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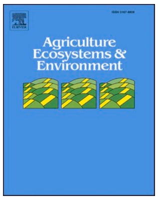

Species specific effects of cover crops on nitrous oxide emissions in hemiboreal cereal production: The importance of freeze-thaw driven emissions

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ABSTRACT

Including cover crops in cereal production systems has the potential to reduce greenhouse gas (GHG) emissions from agriculture by sequestering carbon (C) in soils. However, growing crops during the off-season interferes with cold season soil nitrogen (N) cycling, with uncertain effects on the emission of nitrous oxide (N_2O), the dominant anthropogenic GHG in crop production. In this study, we investigated N_2O emissions in barley production systems with seven different cover crops over two years and modelled soil organic C (SOC) accrual based on biomass production to calculate species-specific GHG balances. We measured N_2O emission rates weekly using manual chambers during the cropping season and more frequently during the off-season with a field flux robot. Off-season emissions exceeded those from the growing season, accounting for 67 % (±14 % SD) of annual emissions. Among the cover crops, oilseed radish had the largest N_2O emissions and the largest off-season contribution, whereas a herb mixture and ryegrasses (*Lolium perenne* and *Lolium multiflorum*) emitted less N_2O than barley grown without cover crops. The largest emissions were observed during diurnal freeze-thaw cycles and spring thaw. Based on the estimated GHG balances (measured N_2O emissions vs. modelled SOC accrual), we conclude that winter-hardy cover crops have the potential to reduce overall GHG emissions. In contrast, frost-sensitive cover crops support large N_2O emissions during winter, undermining the mitigation effect of SOC accrual. Our findings emphasise the importance of including off-season N_2O emissions in C farming schemes that use cover crops in temperate and hemiboreal cereal production systems.

1. Introduction

The increased use of cover crops in arable crop production offers a promising strategy to mitigate climate change by sequestering additional carbon (C) in soils (Guenet et al., 2021; Abdalla et al., 2019). Even a small increase in the soil organic C (SOC) pool could significantly reduce the agricultural sector's climate footprint (Lal, 2004) and serve as a carbon-negative technology in future climate change mitigation scenarios (Luu et al., 2025). The potential for C gains is substantial, as intensive agriculture has depleted SOC stocks on a global scale (Karstens et al., 2022).

The extent to which cover crops can sequester additional C in soils is still debated (Chaplot and Smith, 2023), but most studies highlight a positive effect of cover crops on SOC stocks and soil health (Poeplau et al., 2024; Guenet et al., 2021; Poeplau and Don, 2015). Moreover, cover crops provide a range of other benefits, such as reduced nitrate (NO_3^-) leaching and soil erosion, as well as improved water holding capacity, soil porosity and aggregate stability (Abdalla et al., 2019; Basche et al., 2014; Engedal et al., 2023).

Using legumes as cover crops can reduce the need for mineral fertilisers, thereby contributing to climate-smart fertilisation (Thorup-Kristensen, 2006a; Meena et al., 2018). Additionally, non-leguminous cover crops can minimise the need for fertiliser by reducing nitrogen (N) losses to air and water and retaining N within the cropping system (Thorup-Kristensen et al., 2003). Conversely, the process of sequestering additional C in soils may immobilise reactive N and phosphorus (P). This could lower cash crop yields if N and P fail to replenish through external sources, biological N fixation or mobilisation from the soil. Cover crops are likely to influence N cycling in a species-specific way, depending on factors such as root-to-shoot ratio,

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root architecture, secondary plant metabolites, winter hardiness, biomass accumulation and the method of termination (Abalos et al., 2022; Guardia et al., 2025; Kuo and Sainju, 1998; Seitz et al., 2024).

Nitrous oxide (N_2O) emissions often result from N turnover within the soil-plant system (Firestone and Davidson, 1989). N_2O is the single most important greenhouse gas (GHG) emission associated with crop production and poses a major challenge for mitigating climate change in the agricultural sector (IPCC, 2022). Cover crops can influence N_2O emissions in various, contrasting ways; for example, N_2O emissions may decrease when the cover crop assimilates excess N not taken up by the main crop (Thorup-Kristensen, 1994, 1993; Sedghi and Weil, 2022). Similarly, the uptake of NO_3^- by cover crops from deeper soil layers can reduce leaching and indirect N_2O emissions (Kristensen and Thorup-Kristensen, 2004; Thorup-Kristensen, 2006b; Ding et al., 2021). However, N_2O emissions may increase when cover crops supply fresh organic matter to the soil, for example upon frost kill (Peng et al., 2019) or when ploughed under or sprayed with herbicides (Peyrard et al., 2016; Snapp and Borden, 2005; Abalos et al., 2022; Andersen et al., 2025). The addition of extra biomass can stimulate microbial soil C and N turnover (Singh et al., 2020), increase net N-mineralisation (Vogeler et al., 2022; Rosecrance et al., 2000) and consume oxygen (Lussich et al., 2024), all of which are conditions that affect nitrification and denitrification (Mørkved et al., 2006). The presence of partly frost-sensitive cover crop biomass may enhance off-season N_2O production by increasing both available N and readily available C sources for microbial activity (Byers et al., 2020; Sturite et al., 2021). Frost-sensitive cover crops are species that do not survive freezing temperatures and typically die or suffer severe damage after the first frost events. The risk of plant-induced N_2O emissions is particularly high during the off-season in cool-temperate regions experiencing freeze-thaw cycles (Li et al., 2015; Abalos et al., 2022). Increased N_2O emissions also occur during the growing season following the use of cover crops (Li et al., 2015; Abalos et al., 2022).

N_2O emissions in cool-temperate regions are often dominated by emissions occurring during the spring thaw (Flessa et al., 1995; Wagner-Riddle et al., 2008, 2017; Risk et al., 2013). Several processes contribute to spring-thaw emissions, including: i) subnivean accumulation of N_2O in the subsoil beneath frozen topsoils, followed by its release during spring thaw (Goodroad and Keeney, 1984; Burton and Beauchamp, 1994); and ii) soil conditions that favour denitrification during freeze-thaw cycles, such as increased C and N availability and oxygen depletion (Edwards and Killham, 1986; Chen et al., 1995; Christensen and Tiedje, 1990; Teepe et al., 2001; Dörsch et al., 2004). The duration of frost, often measured as cumulative freezing-degree days, has been shown to be a good predictor of the magnitude of N_2O emissions during spring thaw (Libby et al., 2020; Wagner-Riddle et al., 2017). However, the effect of cover crops on N_2O emissions during the spring thaw remains uncertain. While N_2O emissions and soil C sequestration are often studied independently, these processes are interconnected. Therefore, both processes must be studied together to fully understand the net climate impact of cover crops.

The objective of this study was i) to evaluate how different cover crop species influence N_2O emissions under hemiboreal conditions, and ii) to understand how altered N_2O emissions offset the expected cooling effect by enhanced C sequestration. We quantified annual N_2O emissions using manual chambers during the cropping season and a field flux robot during the off-season over a two-year period in a barley field on silt loam soil in southeastern Norway. Seven different cover crop species, along with a control without cover crops, were established in a field experiment using a factorial design. The selected cover crop species included both annual leguminous and non-leguminous species (Italian ryegrass, oilseed radish, common vetch, hairy vetch), as well as one perennial species (perennial ryegrass) in single stands, and one mixture consisting of 13 different species (perennial and annual leguminous and non-leguminous species). We also investigated two sowing times and two N fertilisation rates. The field was managed as a conventional cereal cropping system following common practices. We further examined the legacy effect of cover crops on wheat yields in the year following the two treatment years. We hypothesised that: i) the growth and winter survival of cover crop species would influence the aggregated climate effect of SOC accrual and N_2O emissions; ii) soils planted with winter-hardy cover crop species would emit less N_2O during the off-season compared to plots with frost-sensitive annual species; and iii) off-season emissions during spring-thaw would dominate annual emissions at this hemiboreal site with cold winters.

