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N_2O emissions and potato yield responses to organomineral, inhibitor-based, and deep-placement fertilizer in East Midlands England

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Abstract

Nitrogen (N) fertilization is essential for potato production but can increase soil nitrous oxide (N_2O) emissions, creating trade-offs between marketable yield and emission intensity. Finding a balance between potato productivity and climate mitigation is critical. Unlike conventional mineral fertilizers, carbon capture organomineral fertilisers (CCOMFs) offer a low-carbon alternative that integrates recycled organic matter with mineral nutrients to sustain crop productivity while reducing the overall carbon footprint. Therefore, we evaluated the effects of five fertilizer type and application strategies; band-placed ammonium nitrate (AN) + N inhibitor (Didin, dicyandiamide; DCD), surface-broadcast AN, band-placed AN, surface-spread CCOMF each applied at 160 kg N ha^{-1} and an unfertilized control on marketable tuber yield, yield-scaled N_2O-N emission, and agronomic N efficiency metrics in a commercial field trial. Results show that fertilizer treatment altered both the magnitude and timing of N_2O emissions. Cumulative N_2O-N emissions were lowest with AN + DCD (2.4 ± 0.2 kg N_2O-N ha^{-1}) but higher with CCOMF (7.9 ± 1.0 kg N_2O-N ha^{-1}) and surface-broadcast AN (7.4 ± 2.7 kg N_2O-N ha^{-1}). Nevertheless, CCOMF produced the highest marketable tuber yield (62.0 ± 1.6 t ha^{-1}), total biomass (93.2 ± 2.6 t ha^{-1}), partial factor productivity (387.5 ± 10.0 kg tuber kg^{-1} N) and agronomic N use efficiency (26.9 ± 10.0 kg tuber per kg^{-1} N). Yield-scaled N_2O-N emissions did not differ significantly among treatments. Our findings demonstrate that low carbon footprint organomineral fertilizer (CCOMF) outperformed mineral fertilizer and mineral fertilizer combined with N inhibitor with respect to tuber yield and N use. Further, CCOMF reduced N_2O emissions and offset emission intensity by increasing potato tuber yield. Our findings validate CCOMF as a viable alternative to conventional fertilizers at farm scale.

Keywords: Fertilizer placement, carbon capture, organo-mineral fertilizer, N use efficiency, United Kingdom

Introduction

Potato (*Solanum tuberosum* L.) production is typically N intensive and often relies on high rates of mineral N fertilizer to achieve commercially viable yields, making potato systems a recognized hotspot for N_2O emissions and a critical target for mitigation within temperate arable landscapes (Ball and Hernandez-Ramirez 2025). In the UK and across north-western Europe, efforts to reduce agricultural N_2O emissions while sustaining crop productivity are central to climate and nutrient management policy, yet farm-scale evidence is still needed on how alternative fertilizer products and placement strategies perform under commercial conditions (Evans et al. 2026). Conventional ammonium nitrate (NH_4NO_3) fertilizers broadcast to the soil surface can create spatially concentrated zones of high mineral N availability and soil moisture that favor denitrification and N_2O production, particularly on fine-textured or moderately drained soils typical of many potato-growing regions (Dobbie et al. 1999; Giles et al. 2012). In response, several mitigation strategies have been promoted, including the use of nitrification inhibitors such as dicyandiamide (DCD) to slow the oxidation of ammonium to nitrate, deep or band placement of fertilizer to better synchronize N supply with root uptake, and organomineral fertilizers that combine mineral N with organic matrices designed to enhance soil health and carbon sequestration (Zaman and Blennerhassett 2010; Di and Cameron 2012; Uddin et al. 2025; Oladele et al. 2025). Nitrification inhibitors can reduce N_2O emissions by moderating nitrate accumulation and subsequent denitrification, and by lowering nitrate leaching risk, although their effectiveness is highly context-dependent and can vary with soil temperature, moisture, and pH (Misselbrook et al. 2014; Li et al. 2020). Organomineral fertilizers and carbon-rich N formulations are promoted as "climate-smart" products that may improve N use efficiency and build soil organic matter, but they can also stimulate N_2O emissions if mineral N and labile carbon are co-supplied under favorable conditions for microbial N transformations (Uddin et al. 2025).

Despite extensive studies on fertilizer type and inhibitors, two gaps constrain current understanding. First, most field studies have focused on a narrow set of fertilization strategies typically comparing mineral N with or without nitrification inhibitors rather

than simultaneously evaluating performance against emerging organomineral products and contrasting application methods that are relevant to growers' practice (Chojnacka and Mikulewicz 2026). Second, mitigation assessments often emphasize plot-scale N_2O fluxes and cumulative emissions but overlook agronomic outcomes such as tuber yield, above-ground biomass, and agronomic efficiency metrics, which are critical for judging whether low-emission strategies are also economically and agronomically viable (Shcherbak et al. 2014; Van Groenigen et al. 2010). For example, yield-scaled N_2O emissions, partial factor productivity of applied N, and agronomic N use efficiency offer integrated metrics that link N_2O flux performance to crop output, yet there remain scarce datasets from commercial potato systems under typical UK management and climate.

The East Midlands of England is dominated by a cool-temperate, humid climate with mild temperatures and moderate rainfall, and contains extensive areas of fertile sandy soils under intensive arable and root-crop cultivation (DEFRA 2026). Within this region, commercial potato growers frequently employ relatively high single-dose N applications, drip or sprinkler irrigation, and modern cultivars. These conditions provide an appropriate scenario for evaluating fertilizer strategies that are both climate and agronomic sensitive. There is thus a need for field-scale studies that compare conventional broadcast NH_4NO_3 fertilizer with band placed N and organomineral products, and that explicitly quantify trade-offs between N_2O emissions, tuber yield, and N use efficiency under commercial management.

