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Nitrogen fertilisation reveals contrasting nitrogen-use efficiency and greenhouse gas emission intensity responses in linseed and oilseed rape

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Abstract

Break crops vary in nitrogen (N) demand, yet direct comparisons of their nitrogen use efficiency (NUE) and greenhouse gas (GHG) emission intensity are limited. We compared four linseed (*Linum usitatissimum*) genotypes with one oilseed rape (OSR; *Brassica napus*) genotype in a controlled glasshouse experiment across four N fertiliser rates (0-120 kg N ha^{-1}). Plant growth traits, NUE, daily and cumulative GHG fluxes (N_2O, CO_2, CH_4) and emission intensity (kg CO_2e kg^{-1} biomass) were quantified.

OSR produced greater biomass, chlorophyll content, and NUE than linseed at all N rates. Absolute GHG emissions rose more steeply with increasing fertiliser in OSR. Consequently, CO_2e emission intensity increased with N rate in linseed but decreased in OSR, consistent with biomass dilution. Fertiliser rate was the dominant driver of GHG fluxes; crop type had no independent effect on cumulative emissions once N rate was accounted for. Genotypic variation within linseed was negligible compared with crop- and fertiliser-driven effects.

These results highlight a yield-emission trade-off: OSR maximises productivity but requires careful N management to control emissions while linseed maintains lower emission intensity under reduced N inputs. Linseed offers potential as a lower-intensity break crop in diversified, low-N rotations. Further field-scale evaluation needed to support agricultural decarbonisation.

Introduction

Agriculture contributes approximately 24% of global greenhouse gas (GHG) emissions, with nitrogen (N) fertiliser use a dominant source of nitrous oxide (N_2O), which accounts for up to 50–60% of crop-related emissions (Smith et al., 2007; Sun and Huang, 2012; Zhang et al., 2015; Guo, Liu and He, 2022). While N fertilisers underpin modern food production, crop uptake of applied N is typically inefficient, with substantial losses to the environment via gaseous emissions and leaching (Cassman, Dobermann and Walters, 2002; Govindasamy et al., 2023). As a result, increasing yields through higher N inputs often delivers diminishing productivity gains while disproportionately increasing GHG emissions and downstream impacts such as nutrient runoff and eutrophication (Sutton and UNEP, 2013; Lassaletta et al., 2014; You et al., 2024). This creates a fundamental tension between crop productivity and climate mitigation, highlighting the urgent need to identify strategies that decouple biomass production from N losses while maintaining yields, in line with sustainability targets such as the UK's 2050 Net Zero commitment (UNFCCC, 2018; DEFRA, 2022; Eory et al., 2022).

Break crops such as linseed (*Linum usitatissimum*) and oilseed rape (*Brassica napus*) play an important role in temperate arable rotations, impacting N demand, soil structure and environmental impacts at the system scale (Kirkegaard et al., 2008; Angus et al., 2015). Oilseed rape is typically characterised by high biomass production and relatively high N requirements (Walter et al., 2015; O'Neill et al., 2021), whereas linseed is often grown with lower fertiliser inputs and offers advantages in low-input or diversified

systems (Biradar et al., 2016; Stahl et al., 2019; Liang et al., 2022). Despite this contrast, comparative evidence on how these crops differ in N response, NUE and associated GHG emissions remains limited (Walthall et al., 2025). Controlled experiments that isolate crop responses across N gradients are therefore needed to clarify whether crop choice can meaningfully alter yield–emissions trade-offs. Beyond these crop-level differences, N_2O production and emissions in soils are governed by microbial processes such as nitrification and dentrification, modulated by environmental factors including soil pH, oxygen availability and labile carbon inputs (Girkin and Cooper, 2022). Plant-soil interactions exert comparable influence, with roots indirectly regulating emissions through exudation of metabolites that fuel denitrifying bacteria and enhance N_2O release, or via rhizosphere pH alterations that shift denitrification product ratios towards N_2O (Maurer et al., 2021; Ahmed et al., 2026). These mechanisms underscore the potential for crop-specific root traits to amplify or mitigate fertiliser-driven emissions, warranting targeted investigation in comparative studies.