2. Materials and methods

2.1. Site and experimental design

The field experiment was conducted at the experimental farm Kjerringjordet at NMBU in Ås, Norway (59°39'50"N, 10°45'40"E) from spring 2021 to spring 2023, with barley as the main crop. An additional growing season with wheat was included in 2023 exclusively for biomass measurements. The soil at the site is classified as a silt loam, consisting of 22 % clay, 54 % silt and 24 % sand (Table S1). The bulk density of the soil was 1.24 ± 0.07 g cm^{-3} and the pH, measured in 1:2.5 dry soil to water, was 5.9 ± 0.1. The soil contained 6.1 % organic matter, 2.33 % C and 0.24 % N (Table S1). The 30-year normal (1991–2020) for the site is a mean annual temperature (MAT) of 6.3°C and a mean annual precipitation (MAP) of 892 mm (Klimaservicesenter, 2025). However, both experimental years were warmer and drier, with a MAT of 6.6°C and 7.3°C and a MAP of 621 mm and 712 mm in 2021 and 2022, respectively. Both winters were snow-poor, with maximum snow cover not exceeding 19 cm in the first winter and 26 cm in the second (Wolff and Grimenes, 2022, 2023).

The treatments were arranged in a completely randomised, partially factorial design without blocks (Fig. S1). The treatment factor 'cover crop' included eight levels: controls without cover crop and seven cover crops, namely perennial ryegrass, Italian ryegrass, oilseed radish, common vetch, hairy vetch, phacelia and a herb mixture (Table 1). The treatment factor 'N fertilisation' had two levels: a single application in

Table 1
Overview of barley controls and cover crop treatments used in 2021 and 2022, some of which had two different fertilisation regimes (N1 = 144 kg N ha^{-1} in spring and N2 = 144 kg N ha^{-1} in spring + 25 kg N ha^{-1} in autumn). Seeding rate is given as kg grain ha^{-1}. Dates for field activities can be found in Table S2.

	Fertilisation	Sown in	Seeding rate (kg ha^{-1})
Barley control (*Hordeum vulgare*)	N1 and N2	Spring	200
Herb mixture[*]	N1	Spring	8
Perennial ryegrass (*Lolium perenne*)	N1 and N2	Spring	8
Italian ryegrass (*Lolium multiflorum*)	N1 and N2	Spring	8
Oilseed radish (*Raphanus sativus*)	N1 and N2	Autumn	36
Common vetch (*Vicia sativa*)	N1	Autumn	210
Hairy vetch (*Vicia villosa*)	N1	Autumn	30
Phacelia (*Phacelia tanacetifolia*)[**]	N1 in 2021 and N2 in 2022	Autumn	15

[*] The Herb Mixture consisted of (by seed weight) 30 % Perennial ryegrass (Lolium perenne), 20 % Meadow fescue (Lolium pratense), 13 % Timothy (Phleum pratense), 8 % Italian ryegrass (Lolium multiflorum), 5 + 5 + 5 %, White-, red- and crimson clover (Trifolium repens, Trifolium pratense, Trifolium incarnatum), 5 % Common bird's-foot trefoil (Lotus corniculatus), 5 % Camelina (Camelina sativa), 3 % Herbs: Common chicory (Cichorium intybus), Burnet (Sanguisorba minor), Caraway (Carum carvi), 1 % Phacelia (Phacelia tanacetifolia).

[**] Phacelia did not establish in single stands and was grouped with the control plots.

spring (N1) or two applications in spring and autumn (N2). All treatments (cover crops and controls) received N1 fertilisation in spring. The leguminous cover crops (common vetch, hairy vetch, phacelia and the herb mixture) received only N1 fertilisation, accounting for the additional N input provided by biological N fixation. The non-leguminous treatments with additional N2 fertilisation (control, Italian ryegrass, perennial ryegrass and oilseed radish) were included to determine whether N availability limited biomass production, as cover crop growth is constrained by the cool and humid climate of southeastern Norway. This design resulted in a total of 12 treatments.

Each treatment had three replicates in the field (Fig. S1). The cover crop species were grouped into four functional classes: grasses (perennial and Italian ryegrass), one brassica (oilseed radish), legumes (common and hairy vetch) and a mixture (perennials, herbs, legumes) (Table 1). The annual herb phacelia was also included in the study but failed to establish in either year, for reasons that remain unclear. Phacelia was sown with N1 fertilisation in the first year, and an additional N fertilisation (N2) was applied in the second year in an attempt to improve establishment; however, these efforts were unsuccessful (Table S3 and Fig. S10). Due to the lack of biomass and negligible contributions to SOC accrual or N_2O emissions, phacelia was grouped with the control treatments for data analysis, which resulted in an unbalanced number of replicates.

Cover crops were sown in either spring, shortly after barley was sown, or three weeks before the barley harvest (Table 1 and Table S2). All treatments were fertilised in spring using strip tillage during barley sowing (N1), with 144 kg N ha^{-1} applied as NPK (YaraMila, NPK 22–3–10). In addition, non-leguminous treatments (including the control) received a small supplemental dose of 25 kg N ha^{-1}, broadcast by hand in autumn (N2), to test whether additional N fertilisation of the cover crops would enhance biomass accumulation and support additional C sequestration. In total, 36 plots, measuring 5 m × 8 m, were established in 2021 on a field that had been used for ~10 years as a dog training turf. The field was limed in February 2021 with dolomite (3.5 tonnes ha^{-1}). During the experiment, the field was treated with glyphosate each spring before harrowing and seeding. In the second year, cover crops were reseeded in the same plots as in the first year. In early summer, the field was irrigated and sprayed with herbicides (Basagran and MCPA in 2021, Mekoprop and Tripoli in 2022). The stubble of the main crop was left after harvest, while straw was removed to prevent confounding the inputs from the cover crops (Table S3). After the two-year experiment, the field was sown with spring wheat in 2023 and received moderate fertilisation (60 kg N ha^{-1}) to investigate the legacy effect of cover crops on soil fertility.

2.2. *Field measurements*

N_2O emissions were measured weekly for two consecutive years. Each year was divided into three seasons (Table S2): the main growing season, spanning from the first fertilisation in spring to the harvest of the main crop in autumn (April/May to August); the autumn growing season, extending from the harvest of the main crop until the first frost (soil temperature <0°C; August to October); and the off-season, encompassing the remainder of the year, including the termination of the cover crops and seedbed preparations for the main crop (October to April/May). Year 1 began with the main growing season in April 2021 and lasted until the end of the off-season in May 2022. Year 2 followed immediately, starting in May 2022 with the onset of the main growing season and ended in May 2023 with the conclusion of the off-season (Table S2).

Manual chambers were used during the main growing season, while a field flux robot (FFR) was used during the autumn growing season and the off-season (Molstad et al., 2014; Hiis et al., 2024, Text S1). The main differences between the two methods and potential biases are addressed in Text S1. Emission rates were predominantly sampled through weekly, mid-morning measurements (9 a.m.–12 p.m.), with increased sampling frequency during freeze-thaw events, as recommended by Ferrari Machado et al. (2019). Winter emissions were measured by the FFR twice on each sampling date (within three hours) and averaged to calculate daily N_2O emission rates. Emission rates were estimated from the change in N_2O concentration over time in both the manual chambers (30–40 min deployment time) and the FFR chambers (three-minute deployment time) using linear regression, with CO_2 measurements used for quality control. For a detailed description of the two sampling methods, see the supplementary materials (Text S1).

Soil temperature and soil volumetric water content were measured in two plots located on opposite sides of the field. Each of the two control plots had five loggers installed at a depth of 5 cm (Decagon Em50; Fig. S1). The data represent the average readings from all loggers. Freezing-degree hours were calculated for each hour during which the soil temperature was below 0°C. Freezing-degree days were then calculated as the sum of daily freezing-degree hours divided by 24 (Libby et al., 2020). Soil moisture measurements were based on time domain reflectometry, which does not detect frozen water. Water-filled pore space (WFPS) was calculated using the measured volumetric water content, measured bulk density and a standard particle density of 2.65 g cm^{-3}. Precipitation data were obtained from a nearby weather station at NMBU in Ås (59°39′37.8″ N, 10°46′54.5″ E) (Wolff and Grimenes, 2022, 2023). Soil samples were collected weekly from a depth of 0–20 cm whenever the soil was not frozen. Additional deeper soil layers (20–40 cm) were sampled twice for Italian ryegrass, oilseed radish, herb mixture and control in autumn 2022 and spring 2023. Ammonium (NH_4^+) and NO_3^- contents were determined in 1 M KCl extracts from wet soil using spectrophotometry (Doane and Horwáth, 2003; Krom, 1980), and the results were related to dry soil weight based on the measured volumetric water content. Dry matter biomass and N-yield of the main crop and the cover crops were determined using a FlashEA 1112 HT (Thermo Fisher Scientific) coupled to a Delta$^{\text{plus}}$XP (Thermo Finnigan). Cover crop biomass was collected as late as possible in the year, after the first frost (Table S2).