Based on current understanding of N_2O production and N cycling, we hypothesized that: (i) surface broadcast NH_4NO_3 and the carbon-rich organomineral fertilizer would generate higher peak and cumulative N_2O emissions than band placed mineral N, due to greater exposure of mineral N and labile carbon to near-surface denitrifying zones; (ii) co-application of NH_4NO_3 with the nitrification inhibitor Didin would reduce growing-season cumulative N_2O emissions relative to non-inhibitor mineral N treatments, by slowing nitrate formation and enhancing synchrony between N availability and crop uptake; and (iii) organomineral fertilizer would enhance tuber yield, total biomass, and N use efficiency relative to conventional mineral N strategies, potentially offsetting higher absolute N_2O emissions when expressed on a yield-scaled basis. Our specific objectives were therefore to: (1) characterize daily and

growing-season patterns of N_2O flux under conventional mineral, inhibitor-based, deep-placed, and organomineral fertilization in a commercial potato system; (2) quantify treatment effects on cumulative N_2O emissions, yield-scaled emissions, and fertilizer-induced emission factors; and (3) assess the impacts of fertilizer strategy on tuber yield, foliage biomass, partial factor productivity, and agronomic N use efficiency. By analyzing N_2O emissions and agronomic outcomes, this study aims to provide farm relevant evidence on the trade-offs and synergies among emerging N fertilizer strategies for potatoes in temperate arable landscapes, and to inform the design of mitigation options that are both climate effective and agronomically viable.

Materials and Methods

Site description and experimental design

The experimental trial was established in May 2024 on a commercial potato farm located at Bardney (53°22'11"N, 0°33'30"W), Lincolnshire, England - a major arable and potato-producing region of the UK. Bardney is characterized by mild temperatures and moderate, evenly distributed rainfall throughout the year, classified under the Köppen-Geiger climate classification as Cfb (temperate oceanic climate with warm summers, cool winters, and no dry season) (Peel et al. 2007; Beck et al. 2018). According to 30-year baseline climate normals (1991-2020) from the nearest official Met Office synoptic station at Waddington (~14 km southwest), the area has a mean annual temperature of 10.2 °C (mean daily maximum 13.9 °C, minimum 6.6 °C), ranging from a January mean of 4.3 °C to a July mean of 17.1 °C, and receives 614.8 mm of annual precipitation across 115.5 rain days (≥1 mm) (Met Office, 2026). The soil at the site is a moderately well drained sandy clay loam classified in the order Cambisol (WRB 2015). Selected soil properties such as soil organic matter was 3.5% as determined by the dry combustion (Dumas) method, while soil pH was determined in deionized water with a pH unit of 7.8, soil total N was 2.1 g kg^{-1}, available Olsen P of 65 mg kg^{-1} and total K of 175.3 mg kg^{-1}.

We designed a randomized complete block of five treatments with five replications to evaluate the effect of conventional and organo-mineral nitrogen (N) fertilizers and application methods on N_2O emission and potato tuber yield. Following routine medium intensity tilling and de-stoning, treated seed potatoes were planted at a depth of 15 cm on prepared beds via a modern tractor driven cup planter. Treatment plots

were randomized complete block designed covering an area of 200 m^2. The N fertilizer treatments evaluated in this study comprised: (i) an unfertilized control [**Control]**; (ii) band-placed ammonium nitrate (AN) with N inhibitor - Didin (dicyandiamide; DCD) [**N+Didin**]; (iii) band-placed AN [**N placed**]; (iv) surface-broadcast AN [**N broadcast]**; and (v) surface-spread carbon-capture organomineral fertilizer [**CCOMF**]. All fertilized treatments received a single application at the standard recommended rate of 160 kg N ha^{-1}, executed according to their respective designated application methods. The potato variety used in this study was Maris Piper, planted on the 6th of May, 2024. Drip irrigation system was deployed to meet crop water demand during the active growing season (May - September). Total irrigation volume was roughly 250-300 mm during the growing season, with irrigation schedules based on local weather conditions, crop requirement and evapo-transpiration rates. All agronomic management, including pest and weed control were performed by the commercial grower in accordance with standard potato cultivation practices in England.

Soil available nitrogen

To ascertain baseline soil available N (NH_4^+-N and NO^-_3-N) prior to planting and residual available N following tuber harvest, soil samples were collected from potato beds at 0 to 60 cm depth at five random location per treatments and replicates using an Edelman soil auger with a diameter of 7 cm across the experimental field and segregated into two depths (0-30 cm and 30-60 cm). Soil available N was extracted by suspending 20 g of field-moist samples into 80 mL of 0.0125 M $CaCl_2$ and analyzed using a Continuous Flow Analyzer Evolution II (Alliance Instruments GmbH, Salzburg, Austria).

N_2O flux measurement

N_2O emissions were measured from circular PVC rings (diameter: 0.2 m and height: 0.115 m, open-ended) installed at the top of potato beds in each replicate per treatment plot and remained in place until the completion of N_2O flux measurements. PVC rings were installed at 0.06 m deep into the beds and leaving it 0.065 m high above the bed surface 24 hours prior to measurements. The soil around the PVC ring's base, both inside and outside, was gently pressed to ensure no air leakage and uniform collar height. The LI-7820 N_2O/H_2O trace gas analyzer equipped with a smart chamber top (LI-COR Biosciences) was used to measure N_2O fluxes from treatment plots. Prior to fertilizer

application, baseline N_2O flux was measured. Two days after fertilization, N_2O flux was measured and sampled intensively thrice per week during the first 4 weeks (May) of potato planting (i.e., sprouting and vegetative phenological phase) and once bi-weekly from June to August (vegetative - maturation phase) between 10 am and 1 pm to account for diurnal variation until harvest. Gas measurements were continued for 5 min in each plot, with the analyzer capturing N_2O concentrations every 1 seconds, with results stored in a data logger. Additionally, a moisture sensor (Stevens HydraProbe II, Stevens Water, Inc.) fitted in the smart chamber was used to measure soil moisture at 0.05-m depth during flux measurements across all treatment plots. The SoilFluxPro (v5.3.1) software (LI-COR Biosciences) was used to calculate N_2O fluxes from the collected gas concentration time series. Flux calculations were executed utilizing the non-steady-state exponential model, applying a deadband of 30 s and a post-purge time of 40 s to ensure data stabilization. For quality control, regression fits were evaluated, yielding a coefficient of determination (R^2) > 0.95 in the majority of sampling events. Exported N_2O fluxes data from the SoilFluxPro (v5.3.1) software for all sampling dates were measured as nmol m^{-2} s^{-1} and converted to g N_2O-N ha^{-1} day^{-1} using Eq. 1:

g N_2O-N ha^{-1} day^{-1} = nmol N_2O m^{-2} s^{-1} $\times 10^{-9} \times 28.0134 \times 86400 \times 10000$ ------- (1)

where 28.0134 g N mol^{-1} is the mass of N contained in one mole of N_2O.

