0.08
R_2	6316 ± 1202	6810 ± 62	0.35 ± 0.05	0.44 ± 0.06
R_3	3410 ± 186	3440 ± 149	1.00 ± 0.15	1.57 ± 0.23

Note: Yield data has been published in Li et al. (2023).

fertilization strategies provide mechanistic insights into the underlying biogeochemical processes. Under N_{min}, the dominance of ecosystem respiration as a predictive variable suggests that N_2O emissions are closely coupled with overall soil biological activity and carbon cycling processes. Ecosystem respiration integrates microbial decomposition activity, root respiration, and substrate availability, all of which influence the oxygen consumption and carbon substrate supply that govern denitrification rates (Butterbach-Bahl et al., 2013). The primacy of temperature control under N_{org} indicates rate limitation by organic matter mineralization rates. The observed temperature effect aligns with enzymatic depolymerization processes governing organic nitrogen release (Conant et al., 2011), suggesting that emission dynamics from N_{org} might be constrained by microbial decomposition rates rather than substrate availability.

4.3. Renovation phase dominates rotational emission budgets

The 55–80 % increase in N_2O emissions during the renovation year relative to the previous production years suggests soil disturbance as the paramount emission hotspot within boreal grassland management cycles. This finding aligns with observations from organic soil systems, where Maljanen et al. (2004) observed up to 15-fold emission increases, relative to mineral soil environments, albeit with more moderate enhancement. The increased N_2O emissions in our study likely reflects both the strategic timing of renovation activities and rapid cover crop establishment that partially mitigated emission potential.

Cumulative emissions during R_3 (3.4 kg N_2O-N ha^{-1} for N_{min}, 5.4 kg N_2O-N ha^{-1} for N_{org}) represented 31 % and 42 % of total three-year emissions, respectively, despite comprising only one-third of the rotation period. This suggests a limitation in current inventory methodologies that apply uniform emission factors across management times, thereby misrepresenting the temporal distribution of grassland N_2O emissions. The N_2O emissions under N_{org} during R_3, despite the absence of fertilizer application, provides evidence for legacy effects that accumulated organic matter provides substrate for mineralization following physical disturbance (Davies et al., 2001; Kristensen et al., 2003). Ploughing disrupts soil aggregate structure, exposing previously protected organic nitrogen to mineralization. Kristensen et al. (2003) reported using ^{15}N labeling that tillage releases nitrogen from pools otherwise protected against microbial degradation, with protected N pools contributing 22–27 % of total mineralized nitrogen. Similarly, Six et al. (2000) showed that conventional tillage induces macroaggregate turnover, exposing physically protected organic matter to microbial