2.3. *Cumulative N_2O emissions*

Cumulative annual N_2O emissions were calculated by linear interpolation of daily N_2O means per plot for each treatment and then averaged. To account for the unbalanced data structure caused by frequent but irregular winter sampling, geometric means were also calculated. Both approaches were based on daily emission rates and included negative rates (543 out of a total of 4663 measured daily emission rates). The geometric mean was calculated from plot-wise data transformed to positive values using the formula $x + a$, where x is the N_2O emission rate and a is a value 1.1 units greater than the most negative rate. To determine the average emission from geometric means, the data were back-transformed for each replicate plot by subtracting a. The R package *DescTools* (version 0.99.54) was used for both linear interpolation (Signorell and Ekstrom, 2024) and geometric mean calculations (Signorell, 2024).

2.4. *Soil organic carbon accrual attributed to cover crops*

Annual SOC accrual rates in the cover crop treatments were estimated using the ICBM model, a dynamic soil C balance model (Andrén and Kätterer, 1997; Kätterer and Andrén, 2001). This version of the model includes two fast C pools, representing above- and below-ground plant residues, respectively, as well as one slow C pool. Model equations and parameter values are detailed in the Supplementary Information (Text S2, Table S5). The kinetic decomposition rate constants and the coefficients defining the fractions of C transferred from the two fast pools to the slow C pool were adopted from Menichetti et al. (2024). The pedoclimatic response parameter for the Oslo Fjord agrozone was derived from Borgen et al. (2012). To simulate mean annual SOC accrual rates from cover crops relative to the control over a 30-year period, the model was initialised with zero C in the three pools and run for 30 years. Mean annual SOC accrual was then calculated by dividing the total simulated SOC stock by the 30-year duration.

C input to the soil from cover crop shoots was calculated based on biomass and C content measured in each experimental plot in 2021 and 2022 (Table S4). Root-derived C inputs were estimated from the harvested shoot C mass using cover crop-specific shoot-to-root ratios (Text S2, Table S6), which were derived from a compilation of field studies conducted primarily in Scandinavia (Henriksen et al., 2025). The estimated root-derived C input was then multiplied by 1.65 to account for an additional 65 % extra-root C input through rhizodeposition, as described by Bolinder et al. (2007).

2.5. Statistics

We tested the effects of year, season, N level and treatment on daily N_2O emission rates using linear mixed-effects models and compared the means of specified contrasts using the '*nlme*' and '*emmeans*' packages in R (Pinheiro and Bates, 2000; Pinheiro et al., 2024). Treatments referred to the combination of cover crop types and N fertilisation regimes. After grouping phacelia with the controls due to crop failure, the experimental treatments included 11 levels. To improve the residual distribution of the models, daily N_2O emission rates were transformed by adding a constant (1.1 higher than the minimum N_2O rate) and applying a log transformation. In the linear mixed-effects model, treatment, year/season and their interaction were included as fixed effects. Plots were treated as repeatedly measured subjects in the random effects for all models testing daily emission rates. Year was also included as a random effect when testing seasonal effects and was crossed with the repeated measures. Temporal correlation among repeated measurements was accounted for using a first-order autocorrelation structure (*corCAR1*). To test the effect of N fertilisation on N_2O emissions, we excluded treatments with only N1 fertilisation and grouped treatments with the same cover crop and two N levels. This new cover crop group and N level were set as fixed effects and analysed with a model similar to the one described above. A simpler model was used to compare annual emissions across treatments using cumulative N_2O emissions calculated from geometric means. To account for variability in annual emissions, the model incorporated weights calculated as the square of the logarithm of the geometric mean. We checked model assumptions for normality by plotting model residuals as a QQ plot and a histogram, and for homoscedasticity by plotting the standardised residuals against fitted values.

Estimated marginal means (*emmeans*) were compared for significant fixed effects in each linear mixed-effects model. For the models based on daily N_2O emission rates, when the interaction with year or season was significant, pairwise comparisons of *emmeans* for the same treatment were performed between the two measurement years or among the three seasons. Effect sizes, calculated as standardised mean difference, were estimated to indicate the magnitude of the differences in *emmeans*. Additionally, a contrast matrix was constructed to compare the *emmeans* of each treatment with the control at the same N level within the same year or season (i.e., control N1 vs. treatment N1, and control N2 vs. treatment N2 by year/season). Finally, *emmeans*, standard errors and 95 % confidence intervals were back-transformed and plotted on the original scale. For the model based on annual geometric means, all treatments were compared to both control N1 and control N2. Barley and wheat yields were tested using ANOVA with Tukey post hoc tests for each year, excluding phacelia from the control treatments. ChatGPT was used to assist in writing R codes (OpenAI, 2024), and all analyses were conducted using R version 4.4.3. The datasets associated with this work are available from Zenodo (Kjær et al., 2025).

3. Results

3.1. Dynamics of daily N_2O emission rates, environmental variables and soil mineral N

Single N_2O emission rates varied over five orders of magnitude across all measurements throughout the two years. The largest N_2O emission rates were measured during periods of diurnal freeze-thaw cycles in the winter of year 1 (Fig. 1A). A distinct but smaller peak in N_2O emissions was observed following spring fertilisation. Throughout the growing season, N_2O emissions remained small and were not noticeably stimulated by post-harvest fertilisation of selected cover crops (Fig. 1A). N_2O emission rates peaked during spring thaw in both years. During this period, single N_2O emission rates exhibited extremely high temporal variability, even within the same day. For example, in one of the perennial ryegrass plots (N2) on 3 March 2022, emission rates increased from 240 μg N m^{-2} h^{-1} at 11:25 a.m., at a soil temperature of 3.4°C, to 22,257 μg N m^{-2} h^{-1} at 12:58 p.m., at a soil temperature of 4.8°C. On this day, soil temperatures ranged from −3.8°C to + 5.1°C. This example illustrates the extreme temporal variability of N_2O emission rates during diurnal freeze-thaw cycles, which complicates the estimation of time-integrated emissions during the off-season. The majority of large N_2O emissions occurred at soil temperatures between 0°C and 10°C and often coincided with freeze-thaw cycles during periods of minimal snow cover (Fig. 1, S2 and S3).

We observed clear differences in the maximum values and frequency of large N_2O emission rates among the different cover crop treatments. The herb mixture and the ryegrass treatments had smaller N_2O emission rates compared to the other treatments (Fig. S4), particularly during freeze-thaw cycles in spring (Fig. S11). While the herb mixture displayed small N_2O emission rates throughout the entire study period, the ryegrasses had a few large emission rates during the off-season; these were observed during spring thaw and following spring fertilisation (Fig. 1 A and S4). In contrast, oilseed radish plots exhibited both larger maximum emission rates and a greater frequency of large emission rates compared with other treatments (Fig. S4). Large emission rates from oilseed radish were observed throughout the frost period, some of which even occurred before spring thaw (Fig. 1A).

Extractable mineral N contents from a depth of 0–20 cm were highest after spring fertilisation and, in some N2 treatments, following autumn fertilisation (Figs. 1B, Fig. 1C). Although NO_3^- contents remained high after the second fertilisation in autumn, N_2O emission rates were small (Figs. 1B, Fig. 1C), suggesting reduced N_2O formation activity as soil temperatures decreased. Soil samples could not be collected when the soil was frozen; however, increased NO_3^- contents were observed in the oilseed radish and hairy vetch treatments just before soil freezing and after soil thawing during the first winter, indicating that N mineralisation continued throughout winter (Fig. 1B). This was further supported by soil samples collected in autumn 2022 and spring 2023 at depths of 0–20 cm and 20–40 cm in the control plots, herb mixture, Italian ryegrass and oilseed radish treatments (Fig. S8). At both depths, spring samples from plots with Italian ryegrass and oilseed radish had higher NO_3^- contents compared to the samples collected in the previous autumn. In contrast, no increase in NO_3^- contents was observed for the control and herb mixture plots. NH_4^+ contents in the soil profile increased at both depths for the control N2, herb mixture, Italian ryegrass N1 and oilseed radish N2 treatments (Fig. S9), although the differences were less pronounced than those observed for NO_3^-.