Cumulative emissions were estimated by trapezoidal numerical integration of daily and bi-weekly fluxes over time using Eq. 2. For this analysis, cumulative N_2O flux during the first 4 weeks of sprouting and vegetative phenological phase (May only) and throughout potato growing season (May - August) were calculated separately.

Cumulative N_2O-N = $\sum_{i=1}^{n-1}$ [Fi + Fi +1 /2 × (t_{i+1} − ti)] / 1000 ---------- (2)

where Fi is daily N_2O-N flux in g N_2O-N ha^{-1} day^{-1}, ti+1 − ti is the interval between sampling dates in days, and division by 1000 converts g ha^{-1} to kg ha^{-1}.

Tuber and biomass yield

Tubers were harvested manually from a 2.0 m x 0.94 m plot (1.88 m^2) to ensure complete crop recovery and eliminate mechanical damage in early September 2024, following three weeks of desiccation. Prior to lifting, desiccated haulms and plot borders were cleared by hand to isolate the central harvest zone per plot and eliminate

edge effects. The soil-tuber matrix of each plot was carefully lifted, and the loose soil was manually sifted to recover all subterranean tubers. The extracted tubers were cured on the soil surface for approximately 30 min, gently cleaned of adhering debris, and collected into pre-labelled, breathable sample bags. Total tuber and foliage yield per plot was determined immediately using a calibrated field scale, after which the tubers were manually graded into standard commercial size categories to evaluate marketable tuber yield expressed as t ha^{-1}

Nitrogen use efficiency indices

Partial factor productivity of applied N fertilizer (PFP_N) of crop yield was calculated by dividing total crop biomass yield by unit of N fertilizer applied;

$$PFP_N = \frac{Y_N}{F_N} \quad \text{----------} \quad (3)$$

Where Y_N = total biomass yield in the plot with N fertilizer applied (kg/ha), F_N = amount of N fertilizer applied (kg/ha).

Agronomic N use efficiency (aNUE) for each fertilized plot was calculated as the increase in crop yield or biomass yield (tuber + foliage) per unit of nitrogen fertilizer applied, compared to a control plot where no nitrogen was added (Lahda et al. 2005);

$$aNUE = \frac{Y_N - Y_0}{F_N} \quad \text{----------} \quad (4)$$

Where, Y_N = Crop yield in the plot with nitrogen fertilizer applied (kg/ha), Y_0 = Crop yield in the control plot with zero N fertilizer applied (kg/ha) and F_N = amount of N fertilizer applied (kg/ha).

Tuber yield-scaled (TYSE) N_2O-N emissions were calculated as the cumulative N_2O-N in kg per ton of fresh weight tuber yield (see Eq. 5) (Carruthers and Congreves 2025) and expressed as kg N_2O-N t^{-1} tuber yield;

$$TYSE = \frac{\text{cumulative } N_2O\text{-N (kg ha}^{-1})}{\text{Tuber yield (t ha}^{-1})} \quad \text{----------} \quad (5)$$

Fertilizer-induced N_2O-N emission factor (EF) was calculated using the control-corrected approach to evaluate the amount of N_2O-N emissions that result from N inputs into soils (Rychel et al. 2020);

$$EF\ (\%) = \frac{E_N - E_0}{N_{applied}} \times 100 \quad \text{----------} \quad (6)$$

Where E_N, is cumulative N_2O-N emission from the N fertilized treatment and E_0 is mean cumulative N_2O-N emission from the control (unfertilized treatment).

Statistical analyses

Prior to analysis, each response variable was screened for distributional assumptions. Residual normality was assessed using the Shapiro-Wilk test, and homogeneity of variance was assessed using Levene's test. Temporal N_2O-N flux dynamics in response to N fertilizer were analyzed separately for the sprouting and vegetative phenological phase (May) and for the full growing season (May-August) using linear mixed-effects models. Fertilizer treatment, sampling time and the Treatment × Sampling time interaction were specified as fixed effects. Repeated measurements were accounted for using plot as a random intercept. Cumulative N_2O-N emissions, tuber yield, foliage yield, total biomass yield, yield-scaled emissions, emission factor, PFP_N, aNUE and available soil N were analyzed using one-way ANOVA. For available soil N, treatment effects were evaluated separately within each depth interval. Where ANOVA indicated significant treatment effects, pairwise comparisons were conducted using Tukey's HSD post hoc test ($p < 0.05$). All statistical analyses were conducted using R v4.3.1 (R Core Team, 2023), and figures were generated using Python (v 3.11) with the matplotlib and seaborn libraries.

Results

Soil available N

Results showed variation in soil available N among fertilizer treatments across the 0-60 cm profile, but treatment effects were not statistically significant at either pre-planting or post-harvest sampling (Fig. 1A-D). Across the growing season, available N at 0-30 cm decreased from pre-planting to post-harvest in N broadcast, N placed, CCOMF and Control, with reductions of -82.9%, -71.5%, -35.6% and -60.4%, respectively. In contrast, N+Didin increased by +19.7% at 0-30 cm. At 30-60 cm, available N decreased under N broadcast, CCOMF and Control by -42.8%, -20.1% and -46.4%, respectively, but increased under N+Didin by +17.3% and N placed by +11.7%. Overall, the post-harvest depletion of available N under N broadcast, CCOMF and Control treatments indicates a lower residual mineral N pool at crop termination, whereas increase in residual soil available N under N+Didin and N placed, particularly at 30-60 cm, indicate greater late-season soil N retention in those treatments.