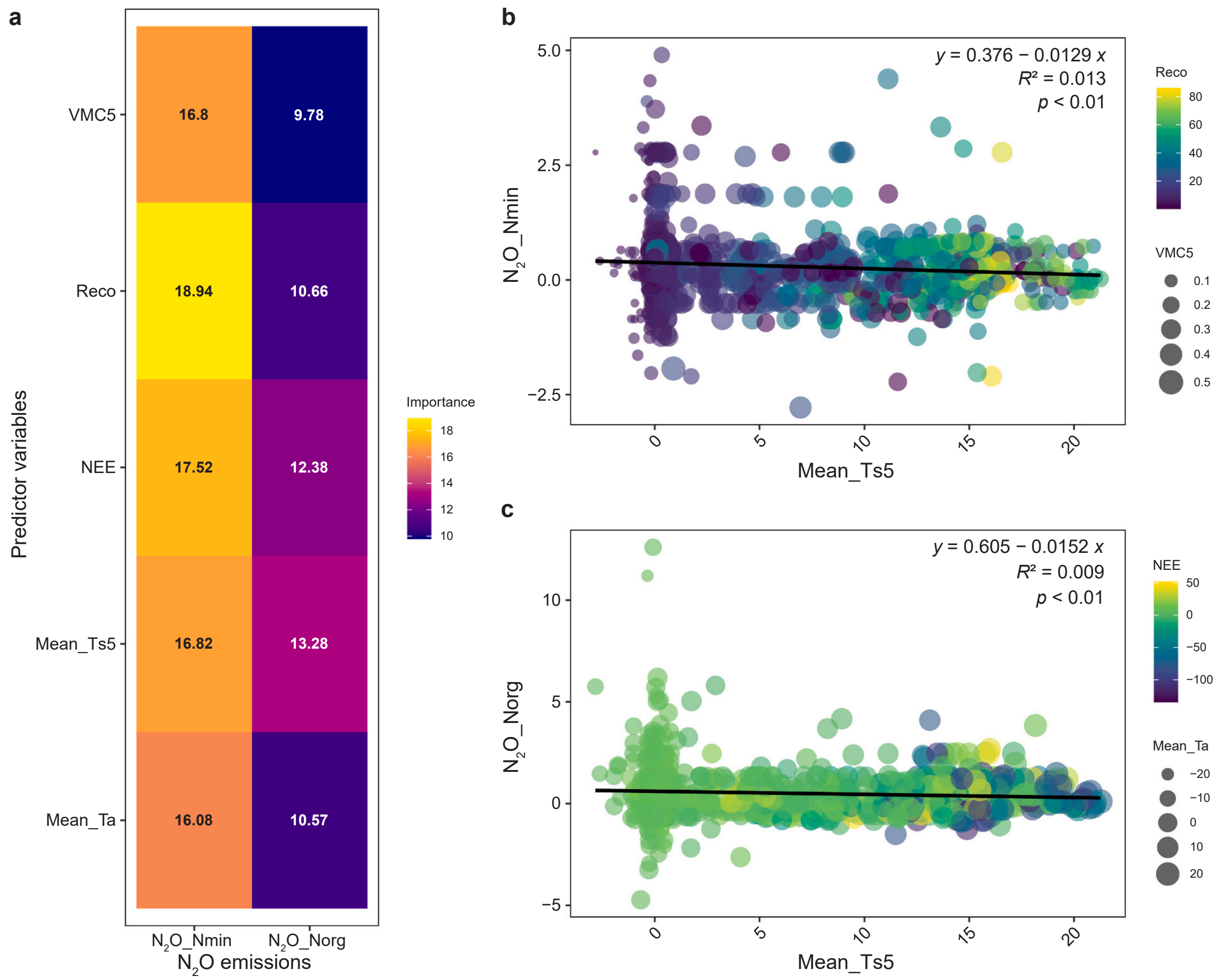

Fig. 5. Environmental drivers of nitrous oxide (N_2O) emissions. (a) Relative importance of predictor variables for N_2O emissions under mineral nitrogen (N_{min}) and biogas digestate slurry (N_{org}) treatments, with higher values (yellow) indicating stronger influence; (b) relationship between soil temperature at 5 cm depth (Mean_Ts5) and N_2O emissions under N_{min} treatment, with point size indicating soil volumetric moisture content (VMC5); (c) relationship between soil temperature at 5 cm depth (Mean_Ts5) and N_2O emissions under N_{org} treatment, with point size indicating air temperature (Mean_Ta) and color indicating net ecosystem exchange (NEE). Linear regression equations and statistical significance are shown for each relationship.

attack. The increased N_2O emissions during the renovation year can additionally be attributed to reduced plant nitrogen uptake capacity. Following reseeding, newly established vegetation has not developed a strong root system capable of competing with soil microorganisms for available nitrogen (Kuzyakov and Xu, 2013; Velthof et al., 2010). Furthermore, ploughing enhances soil porosity and aeration, which affects N_2O production pathways. Estavillo et al. (2002) showed that ploughing promotes soil organic nitrogen mineralization while simultaneously affecting soil aeration conditions. Velthof et al. (2010) indicated that ploughing decreases bulk density and increases oxygen availability, which can affect the balance between nitrification and denitrification processes.