3.2. Annual and seasonal variations of treatment effects on N_2O emission rates

Daily N_2O emission rates differed significantly between treatments ($p = 0.0003$). However, differences between years and interactions between year and treatment were not significant ($p > 0.05$, Fig. S13). These differences were evaluated by comparing *emmeans* across

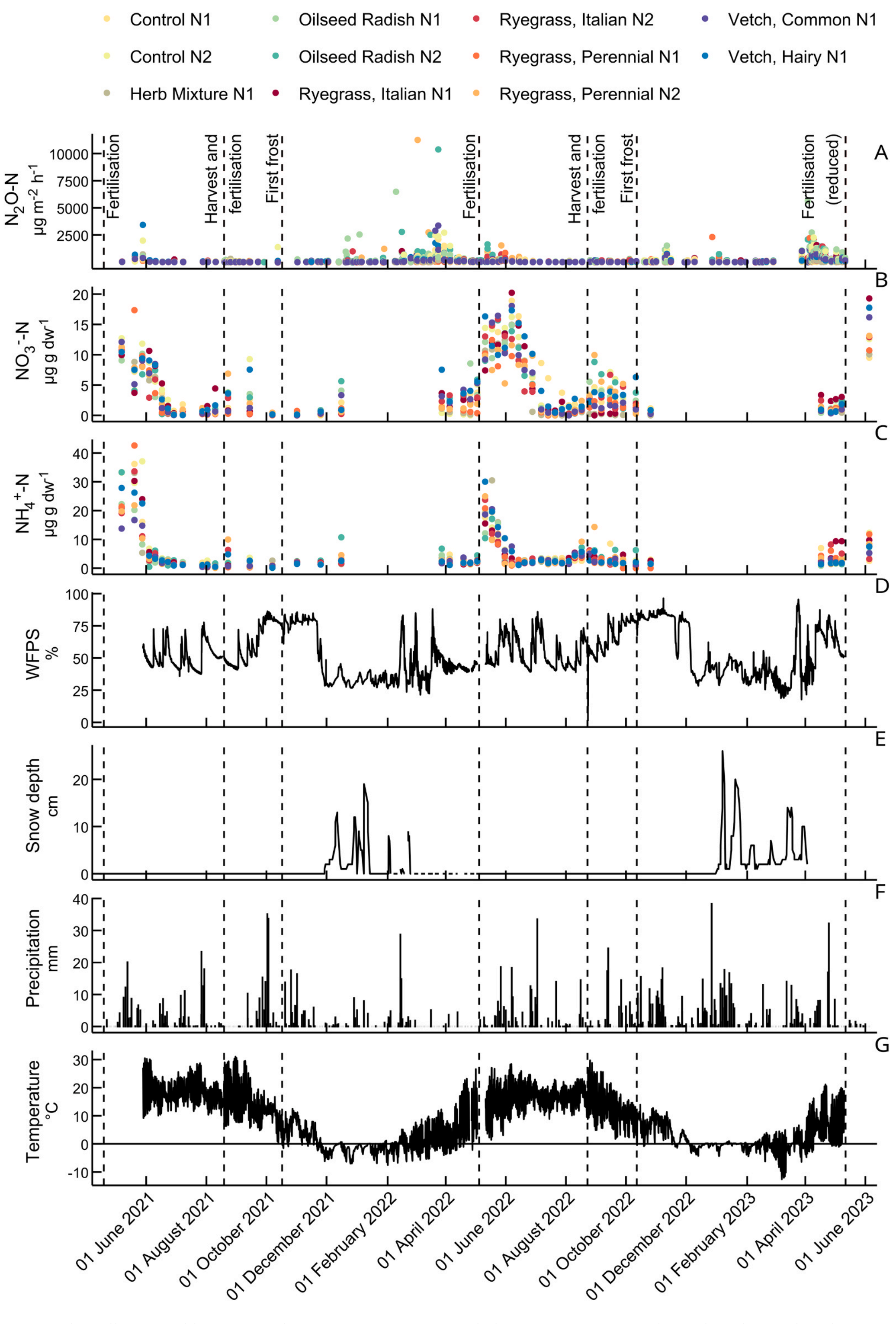

Fig. 1. N_2O emission rates and ancillary variables measured over two years; A: mean daily N_2O emission rates for each replicate plot (three per treatment) measured by either manual chambers or the field flux robot. A boxplot showing daily N_2O emission rates can be found in Fig. S4; B and C: extractable soil NO_3-N and NH_4^+-N per treatment measured weekly in 0–20 cm depth in unfrozen soil. Samples were taken in each plot and pooled per treatment before analysis; D: mean water-filled pore space (WFPS) measured at a depth of 5 cm in opposite ends of the field; E: snow depth (cm); some snow depth data are missing due to instrument failure; F: precipitation (mm day^{-1}). Precipitation and snow depth data were obtained from a nearby weather station (Wolff and Grimenes, 2023, 2022); G: mean soil temperature at 5 cm depth measured in opposite ends of the field.

treatment groups and fertilisation regimes over the two years. For N1 treatments, post hoc comparisons with the control N1 revealed that perennial ryegrass N1 in year 1 had significantly smaller N_2O emissions ($p = 0.0249$). The herb mixture N1 showed a trend towards smaller emission rates in year 1 ($p = 0.0713$). In year 2, no significant differences in N_2O emissions were observed between the cover crops and the control N1. For N2 treatments, perennial ryegrass had significantly smaller N_2O emission rates compared to the control in year 1

($p = 0.0163$), while no significant differences were detected between cover crops and the control N2 in year 2.

Season, treatment and their interaction were all significant fixed effects in the linear mixed-effects model of daily N_2O emission rates. Overall, the main growing season had larger N_2O emission rates than the autumn growing season, regardless of treatment, while off-season N_2O emissions varied more between treatments (Fig. 2, Table S8). Off-season emission rates were largest in the oilseed radish and vetch treatments. Within each treatment, comparisons of *emmeans* showed that most treatments had one or two significant differences in seasonal N_2O rates (Table S8). However, perennial ryegrass N1 and N2 had no significant seasonal differences in N_2O emissions (Fig. 2). When controlling for N level and season (Fig. 2), the herb mixture N1 had significantly smaller N_2O rates than the control N1 ($p = 0.0077$, effect size $= -0.47$), while oilseed radish N1 had significantly larger N_2O emission rates ($p = 0.0055$, effect size $= 0.50$) during the off-season (Table S7). In comparison to the control N2, only perennial ryegrass N2 had significantly smaller N_2O emissions during the off-season ($p = 0.0024$, effect size $= -0.55$).

Four treatments had two N levels (control, perennial ryegrass, Italian ryegrass and oilseed radish) to test the effect of N level on daily N_2O emission rates. Consistent with the previous analyses, treatment was a significant fixed effect ($p = 0.01$), but neither N level nor the interaction between treatment and N level were significant ($p > 0.05$).

3.3. Annual and seasonal cumulative N_2O emissions

Annual cumulative N_2O emissions were estimated using two methods: linear interpolation and geometric means. Emissions calculated by linear interpolation exceeded those calculated from geometric means by a factor of two to three (Fig. 3), primarily due to extraordinarily large emission rates measured during the off-season, which disproportionately increased interpolated emissions (Fig. 1 and S4). Despite these differences, both methods showed that the herb mixture N1 had smaller emissions compared to the controls, while oilseed radish tended to have larger N_2O emissions.