Recent studies highlight variation in N use efficiency and GHG emission profiles within crops generally (Walthall et al., 2025), and oilseed genotypes specifically, with breeding and management efforts increasingly focused on reducing N_2O losses via improved root architecture and N uptake efficiency (Stahl et al., 2019; Li et al., 2023). However, many studies remain focused on within-species variation, often overlooking crop-level aggregations and thereby obscure broader fertiliser-driven patterns, particularly in cases where genotypic differences are small relative to species-level responses (Sieling et al., 2023; Walthall et al., 2025). Biomass dilution, where yield gains outpace emission increases, emerge as a key mechanism decoupling productivity from GHG intensity (Kokubun, 2026; Ortiz-Bobea and Pieralli, 2026). Glasshouse experiments with regulated environments provide a valuable framework to isolate these effects, informing field-scale validation and potentially policy for low-emission rotations (Limpens et al., 2012).

Here, we use a controlled glasshouse experiment to quantify how N fertiliser rate and crop type interact to influence plant growth, NUE, and GHG emissions in four linseed genotypes and a contrasting oilseed rape genotype, enabling mechanistic isolation crop-level effects from confounding field variables such as weather and soil heterogeneity. We hypothesised that OSR would exhibit steeper biomass gains with increasing N, leading to dilution effects and declining intensity, while linseed maintains lower intensity at low N rates, consistent with its use in lower-input break-crop systems. We also hypothesised that within-linseed genotypic variation would be small relative to crop-level and fertiliser-driven effects, with limited differentiation in GHG emissions or associated plant traits among genotypes.

Method

Experimental design and plant culture

A controlled glasshouse experiment was conducted to quantify crop- and N-driven differences in plant growth, NUE and GHG emissions. Four spring linseed (*Linum usitatissimum*) genotypes (VT50, Omegalin, Empress and Richess) and one oilseed rape (*Brassica napus*) genotype (Rocca) were grown under four N

fertiliser rates. Seeds were sown on 8th January 2025 in 5L free-draining plastic pots (20cm diameter, depth of 43cm) filled with Westland topsoil (approximate pH of 5.7, ideal temperature of 20°C). The four linseed genotypes were selected due to their recent registration to UK agriculture, having all been grown within the last 10 years, and sourced from Premium Crops (Hampshire, UK). VT50 was first bred in Canada, and the other three genotypes were all bred in France. All four genotypes are high yielding linseed varieties, with VT50 being particularly favourable for high omega-3 content (Premium Crops, 2022). They are currently the four most abundantly grown linseed genotypes within the UK, however, their N response rate and GHG emissions are not yet studied. Rocca was selected as the OSR genotype due to having high vigour and suitability for most soil types and growing conditions (Liang et al., 2022). Pots were arranged in a randomised complete block design across four N fertiliser treatments (0, 40, 80 and 120 kg N ha^{-1}), with three replicates per genotype × fertiliser combination (n = 60 planted pots), plus unplanted control pots. Pots were spaced to minimise canopy overlap and edge effects (Fig. 1).

Linseed was sown at a density equivalent to 400 seeds m^{-2} (approximately 50% of the standard field rate), while OSR was sown at its typical field density (20 seeds m^{-2}). Reduced linseed sowing density was used to limit in-pot competition and ensure that observed responses replicated fertiliser and crop effects rather than density-dependent constraints, which are known to influence biomass allocation in pot experiments (Poorter et al., 2012; Eddy et al., 2016). OSR density was maintained at field-relevant levels to preserve its characteristic growth form and nutrient demand. This differential sowing approach means that crop comparisons are not strictly equivalent on a per-plant basis, potentially influencing GHG emissions through variations in canopy density, soil coverage and associated microclimatic effects. The setup was designed to approximate a scaled-down field system, facilitating translation from controlled glasshouse conditions to real-world arable scenarios, rather than isolating individual plant-level responses.

Pots were maintained in a temperature-controlled glasshouse at Cranfield University (52°04'10.0"N, 0°37'44.4"W), with temperature maintained between 15 and 18°C. Soil moisture was maintained via regular irrigation to avoid water limitation, with all treatments receiving identical watering regimes throughout the experiment. N fertiliser was applied as granular urea (46% N) at rates equivalent to 0, 40, 80 and 120 kg N ha^{-1}, spanning the typica agronomic range for linseed and oilseed rape in the UK. Fertiliser was applied in two equal split applications to reflect standard field practice, with the first application shortly after crop establishment and the second during vegetative growth. Plants were harvested on 10th April 2025 at a comparable developmental stage across treatments. At harvest, above- and below-ground biomass and associated plant traits were measured as described below.