The 55–80 % increase in N_2O emissions during the renovation year relative to the previous production years aligns with findings from temperate grassland systems. Wall et al. (2023), using eddy covariance measurements on intensively grazed pastures in New Zealand, reported that grassland renewal contributed significantly to annual greenhouse gas budgets, with renovation-related emissions representing a critical but often underquantified component of pastoral carbon footprints. Chamber-based studies have reported similar patterns: Velthof et al. (2010) observed 1.8–3.0-fold increases in N_2O emissions following grassland renovation in the Netherlands, while Reinsch et al. (2018) reported annual emissions of 1.9–21.3 kg N_2O-N ha^{-1} in the reseeding year for German grass-clover swards, with freeze-thaw events and enhanced soil mineral N driving emission peaks.

Buchen (2017) reported that soil mineral N dynamics following grassland renewal are characterized by rapid accumulation of NO_3^- and NH_4^+ from mineralization of ploughed-in residues, creating conditions favorable for both nitrification and denitrification-derived N_2O production. The magnitude of renovation effects in our boreal system (55–80 % increase) falls within the lower range of reported values from temperate studies (80–500 %), likely reflecting the strategic timing of renovation activities and the rapid establishment of cover crops that partially mitigated emission potential (Semberg et al., 2026).

4.4. Yield-scaled emissions suggest complex sustainability trade-offs

Yield-scaled emissions provide context for evaluating management sustainability beyond simplistic area-based metrics. During grass production years (R_1-R_2), yield-scaled emissions of 0.32–0.53 g N_2O-N kg^{-1} DM are consistent with reported ranges from European managed grasslands. Area-based emissions from 14 European grassland sites ranged from 0.1 to 4.2 kg N_2O-N ha^{-1} yr^{-1} across management intensity gradients (Hörtnagl et al., 2018), which correspond to yield-scaled intensities of approximately 0.01–0.70 g N_2O-N kg^{-1} DM when combined with typical intensive grassland yields (6–12 t DM ha^{-1}).

These renovations induced emissions suggest that extending rotation length might be a more effective mitigation strategy than fertilizer type substitution alone. Process-based modeling studies indicate that lengthening rotations from conventional 3–4 year cycles to 5–7 years could reduce time-averaged annual emissions by 25–40 % (Del Grosso et al., 2022). However, such extensions must be balanced against potential yield or forage quality decline in aging grasslands (Iepema et al., 2020), particularly under boreal conditions where winter stress and frost heaving can accelerate grassland degradation (Rochefort and Lode, 2006). Maintaining productive capacity in extended rotations may necessitate complementary management practices including strategic overseeding, adjusted fertilization practices, or integration of deep-rooting species to enhance system resilience.

4.5. Non-growing season emissions constitute a substantial fraction of annual emissions

The 22–78 % contribution of non-growing season emissions to annual N_2O emissions challenges temperate-derived assumptions regarding dormant season fluxes and highlights the unique biogeochemical dynamics of high-latitude agroecosystems (Krogstad et al., 2022; Maljanen et al., 2004; Virkajärvi et al., 2010). These proportions exceed typical estimates of 10–15 % for continuously snow-covered systems but remain below the 40–78 % reported from sites experiencing multiple freeze-thaw cycles (Sturite et al., 2021; Wagner-Riddle et al., 2017). The N_2O emissions observed in our study likely reflect the moderating influence of persistent snow cover, which provides thermal insulation against extreme temperature fluctuations while maintaining conditions for N_2O productions and emissions (Maljanen et al., 2007).

4.6. Implications for inventory improvement and policy development

Our findings indicate reconsideration of emission factor development for boreal grassland systems. The current practice of applying uniform factors across management phases fails to capture the 4-fold variation observed between grass production and renovation years. Development of phase-specific factors would improve inventory accuracy, though implementation requires corresponding refinement in activity data collection to track renovation frequency at regional scales.

The emission differences between fertilizer types suggest that differentiated emission factors based on nitrogen sources would enhance predictive capacity beyond current categorical approaches. However, the interaction between fertilizer type and management phase, exemplified by the amplified organic fertilizer effect during renovation, indicates that simple categorical adjustments may prove insufficient for capturing system complexity. Process-based models such as DNDC currently show limited capacity to capture the complex biogeochemical changes associated with organic amendments and soil disturbance during grassland renovation (Thentu et al., 2025), highlighting the critical importance of empirical measurements for validating and improving model predictions.