The effect of the cover crops on N_2O emissions was greatest during the off-season compared to the growing seasons (Fig. S11). In the control plots, off-season emissions accounted for 62–80 % of the annual N_2O emissions, whereas only 43–72 % of annual emissions were emitted in the herb mixture and ryegrass treatments over the two measurement years (based on geometric means). Among all the treatments, oilseed radish had the largest proportion of annual N_2O emitted in the off-season (73–87 %). The vetches had a similar proportion of off-season emissions to the controls, with 64–79 % of their total annual emissions occurring during this period (Fig. S11). N_2O emissions determined by linear interpolation showed the same seasonal trends as those calculated using the geometric mean (Fig. S12).

Treatment, year and their interaction were significant fixed effects in a linear mixed-effects model of annual N_2O emissions based on geometric means ($p < 0.05$). Comparing *emmeans* of annual N_2O emissions at the same N level and year, oilseed radish N1 had significantly larger annual N_2O emissions compared to the control N1 in both years, while perennial ryegrass N2 had significantly smaller emissions than the control N2 in the first year ($p < 0.05$, Fig. 3B).

3.4. Simulated soil organic carbon accrual by cover crops

The impact of cover crops on GHG emissions, compared with control plots without cover crops, was highly species-dependent (Fig. 4). Estimated mean annual SOC accrual rates were larger in 2021 than in 2022. Annual SOC accrual ranged from 0.01 Mg ha^{-1} in the vetches to 0.24 Mg ha^{-1} in Italian ryegrass (Table S6). The herb mixture and ryegrass treatments achieved the greatest overall reduction in GHG emissions due to a synergistic effect of both SOC accrual and reduced N_2O emissions. In some cases, the reduction in N_2O emissions outweighed the benefits of estimated SOC accrual. This was particularly evident in year 1 for perennial ryegrass N1 and across both years for the herb mixture and

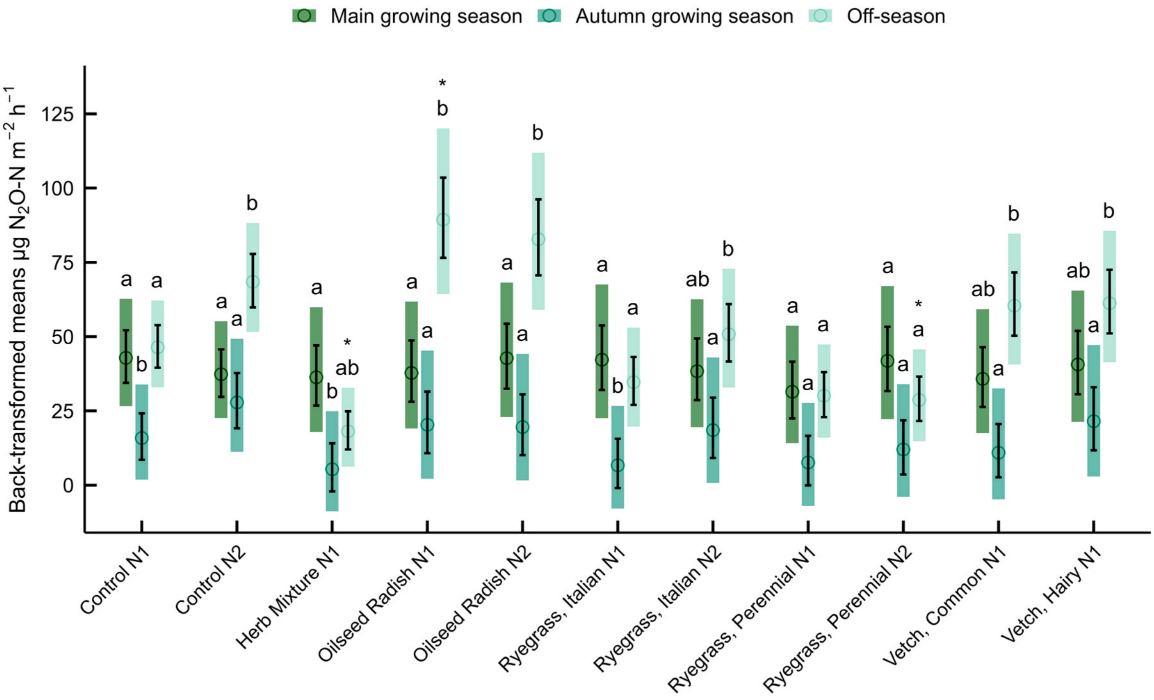

Fig. 2. Mean daily N_2O emission rates back-transformed from estimated marginal means (*emmeans*) of N_2O emission rates (µg N_2O-N m^{-2} h^{-1}) categorised by season and treatment. Means sharing a common letter are not significantly different between seasons in each treatment ($p < 0.05$, alpha $= 0.05$, main growing season was used as the reference group in assigning letters). '*' denotes significant differences between the treatment and the control with the same N level in the same season. Symbols are back-transformed *emmeans*, columns 95 % confidence intervals and error bars denote standard error. Effect sizes of the *emmeans* differences are available in table S7 and table S8.

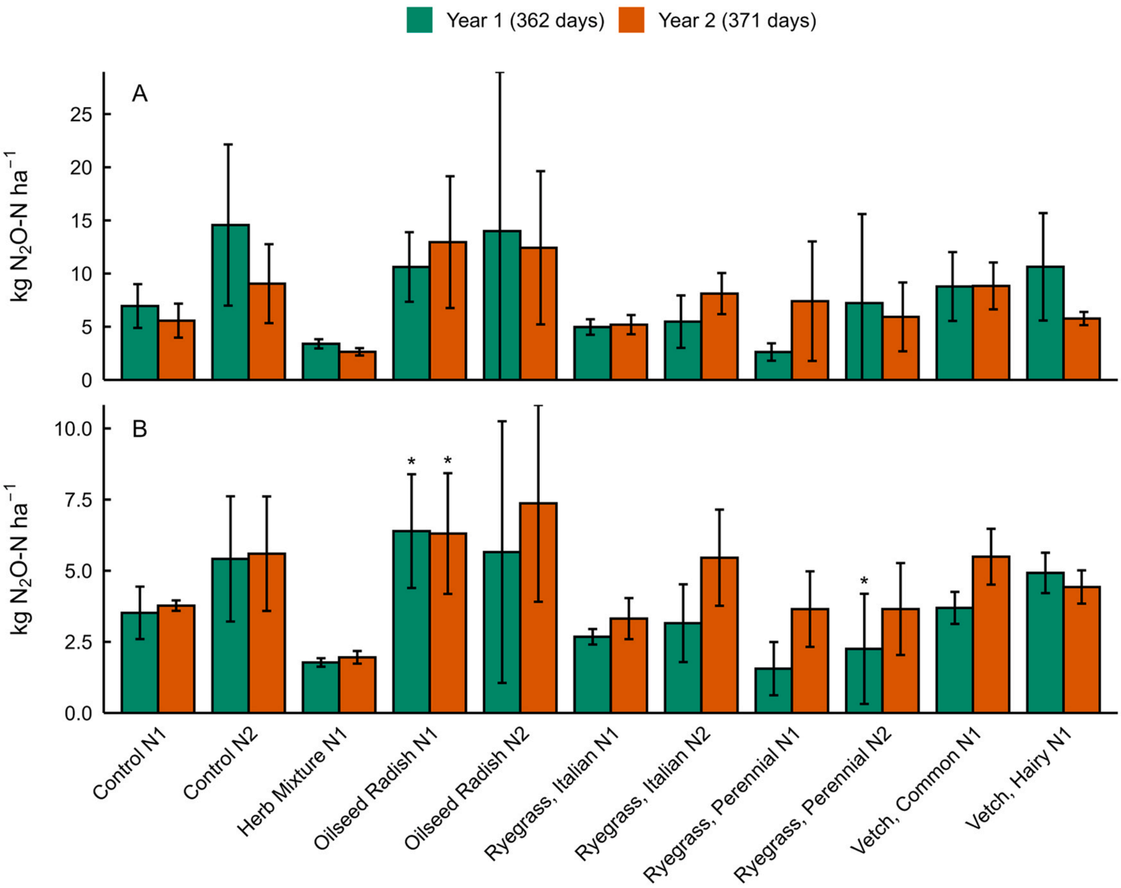

Fig. 3. Cumulative annual N_2O emissions determined (A) by linear interpolation between mean daily emission rates and (B) by multiplying the annual geometric mean of mean daily emission rates by 362 and 371 days, respectively. Each bar shows the average emission rate of three replicate plots ± standard deviation (except for control N1 in 2021 with $n = 6$ and control N2 in 2022 with $n = 6$). '*' denotes significant differences between the treatment and the control with the same N level in the same year. Linear-interpolated annual emissions were not tested for significant differences due to large standard deviations.

perennial ryegrass N2 (Fig. 4). In contrast, the benefits of SOC accrual from oilseed radish were outweighed by large N_2O emissions. The vetches showed similar results, although their SOC accrual was minimal and N_2O emissions were lower than those of oilseed radish. Overall, the large N_2O emissions from oilseed radish and vetches negated GHG reductions of SOC accrual by cover crops.