Temporal daily N_2O-N flux pattern during early potato growing stage (sprouting and vegetative phase)

Daily N_2O-N fluxes showed marked temporal variation across early potato growing period, with the largest treatment-specific emissions occurring during this phase (intensively sampled May period). We observed significant treatment × sampling time interaction, indicating that temporal flux patterns differed among fertilizer treatments during the first four weeks of potato growth (Table 1). Mean daily N_2O-N fluxes were generally within 43.2-160.3 g N_2O-N ha^{-1} day^{-1} during the first week of sampling (8^{th} - 16^{th} May), before divergent late-May responses were observed. The largest emission occurred under N broadcast in late May, reaching 418.9 ± 163.5 g N_2O-N ha^{-1} day^{-1}, which was 4.3 fold higher than the Control on the same date (98.4 ± 39.5 g N_2O-N ha^{-1} day^{-1}). N broadcast remained elevated on 31^{st} May at 274.9 ± 165.9 g N_2O-N ha^{-1} day^{-1}, equivalent to 2.2-fold the Control value on that date. CCOMF also showed a late May increase, peaking at 174.0 ± 54.3 g N_2O-N ha^{-1} day^{-1} on 29^{th} May, while N+Didin decreased from 139.7 ± 39.0 g N_2O-N ha^{-1} day^{-1} on 13^{th} May to 18.0 ± 5.3 g N_2O-N ha^{-1} day^{-1} by 31^{st} May (Fig 2A).

N_2O-N flux pattern during potato growing season

Across the whole experimental period, we found significant interaction effect of Treatment × Sampling time (Table 1). Following the late-May emission pulse, mean daily fluxes generally declined from June onwards. By early August (9^{th}), daily fluxes were 7.3 ± 1.6, 32.5 ± 23.9, 18.8 ± 9.5, 22.5 ± 3.0 and 14.5 ± 5.1 g N_2O-N ha^{-1} day^{-1} for N+Didin, N broadcast, N placed, CCOMF and Control, respectively (Fig. 2B). A secondary CCOMF flux was observed on 12^{th} July, with mean flux of 119.9 ± 32.8 g N_2O-N ha^{-1} day^{-1}, compared with 15.7 ± 4.5 g N_2O-N ha^{-1} day^{-1} under the Control on the same date (Fig. 2B).

Cumulative N_2O-N emissions

Cumulative N_2O-N emissions during the early crop growth stage - sprouting and vegetation phase (May) ranged from 1.67 ± 0.28 kg N_2O-N ha^{-1} under N+Didin to 2.61 ± 0.54 kg N_2O-N ha^{-1} under N broadcast (Fig. 3A). Mean cumulative emissions during the early growth phase were 1.67 ± 0.28, 2.60 ± 0.54, 1.92 ± 0.10, 2.60 ± 0.46 and 1.95 ± 0.29 kg N_2O-N ha^{-1} for N+Didin, N broadcast, N placed, CCOMF and Control, respectively. Relative to the Control, cumulative emissions during the early growth

phase were 33.6% higher under N broadcast and 33.1% higher under CCOMF, whereas N+Didin and N placed were 14.7% and 1.6% lower, respectively. However, these differences were not statistically significant during this phase (Fig. 3A). Over the entire growing season (May-August), cumulative emissions ranged from 2.44 ± 0.23 kg N_2O-N ha^{-1} under N+Didin to 7.94 ± 0.98 kg N_2O-N ha^{-1} under CCOMF (Fig. 3B). Mean cumulative emissions were 2.44 ± 0.23, 7.40 ± 2.66, 4.42 ± 0.27, 7.94 ± 0.98 and 3.57 ± 0.70 kg N_2O-N ha^{-1} for N+Didin, N broadcast, N placed, CCOMF and Control, respectively. Compared with the Control, growing season cumulative emissions were more than doubled under CCOMF (+122.3%; 2.2-fold) and N broadcast (+107.1%; 2.1-fold), while N placed was 23.6% higher and N+Didin was 31.8% lower (Fig. 3B). Again, no statistically significant differences were observed.