4.7. Interpretation of negative N_2O fluxes

Negative N_2O fluxes were observed during 15–22 % of measurement periods, predominantly during winter dormancy and early spring before soil thaw. While such observations require cautious interpretation, negative N_2O fluxes have been reported in grassland ecosystems (Chapuis-Lardy et al., 2006) and may result from: (1) microbial N_2O reduction to N_2 via denitrification under highly reducing conditions; (2) N_2O consumption in sub-surface soils; or (3) measurement artifacts associated with low flux magnitudes near detection limits. Shurpali et al. (2016) reported diurnal variations in N_2O fluxes including periods of net N_2O uptake and reduced N_2O emissions during daytime at this study site cultivated during 2009 – 2011 with reed canary grass (*Phalaris arundinaceae, L*), a perennial bioenergy crop. They suggested that neglecting such diurnal patterns introduces significant uncertainties in annual emission estimates.

We assessed whether negative fluxes represented systematic patterns or random measurement noise (Liang et al., 2018; Wecking et al., 2020). The negative fluxes in our study showed non-random temporal clustering. For annual budget calculations, we retained negative fluxes to avoid positive bias, while acknowledging this introduces uncertainty.

4.8. Study limitations and future research priorities

The absence of concurrent ammonia volatilization, N_2 emission, soil nitrogen availability, and leaching measurements underestimates complete nitrogen budget calculation, though typical volatilization losses of 5–15 % from digestate applications suggest relatively minor impacts on emission factor calculations (Smith et al., 2020).

Future research should prioritize: (1) integrating automated chamber networks with tower measurements to resolve spatial heterogeneity while maintaining temporal coverage; (2) to include also N loss as N_2 and via leaching; and (3) developing coupled biogeochemical-management models capable of simulating renovation impacts under climate change scenarios. These would enable transition from empirical emission factors to process-based predictions supporting adaptive management under changing environmental conditions.

5. Conclusion

This study provides a multi-year eddy covariance dataset of N_2O emissions from boreal legume grasslands, showing that while mineral nitrogen resulted in a wider emission factor range across R_1 to R_3 (1.79–7.56 %), organic fertilization resulted in consistently higher emission factors in R_1 and R_2 (2.65–3.06 %). The grassland renovation phase emerged as the dominant emission period, contributing 31–42 % of three-year cumulative emissions despite representing only one-third of the rotation cycle. Contrary to expectations, organic fertilization increased emissions by 37–59 % relative to mineral fertilization across all rotation years. The identification of divergent environmental controls, ecosystem respiration dominance under mineral fertilization versus temperature control under organic amendments, provides insights into fertilizer-specific emission pathways. Non-growing season emissions contributed 22–35 % of annual budgets, highlighting the importance of continuous measurements for capturing cold-season dynamics in boreal systems. These findings highlight that emission factors derived from eddy covariance measurements consistently exceed IPCC Tier 1 default values derived from chamber-based approaches. While this difference partly reflects fundamental methodological distinctions between the two approaches, the variation between grass production and renovation phases highlights the need for phase-specific emission accounting within grassland rotation cycles.

CRediT authorship contribution statement

Narasinha Shurpali: Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Hem Raj Bhattarai:** Writing – review & editing. **Perttu Virkajärvi:** Writing – review & editing. **Pertti J Martikainen:** Writing – review & editing, Conceptualization. **Tulasi Lakshmi Thentu:** Writing – review & editing, Validation, Conceptualization. **Yuan Li:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was funded by the funding from the Research Council of Finland funded grants (INDO-NORDEN (2017 – 2020), ENSINK (2020–2024), Just Transition Fund (JTF) through the Regional Council of Pohjois-Savo (N-Fiksu; grant number J10804), ORMINURMI project, and AGCLIMATE project. The authors acknowledge the technical support provided by Luke Maaninka staff for the field trial and measurements.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2026.107143.

Data availability

Data will be made available on request.

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