3.5. Effect of cover crops on the main crop and subsequent crop yields

Spring barley grain dry matter yield was larger in 2022 than in 2021 (Fig. S6 and Table S4). However, no significant differences were observed among treatments within each year ($p > 0.05$). In 2023, following two seasons of spring barley with cover crops, spring wheat was grown under a low fertilisation rate (60 kg N ha^{-1}) to evaluate the legacy effect of cover crops on subsequent crop production. Similar to barley in the treatment years, there was no significant effect of cover crops on wheat grain dry matter yield in the following year ($p > 0.05$, Fig. S7).

4. Discussion

This study evaluated the GHG mitigation potential of seven cover crops over two years in a hemiboreal cereal production system, focusing on off-season N_2O emissions. By combining measured N_2O emissions with modelled SOC accrual rates, we assessed the aggregated climate impact of each cover crop. To our knowledge, this is the first study to address trade-offs between cover crop-induced SOC accrual and off-season N_2O emissions in a cool-temperate climate

4.1. Aggregated climate effect of different cover crop species

Our findings suggest that perennial ryegrass undersown in spring barley may represent a 'win-win' strategy in cool-temperate cereal cropping systems. Ryegrass effectively retained N, resulting in smaller annual N_2O emissions compared to the controls, while achieving equal or greater estimated SOC accrual rates than other cover crops (Fig. 4). Specifically, ryegrass plots substantially reduced off-season N_2O emissions compared to the controls (Fig. 2). In Nordic climates, ryegrass is often associated with poor winter survival (Thorsen and Höglind, 2010), which can lead to increased off-season N_2O emissions. However, in our study, both ryegrass treatments survived the winters surprisingly well, as indicated by visual inspection (Fig. S11) and the observed reduction in off-season N_2O emissions compared to the controls (Fig. 4). The strong winter survival may have been due to the shallow snow cover during both winters (Fig. 1E), which likely prevented snow mould. Moreover, we did not observe ice encasement, a condition commonly caused by rain on exposed frozen soil and known to be detrimental to winter survival of grasses. That said, the potential impact of reduced winter survival during snow-rich winters on the GHG balance remains uncertain, and our findings should therefore be interpreted with caution, even though recent studies in boreal climates have demonstrated that pure grass stands emit little N_2O in winter (Sturite et al., 2021; Byers et al., 2020).

Similar to ryegrass, the perennial herb mixture exhibited a clear GHG-saving effect, driven primarily by its substantial reduction in N_2O emissions (Fig. 4). Although its estimated SOC accrual was smaller than that of ryegrass, the herb mixture's ability to suppress N_2O emissions

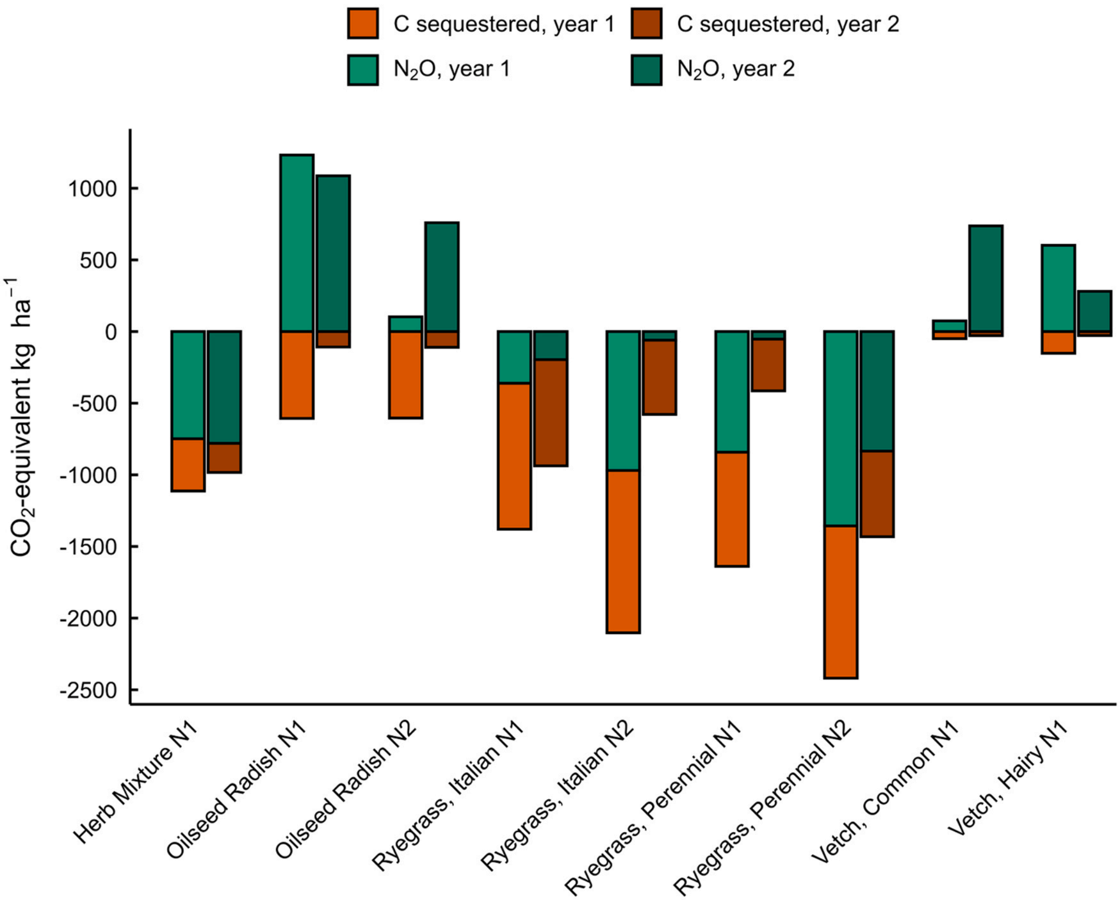

Fig. 4. GHG balance between cover-crop related C accrual (modelled) and cover-crop-induced N_2O emissions (measured) expressed in CO_2 equivalents. N_2O emissions were calculated as geometric mean of annual emissions. A global warming potential (GWP_{100}) of 273 was used to transforming N_2O emissions into CO_2-equivalents (IPCC 2022). N_2O emissions are given as the difference from control treatments, where N1 cover crop treatments are compared to control N1, and N2 cover crop treatments to control N2.

highlights its potential as a climate-smart cover crop in cold climates.

In contrast, oilseed radish and vetches increased aggregate GHG emissions relative to the control (Fig. 4), primarily due to elevated off-season N_2O emissions. This was likely caused by the release of readily available C and N from frost-killed biomass, which stimulated microbial nitrification and denitrification. Among all treatments, oilseed radish produced the largest N_2O emissions, particularly during the off-season, with peak emission rates observed at soil temperatures around 0°C (Fig. 1 A and S2). Oilseed radish is widely used to reduce NO_3^- leaching (Engedal et al., 2023) and is favoured by farmers for its frost sensitivity, which minimises the need for termination by herbicide application or tillage (Dean and Weil, 2009). However, frost-killed oilseed radish biomass has consistently been shown to result in large N_2O emissions (Thomas et al., 2017; Olofsson and Ernfors, 2022). Similarly, leguminous vetches are frost-sensitive, but in our study, they produced little biomass (Fig. 3 and S10), which likely limited N_2O emissions to levels only slightly larger than those of the controls (Figs. 2 and 3).