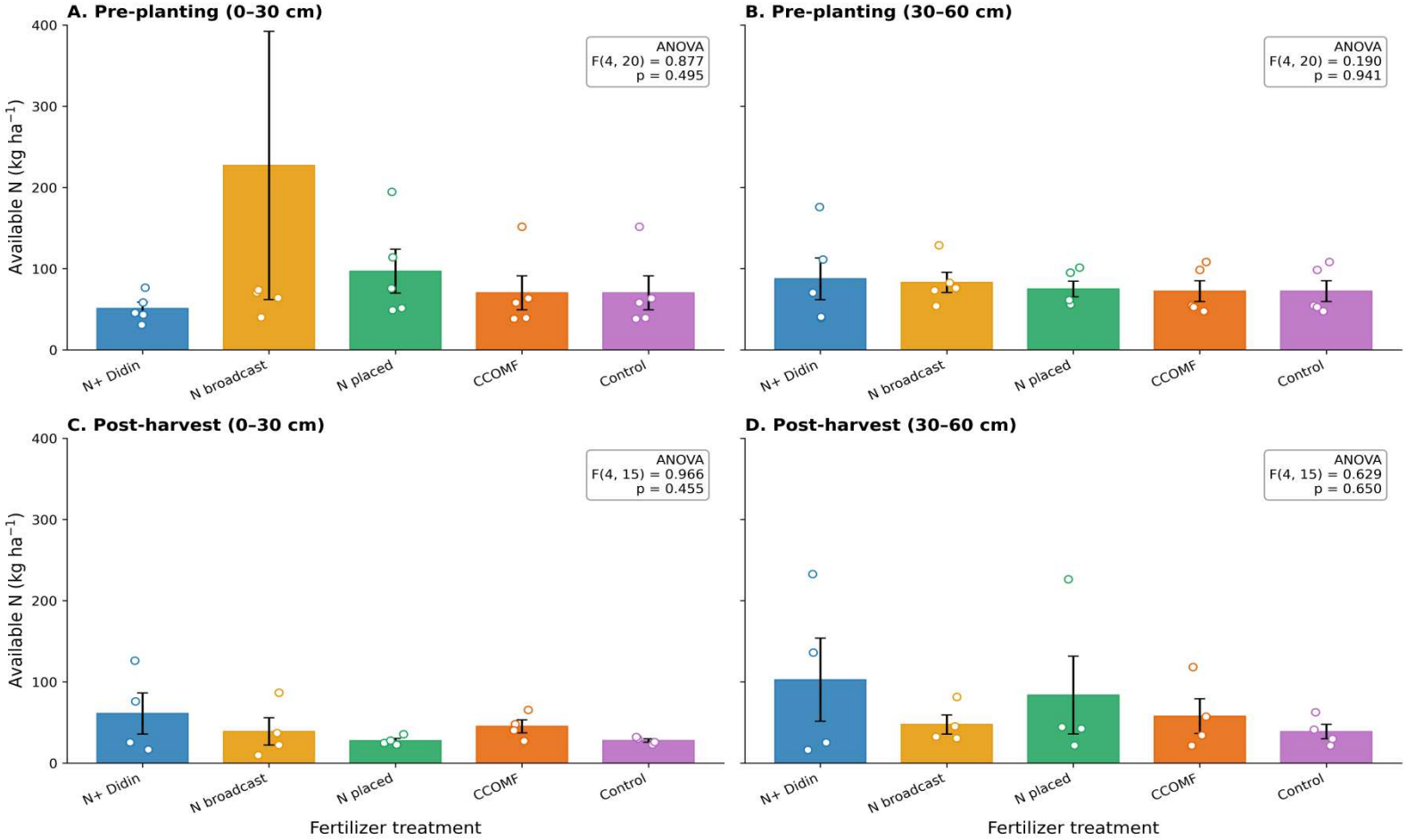


Fig. 1A-D. Values mean ± standard error ($n = 4$) at post-harvest and ($n = 5$) at pre-planting. Mean values with the same letter on each bar are not significantly different at $p < 0.05$ based on Tukey HSD test. No significant differences at $p < 0.05$ based on Tukey HSD test were detected.

Table 1. Linear mixed model *P*-value for nitrous oxide (N_2O) emissions

	Factors					
	Fertilizer × Time		Fertilizer		Time	
	F	*p*-value	***F***	*p*-value	***F***	*p*-value
May only	1.963	**< 0.001**	1.789	0.132	3.675	**< 0.000**
May-August	1.909	**< 0.000**	2.643	**0.033**	7.545	**< 0.000**

Model residuals: df_res for early potato growing stage (May) = 200, df_res for potato growing season (May-August) = 300, Significant *p*-values are indicated in boldface

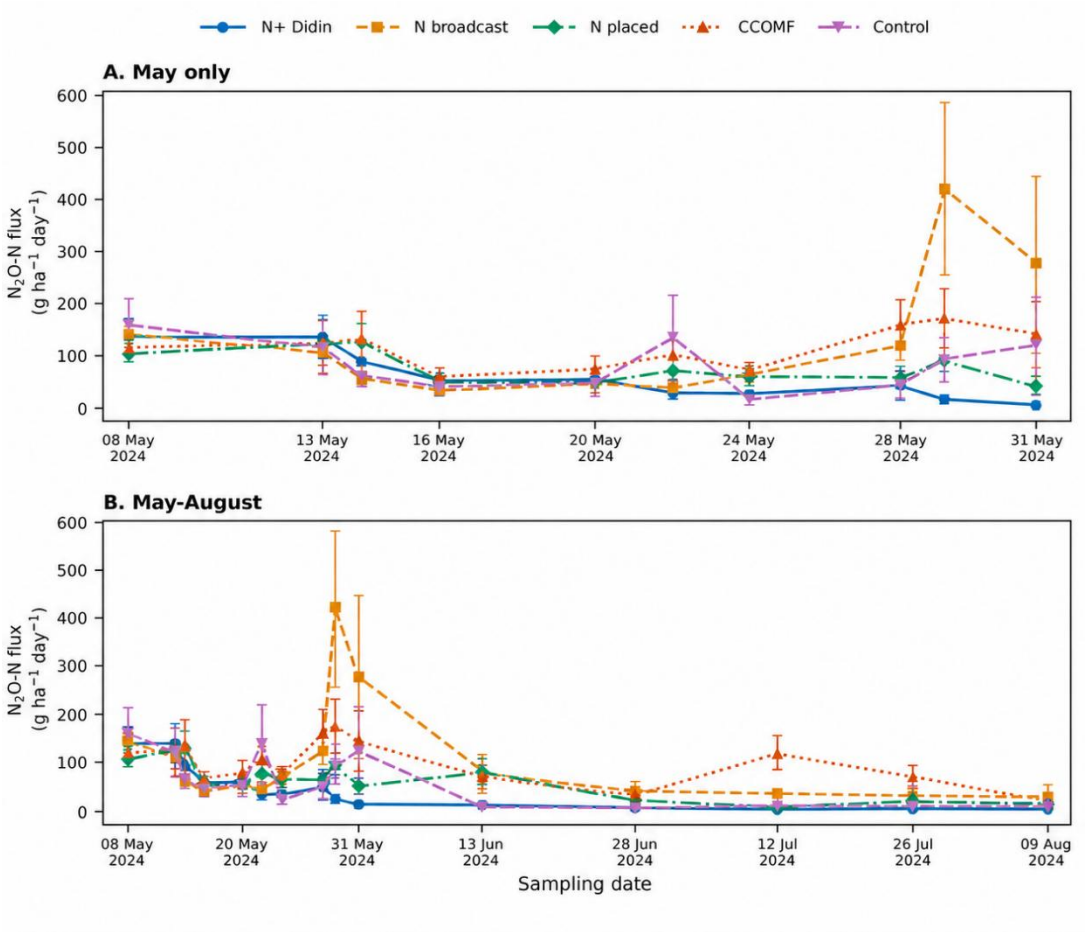


Fig 2. N_2O-N temporal fluxes during the early crop growth stage (sprouting and vegetation phase) of potato in May (**A**) and throughout the potato growing season (**B**). Each point represents the mean flux across five replicates for a given treatment and date.