Our results suggest that the combination of high N retention and frost sensitivity can lead to substantial off-season N_2O emissions, highlighting the role of frost-killed biomass in enhancing microbial activity. Nasser et al. (2025) reported pronounced N_2O emission peaks following frost events in frost-sensitive cover crop treatments, attributing them to the degradation of frost-damaged biomass, which increased the availability of labile C and N. These findings emphasise that both the extent of frost damage and the availability of organic substrates are critical drivers of N_2O emissions during freeze-thaw periods. Overall, our results support the hypothesis that the aggregated climate effect of cover crops, in terms of SOC accrual and associated N_2O emissions, strongly depends on species-specific growth performance and winter survival.

We found no measurable increase in N_2O emissions in spring following the termination of perennial cover crops, likely because termination occurred during periods of relatively dry and cool soil conditions (Fig. 1). Therefore, we refrain from speculating about the effects of cover crop quality or maturity on N_2O emissions during termination (Abalos et al., 2022). Instead, in cool-temperate regions with soil freezing, focus should shift to the interplay between frost-hardiness, winter survival and cover crop quality in driving off-season N_2O emissions. For instance, while oilseed radish had the lowest C:N ratio among all cover crops (Table S4), C:N ratios had no measurable effect on springtime N_2O emissions. This was likely because the N_2O formation potential of cover crop residues differing in C:N ratio was depleted due to the rapid decomposition of frost-killed biomass.

4.2. *Soil organic carbon accrual potential*

Any initiative or policy addressing climate change should consider the coupling of C and N cycles and their combined impact on GHG emissions (Lugato et al., 2018). Detecting changes in SOC stocks at the field level over short timescales is challenging due to high spatial variability (Bradford et al., 2023), making model-based approaches essential for estimating C stock changes in short-term experiments. In our study, we applied the ICBM model, which has previously been used in cover crop studies (Barrios Latorre et al., 2024). The most sensitive model parameters, which determine the fraction of above- and below-ground C inputs from cover crops transferred from the fast to the slow SOC pool, were derived from a recent Bayesian calibration of the ICBM model

(Menichetti et al., 2024). These parameters are consistent with earlier applications of the model (e.g., Barrios Latorre et al., 2024) and have been validated by empirical studies (e.g., Kätterer et al., 2011). To minimise uncertainty, we used shoot-to-root ratios measured under similar pedoclimatic conditions in Scandinavia, which we consider representative of our study area. We also incorporated directly measured above-ground biomass data from our study fields, ensuring robust model inputs. Rhizodeposition rates were based on literature values for temperate systems (Bolinder et al., 2007). Although these parameters are considered robust, their variability may introduce some uncertainty. For instance, changes in shoot-to-root ratios or rhizodeposition rates could influence the estimated C input, thereby affecting modelled SOC accrual rates. Such uncertainty should be taken into account when interpreting the GHG balance (Fig. 4).

The modelled SOC accrual rates in our study ranged from 0.01 to 0.24 Mg C ha^{-1} $year^{-1}$ (Table S6). These rates are slightly lower but comparable to the 0.32 ± 0.28 Mg C ha^{-1} $year^{-1}$ reported by Poeplau et al. (2015) for Swedish long-term field trials with perennial ryegrass and winter rye. However, our rates were lower than the average accrual rates reported in recent meta-analyses for global estimates (0.39 Mg C ha^{-1} $year^{-1}$; Schön et al., 2024) and for the temperate zone (0.21 Mg C ha^{-1} $year^{-1}$; Qin et al., 2023). This discrepancy is unsurprising, as the short growing seasons in Norway and the reduced biomass production of cover crops at higher latitudes inherently limit SOC accrual potential. In our study, the lower SOC accrual rates observed during the second year likely resulted from late sampling after frost events, which may have underestimated realised biomass (Fig. S10), despite similar soil coverage by cover crops in both years (Table S3). The modelled accrual rates represent mean annual SOC uptake over a 30-year period. While these rates decline over time as soils approach a steady state, the timeframe required for this process remains uncertain. Therefore, we used the average accrual rate as a conservative estimate of SOC sequestration in our fields.

Although SOC accrual and N_2O emissions are important components of the GHG balance associated with cover crops, other sources and sinks of GHGs should also be considered for a more comprehensive climate impact assessment. One significant climate cost is the production of cover crop seeds. Emissions from seed production can range from 0.08 to 0.70 Mg CO_2-eq ha^{-1} (excluding land-use change), with an average of 0.39 Mg CO_2-eq ha^{-1} (Schön et al., 2024). These emissions depend on factors such as species, seeding rates, management practices and pedoclimatic conditions. Additional emissions include 0.08 Mg CO_2-eq ha^{-1} from processing, packaging and transport of cover crop seeds, as well as 0.14 Mg CO_2-eq ha^{-1} from machinery use during field operations. On the positive side, changes in surface albedo could provide a cooling effect, averaging −0.2 Mg CO_2-eq ha^{-1}, although albedo impacts vary widely across sites (-0.78–0.37 Mg CO_2-eq ha^{-1}). Other potential climate benefits, such as increased yields in subsequent crops and N fertiliser savings resulting from cover crop residue mineralisation (Schön et al., 2024), are likely minor in Norway, as indicated by the results of this study. When these factors are accounted for, the net GHG balance of cover crops is approximately 0.4 Mg CO_2-eq ha^{-1} (0.39 + 0.08 + 0.14 – 0.2). This value complements the results presented in Fig. 4, providing a more comprehensive estimate of the climate impact of cover crops.

Integrating measured N_2O emissions and modelled SOC accrual rates remains challenging. In our study, we anchored the SOC accrual rates to measured N_2O emissions by using above-ground cover crop yields to parameterise the model and by applying a pedoclimatic response function representative of the local climate. However, we acknowledge that the modelled SOC accrual rates represent long-term estimates based on assumptions and parameterisation, whereas N_2O emissions were measured only over two years. Future research should aim to reduce these uncertainties by incorporating field-based measurements of parameters such as shoot-to-root ratios and rhizodeposition rates, under local conditions.

4.3. *Off-season N_2O emissions determine the climate impact of cover crops in cool-temperate regions*

In cool-temperate climates, off-season N_2O emissions are a critical factor in determining the aggregate climate effect of cover crops. In our study, the contribution of off-season emissions to annual emissions ranged from 43 % ± 8 % in the winter-hardy herb mixture during the first year to 87 % ± 12 % in the frost-sensitive oilseed radish treatments during the second year (geometric mean, Fig. S11). This stark contrast highlights the importance of winter survival in controlling off-season N_2O emissions. Recent reviews on the GHG mitigation potential of cover crops often fail to account for the potentially large contribution of off-season N_2O emissions in cool-temperate regions (e.g., Abdalla et al., 2019; Guenet et al., 2021; Han et al., 2017). Our findings indicate that omitting off-season emissions could lead to an overestimation of the climate benefits of cover crops in cold regions, especially for frost-sensitive species such as oilseed radish.

High off-season emissions, which contribute substantially to annual N_2O emissions in cool-temperate regions, have been reported in previous studies (Wagner-Riddle and Thurtell, 1998; Flessa et al., 1995; Christensen and Tiedje, 1990; Wagner-Riddle et al., 2024). Peak emissions triggered by freeze-thaw events likely result from *de novo* N_2O production in thawing soil (Risk et al., 2013). The magnitude of these emissions depends on soil moisture, substrate availability (C and N) and the duration and temperature of freeze events, all of which influence microbial activity upon thawing. Longer and colder frost events typically result in larger post-thaw N_2O emissions (Risk et al., 2013; Wagner-Riddle et al., 2017). Additionally, snowmelt increases soil moisture, which promotes microbial denitrification. However, even after the soil partially dries, the formation of ice crystals in soil pores can restrict gas diffusion and create anoxic zones in the soil (Teepe et al., 2001). The largest N_2O emission rates in our study occurred during spring thaw and intermittent snowmelt, combined with diurnal freeze-thaw cycles in mid-winter (Fig. 1). These findings align with the notion that observed N_2O emission peaks were driven by *de novo* denitrification.

The winters in our study were relatively warm and snow-poor (Fig. 1). Climate models for the hemiboreal zone predict warmer and wetter conditions with less snow in winter (Hanssen-Bauer et al., 2017). Shallower and shorter-lived snowpacks are expected to lower soil temperatures and increase the frequency of freeze-thaw cycles (Groffman et al., 2001). Higher cumulative freezing-degree days have been associated with larger post-thaw N_2O emissions (Libby et al., 2020; Wagner-Riddle et al., 2017). In our study, cumulative freezing-degree days totalled 217 and 143 for the first and second winter, respectively (calculated as in Libby et al., 2020). Using the non-linear regression between cumulative freezing-degree days (November to April) and N_2O emissions developed by Wagner-Riddle et al. (2017), we estimated off-season N_2O emissions of 1.57 and 1.28 kg N ha^{-1} for the first and second winter, respectively. In contrast, our measured off-season emissions (October to April/May), based on geometric means averaged across all treatments, were 2.5 ± 1.9 and 3.5 ± 2 kg N ha^{-1} for the first and second winter, respectively (Fig. S11), clearly exceeding the regression-based predictions. Notably, when the predicted values from Wagner-Riddle et al. (2017) are compared with our linearly interpolated estimates (Fig. S12), the discrepancy becomes even greater (see Ch. 4.5). It may be speculated whether this is due to differences in winter conditions, such as snow cover depth and duration, or whether the presence of cover crops in our fields increased winter emissions.

4.4. *N retention by cover crops and off-season N_2O emissions*

Soil NO_3^- content prior to soil freezing is another factor that has been proposed to control off-season N_2O emissions (Wagner-Riddle et al., 2024; Wagner-Riddle and Thurtell, 1998). However, we did not find any significant effect of autumn NO_3^- content on off-season N_2O emissions during the two years of our study ($R^2 = 0.11, p = 0.14$; based on a linear regression between the last NO_3^- measurement in each year and the corresponding off-season N_2O emissions, calculated as geometric means). Following the first frost, NO_3^- contents in autumn were generally low (0–5.6 μg N g dw^{-1}; Fig. 1), likely due to cover crop uptake of mineral N. For example, oilseed radish N2 had lower NO_3^- contents than the control plots in autumn 2022 (Fig. S8), despite having larger off-season N_2O emissions (Fig. S11). Similar to our findings, incubation studies with induced freeze-thaw cycles did not identify pre-freezing soil mineral N as a reliable predictor of post-thaw N_2O emissions (Ejack and Whalen, 2021; Pelster et al., 2019). Instead, fluctuations in soil moisture during freeze-thaw cycles, combined with the inputs of readily available C and N from frost-killed plants, likely stimulated microbial nitrification and denitrification, driving N_2O emissions regardless of residual mineral N present in autumn (Li et al., 2013).

We observed a significant increase in soil extractable NO_3^- throughout winter in Italian ryegrass and oilseed radish, but not in the herb mixture or control plots (Fig. S8), indicating over-winter mineralisation of organic N despite low temperatures. Among all cover crops, the herb mixture showed the greatest potential for reducing off-season N losses, with consistently low soil NO_3^- contents throughout the study (Fig. S5A) and the smallest off-season N_2O emissions among all treatments (Fig. 2). These findings suggest that the herb mixture efficiently took up and retained mineral N, thereby limiting NO_3^- availability for denitrification year-round.

Cover crop mixtures have been proposed as a strategy to reduce NO_3^- leaching (Lapierre et al., 2022), and our data further suggest they could mitigate downstream N_2O emissions by retaining more N within the cropping system. Additionally, cover crop mixtures have been suggested as a means to mitigate yield reductions often observed with single-species cover crops (Abdalla et al., 2019). However, we found no significant effect of cover crops on barley yields in either year ($p = 0.16$ and $p = 0.11$ for 2021 and 2022, respectively; Fig. S6). In the third year, a near-significant negative legacy effect of the herb mixture on wheat yields was observed ($p = 0.064$; Fig. S7). Additional N fertilisation had no significant effect on subsequent crop yields or on N_2O emissions, suggesting that low doses of additional N do not alleviate possible N limitation of cover crop growth.

4.5. Technical considerations for estimating seasonal and annual N_2O emissions from chamber measurements

Estimating annual emissions from chamber measurements (Clough et al., 2020) using linear interpolation between measurement dates involves well-known risks of overestimation (e.g., Ferrari Machado et al., 2019; Wu et al., 2021). Unlike CO_2 emissions, which can be gap-filled using well-established relationships with soil temperature and moisture, no valid or easily measurable variables have yet been identified to gap-fill N_2O emission data. This limitation is particularly problematic during periods of large and rapid fluctuations in N_2O flux rates, as observed during winter in the present study.

Off-season fluxes in our study spanned five orders of magnitude, introducing substantial uncertainty to the cumulative emissions. In particular, measuring N_2O fluxes exclusively during daytime in periods of diurnal freeze-thaw cycles may have introduced biases. We acknowledge that our cumulative N_2O estimates likely overestimate emissions due to few extraordinarily high off-season emission rates. Diurnal fluctuations in soil temperatures around the freezing point can promote N_2O emissions (Dörsch et al., 2004; Peng et al., 2019). In this study, N_2O emissions were measured twice per day on most sampling dates, primarily during the thawing phase of diurnal cycles, within a few hours (Text S1). Duplicate measurements on the same sampling date showed large deviations, and no consistent relationship was observed between diurnal thawing duration and emission rates (Fig. S3). This variability may be attributed to the field flux robot used during the off-season, which was programmed to avoid measuring the exact same spot within each plot to avoid damaging the cover crop due to repeated chamber deployment (Text S1). As a result, differences in flux rates measured on the same day may reflect small-scale variability in cover crop residues and soil thawing rather than thawing duration. To account for this variation, we used average 'daily' emission rates when scaling up fluxes.

To better represent flux data for temporal upscaling, we based seasonal and annual flux estimates on average emission rates. Geometric means were used to account for the strongly skewed distribution of the data, and cumulative back-transformed averages for different periods were calculated by multiplying them by the number of days (Fig. 3B, S11). This approach yielded smaller annual emissions (Fig. 3B) compared to those derived by linear interpolation (Fig. 3A). However, the estimated annual rates are still larger than most reported annual N_2O emissions for cool-temperate regions (Stehfest and Bouwman, 2006). This discrepancy may result from the omission of high winter emissions in many studies, especially during spring-thaw, or from potential biases in the chamber technique, which may over-represent low flux rates during periods of strong emission fluctuations. Ultimately, capturing 'true' off-season N_2O emission rates in cold regions requires non-invasive methods for measurements of N_2O soil-atmosphere exchange at sub-daily resolution (Baral et al., 2022). Notwithstanding the limited temporal resolution of flux measurements in our study, our data provide strong evidence for the importance of off-season N_2O emissions for the assessment of aggregated climate effects of cover crops in cold regions.

5. Conclusion

Our study highlights the critical role of off-season N_2O emissions in assessing the aggregate climate effects of cover crops as a strategy to reduce GHG emissions in cool-region crop production. While cover crops had negligible effects on N_2O emissions during the growing season, clear differences emerged during the off-season. Winter-hardy cover crops such as a multi-species herb mixture and ryegrasses reduced N_2O emissions and increased SOC accrual compared to controls without cover crops, thereby mitigating aggregate GHG emissions. In contrast, frost-sensitive cover crops, such as oilseed radish and vetches, disproportionately increased N_2O emissions, turning the crop production system into a net GHG source despite increased SOC accrual. Our results support the integration of winter-hardy cover crops into crop management strategies as an effective means to mitigate climate change impacts in cold regions. Policymakers and farmers should consider region-specific climate conditions when selecting cover crops to optimise environmental benefits.

CRediT authorship contribution statement

Sigrid Trier Kjær: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Rong Lang:** Writing – review & editing, Supervision, Formal analysis. **Thomas Kätterer:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Peter Dörsch:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization.

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Declaration of generative AI and AI-assisted technologies

During the preparation of this work, ChatGPT (OpenAI) was used to improve readability and language in the manuscript and for data handling by writing code for R. All output from the AI tool was quality checked and revised by the authors.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.110061.

Data availability

Data is available on Zenodo. Link can be found in the paper.

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