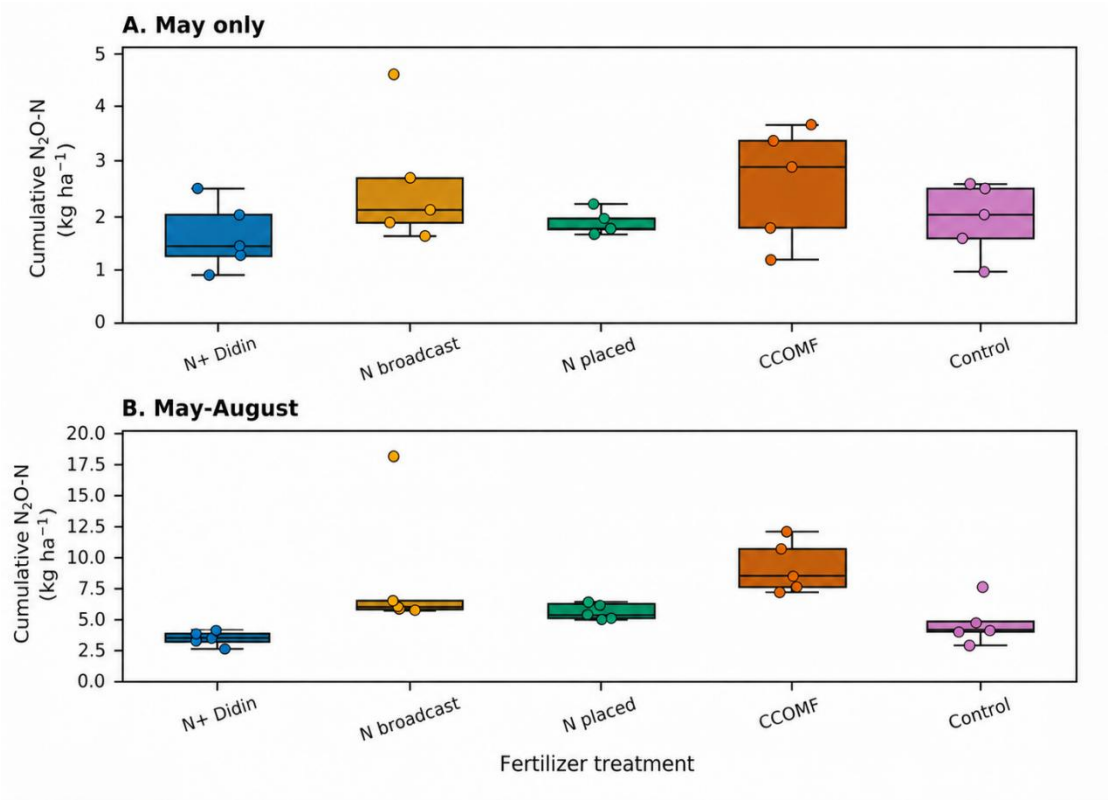


Fig 3. Cumulative N_2O-N temporal fluxes during the early growth stage (sprouting & germination) of potato in May (**A**) and throughout potato growing season (vegetative growth - maturation) (**B**). Each point represents the mean flux across five replicates for a given treatment. No significant differences at $p < 0.05$ based on Tukey HSD test were detected.

Marketable tuber yield, foliage yield and total biomass yield

Marketable tuber yield differed significantly among fertilizer treatments ($F_{4, 15} = 6.648$; $p = 0.002$; Table 2). Tuber yield was highest under CCOMF, followed by Control, N broadcast, N placed and N+Didin. Relative to the Control, CCOMF increased tuber yield by 7.5%, whereas N broadcast, N placed and N+Didin were 1.6%, 13.1% and 27.5% lower, respectively. Foliage yield also showed significant differences among fertilizer treatments ($F_{4, 15} = 4.194$; $p = 0.017$; Table 2). CCOMF increased foliage yield by 43.1% relative to the Control and was significantly greater than Control and N+Didin (Table 2). Further, total biomass yield differed significantly among treatments ($F_{4, 15} = 9.782$; $p < 0.001$; Table 2). Relative to the Control, total biomass yield was 17.2% higher under CCOMF and 5.2% higher under N broadcast, whereas N placed and N+ Didin were 7.2% and 21.2% lower, respectively.

Yield-scaled N_2O-N emissions

Yield-scaled N_2O-N emissions expressed in kg per unit tuber yield showed non-significant differences among fertilizer treatments ($F_{4, 15} = 1.575$; $p = 0.232$; Table 2). Nevertheless, relative to the Control, yield-scaled emissions were more than doubled under N broadcast (2.3 fold) and CCOMF (2.0 fold), while N placed and N+Didin were 40.3% and 9.0% higher, respectively (Table 2).

Emission factor

Emission factor (EF) values were calculated only for fertilized treatments because the Control treatment received no N input and therefore had no defined fertilizer-derived EF (Table 2). Treatment effects on EF were statistically non-significant ($F_{3, 12} = 2.339$; $p = 0.125$; Table 2). Mean EF was highest under N broadcast, followed by CCOMF, N placed and N+Didin. We found negative mean EF under N+Didin because cumulative N_2O-N emissions in that treatment were lower than the Control baseline used in the EF calculation.

Partial factor productivity and agronomic N use efficiency

PFP_N differed significantly among fertilizer treatments ($F_{3, 12} = 6.644$; $p = 0.007$; Table 2). ANOVA showed that mean tuber-based PFP_N was highest under CCOMF, followed by N broadcast, N placed and N+Didin. Relative to N+Didin, PFP_N was 48.2% higher under CCOMF, 35.8% higher under N broadcast and 19.9% higher under N placed (Table 2). Agronomic N use efficiency (aNUE) was significantly different among fertilized treatments ($F_{3, 12} = 6.644$; $p = 0.006$; Table 2). Among fertilized treatments, CCOMF was the only treatment with positive mean tuber-based aNUE (Table 2). Total biomass aNUE also differed significantly ($F_{3, 12} = 11.420$; $p < 0.001$), with CCOMF and N broadcast exhibiting higher positive mean values increases respectively (Table 2).

Discussion

N_2O-N emissions and dynamics

The significant fertilizer and sampling time interaction during both the early growth phase and the full season demonstrates that fertilizer strategy primarily altered the timing and magnitude of episodic N_2O-N emissions rather than baseline flux levels. The late-May increase in N_2O-N emissions under N broadcast, and to a lesser extent under CCOMF, are consistent with the rapid accumulation of nitrate and labile carbon

in surface soil layers when fertilizer is broadcast or when carbon-rich organomineral granules are placed near the surface, creating conditions conducive to denitrification under transient wet or precipitation events (Lacroix et al. 2023; Petersen et al. 2023; Surey et al. 2020). By contrast, N+Didin showed decreasing emissions level at the early crop growth stage and the lowest cumulative N_2O-N emissions of all fertilized treatments. This supports our second hypothesis that co-application of NH_4NO_3 fertilizer with nitrification inhibitor would reduce growing season cumulative N_2O emissions relative to non-nitrification inhibitor mineral N fertilizer treatments. Similar reductions in cumulative N_2O-N with nitrification inhibitors such as Didin (DCD) have been reported in arable and grassland systems in the UK (Bell et al. 2015; Thorman et al. 2020), although effect sizes vary with soil moisture and temperature regimes (Malyan et al. 2025; Monzon Diaz et al. 2025). Seasonal cumulative emissions under N broadcast and CCOMF were more than double those of the control. These findings agrees with our first hypothesis: surface-applied NH_4NO_3 and the carbon-rich organomineral fertilizer generated higher cumulative N_2O-N emissions than deep-placed mineral N. Meta-analysis from potato systems have similarly found that high single-dose mineral N applications, particularly when broadcast, are associated with pronounced N_2O-N fluxes and elevated seasonal emissions (Ball and Hernandez-Ramirez 2025). Our findings extend this evidence to a commercial potato system and show that organomineral fertilizer spreading may prime more N_2O emissions when applied at high N rates to frequently irrigated soils with high baseline mineral N. It is important to note that the significant interaction between fertilizer treatments and sampling time underscores the importance of high-frequency sampling to capture episodic peaks that dominate seasonal/cumulative totals (Barton et al. 2015). It also suggests that targeted mitigation strategies should prioritize the suppression or temporal shifting of peak episodic emission events, rather than the modification of stable, low-magnitude baseline fluxes.

Table 2. Fertilizer treatments effect on tuber yield, yield scaled N_2O emissions and agronomic N use metrics.

Treatments	Marketable yield (t ha^{-1})	Foliage yield (t ha^{-1})	Total biomass (t ha^{-1})	YESE N_2O-N (kg t^{-1} tuber)	Emission factor (%)	PFP_N	aNUE kg tuber kg^{-1} N	aNUE kg total biomass kg^{-1} N
N + Didin	41.8 ± 6.1^{b}	20.9 ± 1.2^{b}	62.7 ± 6.1^{c}	0.07 ± 0.01	-0.66 ± 0.17	261.48 ± 38.12^{b}	-99.14 ± 38.12^{b}	- 105.23 ± 37.89^{c}
N broadcast	56.8 ± 1.0^{a}	26.9 ± 1.9^{ab}	83.7 ± 2.5^{ab}	0.14 ± 0.05	2.87 ± 2.06	355.00 ± 6.05^{a}	-5.63 ± 6.05^{a}	25.94 ± 15.75^{ab}
N placed	50.2 ± 2.2^{ab}	23.6 ± 1.3^{ab}	73.8 ± 3.3^{b}	0.09 ± 0.00	0.43 ± 0.16	313.44 ± 13.99^{ab}	-47.19 ± 13.99^{ab}	- 35.94 ± 20.28^{bc}
CCOMF	62.0 ± 1.6^{a}	31.2 ± 3.2^{a}	93.2 ± 2.6^{a}	0.12 ± 0.02	2.49 ± 0.71	387.50 ± 10.00^{a}	26.88 ± 10.00^{a}	85.62 ± 16.03^{a}
Control	57.7 ± 0.9^{a}	21.8 ± 2.0^{b}	79.5 ± 2.4^{b}	0.06 ± 0.01	-	-	-	-

Values mean ± standard error (n = 4). Mean values with the same letter are not significantly different at $p < 0.05$ based on Tukey HSD test.

Tuber yield responses and agronomic performance

CCOMF delivered the highest increase on marketable tuber yield and total biomass. This validates a controlled pot trial (Oladele et al. 2025), confirming that carbon capture organomineral fertilizers can effectively replace conventional N fertilizers to enhance potato yield and N uptake. This enhancement is driven by improved nutrient synchrony and the supply of organic C, which concurrently stimulates root growth and soil microbial activity (Aguilar et al. 2019; Ferreria et al. 2022). In marked contrast, the inhibitor treatment (N+Didin) reduced tuber yield compared with the control and CCOMF. This outcome indicates that, under the localized conditions of this field trial, the rate and timing of nitrate release with DCD slowed N availability beyond the optimum for Maris Piper, and that early season N limitation may have constrained canopy development and tuber initiation. A meta-analysis reported yield trade-off when nitrification inhibitors are used in cool, well-drained soils where nitrification is already relatively slow, or when single pre-plant applications are not well aligned with crop N demand (Pan et al. 2023). Our data therefore partially confirm the second hypothesis (reduced emissions with N+Didin) but clearly reject the assumption that this would be achieved without compromising yield. Deep placement of mineral N (N placed) provided intermediate agronomic performance suggesting that, at the applied rate and placement configuration, deep placement did not confer a yield advantage over conventional spreading. This contrasts with some studies in maize and cereals where band or deep placement improved N use efficiency and yield by placing fertilizer closer to the root zone and reducing volatilization (Rychel et al. 2020; Sharifi et al. 2023). In potatoes on ridged beds, root distribution and the interaction with irrigation patterns may reduce the advantage of deeper bands (Niedzinski et al. 2023), particularly on a moderately well-drained medium textured soil where leaching potential is significant.

Yield-scaled N_2O emissions and emission factors

Emission intensity was higher under N broadcast and CCOMF, but lower under N+Didin suggesting that conventional broadcast of fertilizers without inhibitors may represents a relatively inefficient method of N fertilizer application. These findings echo studies showing that yield-scaled emissions often remain high under N-rich systems even when absolute yields increase, especially when N rates approach or exceed the agronomic optimum (Zhao et al. 2017; Zeng et al. 2026). EF further illustrate the differential performance of the fertilizer strategies. N broadcast and CCOMF had

EF of 2.87% and 2.49%, respectively, exceeding the default IPCC Tier 1 value (IPCC 2007) of 1% and falling within the range reported for intensively managed, high N input arable and grassland systems in temperate countries (Cardenas et al. 2019; Smith et al. 2012). N placed had a substantially lower EF (0.43%) - less than half of IPCC Tier 1 value, indicating that deep placement reduced fertilizer induced N_2O-N relative to surface broadcast at the same N rate. At 0.43%, the deep-placement EF is less than half of the standard 2006 IPCC Tier 1 default (1.0%) and roughly a quarter of the 2019 wet-climate default (1.6%). This suggests that management practices (how and where fertilizer is placed) matter significantly more than a one-size-fits-all global default. The negative EF for N+Didin (-0.66%) reflects N_2O-N emissions below unfertilized treatment and is consistent with strong inhibition of nitrification and denitrification pathways, as reported in other DCD studies (Roche et al. 2016; Cardenas et al. 2019; Thorman et al. 2020). Taken together, the yield-scaled emissions and EF suggest that, in this system, fertilizer placement and inhibitor use are effective levers for N_2O emission mitigation.

Agronomic N use efficiency

CCOMF achieved the highest PFP_N and a uniquely positive tuber-based aNUE amongst fertilizer treatments confirming our third hypothesis that organomineral fertilizer would enhance N use efficiency relative to conventional mineral N strategies. The improved N use efficiency likely reflects a combination of slower N release, improved soil structure and water retention, and enhanced microbial activity, as observed in other organomineral studies in potato (Paul et al. 2025; Zebarth et al. 2005). Surprisingly, both N placed and N broadcast resulted in negative tuber-based aNUE and only moderate PFP_N. This likely occurred because high baseline soil mineral N level in both treatments averaging 97 kg N ha^{-1} and 227 kg N ha^{-1}, respectively meant that the subsequent application of 160 kg N ha^{-1} exceeded the agronomic optimum. Similar patterns of high PFP_N but negative aNUE at high N rates have been reported in arable systems, and are interpreted as evidence of N saturation where additional fertilizer leads to losses rather than increased yield (Shcherbak et al. 2014; Van Groenigen et al. 2010). The application of nitrification inhibitor (N+Didin) resulted in negative aNUE and the lowest PFP_N highlighting trade-off between emission mitigation and yield productivity. Given this premise, it may be more promising to explore reduced N rates and split applications with inhibitors tailored to potato N demand curves (Li et al. 2020).

However, from this study, CCOMF offered the best combination of yield and agronomic N efficiency offsetting N_2O emissions, whereas N+Didin minimized N_2O emissions at the cost of yield and efficiency.

Fertilizer types and application methods, soil mineral N and implications for N losses

Soil mineral N was measured only twice (pre-planting and harvest), so we could not resolve within-season NO_3^- and NH_4^+ dynamics, nor directly quantify leaching. Therefore, observed residual N differences provide only a qualitative indication of retention, and may have missed transient peaks of NO_3^- at depth following rainfall/irrigation events. However, soil mineral N at 30 cm depth averaged 51 - 227 kg N ha^{-1} prior to fertilizer treatment application across treatment plots at the field trial site indicating a high N input system. N Broadcast, CCOMF and the un-fertilized control all showed substantial uptake or depletion of soil mineral N at 0-30 cm. Whereas nitrification inhibitor (N+Didin) and N placed both showed an increase at 0-30 cm and accumulated mineral N at 30-60 cm. This pattern suggests that the inhibitor treatment effectively slowed nitrification and/or subsequent plant N uptake and losses, retaining more mineral N in the profile late in the season, while deep placement favored retention at depth rather than in the surface layer. Similar increases in residual soil mineral N under nitrification inhibitor applied treatments have been reported in temperate systems and are often interpreted as an indication of reduced nitrification and leaching during the main growing period (Muller et al. 2023; Soares et al. 2023; Tufail et al. 2023). From a mitigation perspective, higher residual mineral N under N+Didin and N placed at 30-60 cm could imply a greater risk of off-season N_2O-N emissions or NO_3^- leaching during wet periods in autumn or winter. Hence, more frequent sampling, including in the inter-row and below 60 cm, would be required to fully capture vertical N redistribution and potential off-site losses.

Study limitations

Some limitations should be considered when interpreting the findings from this study. First, our experiment covered a single growing season, soil type, and one commercial field/site, therefore annual variability in weather and background N mineralization could not be assessed. Given the strong dependence of N_2O emissions on soil texture, moisture regime and temperature, at least 2-3 year trials are needed to confirm the robustness of treatments across wetter and drier seasons. Further, we did not maintain continuous soil moisture time series measurements which limited our ability to link N_2O emission peaks to specific moisture levels or water-filled pore space, and to distinguish between irrigation and rainfall-driven events. Second, we evaluated a single N rate (160 kg N ha^{-1}), as N_2O-N responses may be non-linear with respect to different N input rates (Shcherbak et al. 2014).

Conclusions

This commercial scale field experiment in the East Midlands provides evidence on how fertilizer type and placement influence N_2O emissions, yield and agronomic N use efficiency in intensive potato production. Among the tested fertilizer and application strategies, CCOMF was the most promising from an agronomic perspective, delivering the highest marketable tuber yield, partial factor productivity, agronomic N use efficiency and low yield-scaled N_2O-N emissions. On the other hand, the inhibitor treatment (N+Didin) provided a strong N_2O-N mitigation albeit a yield penalty at the tested rate and timing. Deep placement of mineral N also provided an intermediate option, with lower emission factors and only moderate yield loss, and thus appears a plausible foundation for future optimization through reduced N rates and refined timing. Overall, our results suggest that spreading low carbon footprint organomineral fertilizer (CCOMF) can simultaneously minimizes N_2O emissions and maximizes tuber yield at 160 kg N ha^{-1} under localized conditions. For much lower N_2O emissions without yield compromise, a promising pathway to explore may involve the combination of (i) split application, (ii) band or deep placement of organomineral fertilizers, and (iii) context-specific use of nitrification inhibitors tailored to crop N demand and soil type. Future multi-year trials that integrate continuous soil moisture and mineral N monitoring, and that explore a wider range of N rates and application timings, will be

essential to refine these strategies and to support their inclusion in farm level mitigation planning and policy framework.

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Contributions

SO, SV and IG conceived the study, SO collected and analyzed the data. The first draft of the manuscript was written by SO, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

This study received a favorable ethics opinion by the University of Lincoln Ethics committee (2022_9271).

Competing interests

The authors declare no competing interests.