GHG measurements

GHG fluxes of CO_2, N_2O and CH_4 were measured weekly using the closed static chamber method following established protocols for pot-based experiments (de Klein and Harvey, 2013). Measurements commenced on 23rd January 2025, prior to fertiliser application, and continued throughout the

experimental period, capturing post-fertilisation emission dynamics. Each pot was enclosed within an airtight chamber fitted with inlet and outlet ports connected to a gas analyser (Supplementary Fig. 1). Gas concentrations were recorded over a 150 seconds enclosure period. On the first two sampling dates, gas concentrations were measured using a portable Fourier-transform infrared (FTIR) Gasmet analyser and subsequent measurements used a Picarro G2508 cavity ring-down spectrometer due to instrument availability. Both instruments quantify CO_2, N_2O and CH_4 at high precision and are widely used for chamber-based flux measurements. As measurements were consistently applied across all treatments on each sampling date, analyser choice did not confound treatment comparisons.

Gas concentration data were converted from parts per million (ppm) to surface-area-normalised fluxes (μg m^2 day^{-1}) using standard linear regression of concentration change over time, accounting for chamber volume, surface area and enclosure duration. Daily fluxes were subsequently integrated over time to derive cumulative emissions (g or kg per ha^{-1}) for each pot across the full experimental period (Somers et al., 2019). Cumulative emissions of CO_2, N_2O and CH_4 were converted to CO_2-equivalents (CO_2e) using 100-year global warming potentials to facilitate comparison of emission intensity among crops and fertiliser treatments (IPCC, 2023). Further plant and soil measurements were also taken to allow comparisons of traits between the genotypes, including volumetric soil moisture content with a Delta T soil moisture sensor, plant chlorophyll content with a Minolta SPAD-502 chlorophyll meter, stomatal conductance with a METER SC-1 porometer, crop height using a standard tape measure, harvest biomass using scientific scales, root length and root weight both using the WinRHIZO image analysis system.

Plant and soil measurements

Plant and soil traits were measured to characterise crop growth responses to N fertilisation and to evaluate potential physiological and morphological drivers of GHG emission intensity. Plants were not grown to full maturity to avoid them becoming pot bound during the experiment.

Plant height (cm) was measured weekly from the soil surface to the apical meristem. Leaf chlorophyll content was assessed using a handheld SPAD meter, with measurements taken on fully expanded leaves and averaged per pot. Volumetric soil moisture content was monitored periodically using a soil moisture probe to confirm that pots remained well-watered and that water limitation did not confound treatment effects. Stomatal conductance was measured using a SC-1 leaf porometer.

At final harvest (10th April 2025) above-ground biomass was cut at the soil surface and weighed to determine fresh harvest biomass. Subsamples were oven-dried at 60°C to constant mass to determine dry plant weight. Roots were carefully washed free of soil, dried and weighed to obtain dry root biomass. Total dry biomass was calculated as the sum of above- and below-ground dry weights. Root length (cm) was measured after washing using the WinRHIZO root image analysis system (Regent Instruments,

2025). Harvest traits were used to calculate NUE and emission intensity metrics, and to test for crop- and genotype-level differences in growth allocation.

Derived metrics and trait integration

NUE was calculated for each genotype and fertiliser treatment as the increase in harvest biomass relative to the unfertilised control divided by the amount of nitrogen applied (g biomass kg^{-1} N) (Roobroeck et al., 2021). GHG emission intensity was calculated as cumulative GHG emissions (kg ha^{-1}) normalised by harvest biomass (g), expressed for individual gases and as CO_2-equivalents (CO_2e). Plant traits were selected to capture variation in canopy development, biomass accumulation and below-ground allocation that could plausibly mediate crop-specific responses of emission intensity to N fertilisation.

Statistical Analysis

All statistical analyses were performed using R version 4.3.2 (R Core Team, 2025). Analyses were structured to 1) quantify crop- and N-driven effects on plant traits and GHG emissions, and 2) assess whether crop-specific differences in emission intensity were mediated by biomass production.

Final plant growth traits (e.g. harvest biomass, dry plant weight, chlorophyll content, height and root traits) and cumulative GHG emissions were analysed using two-way ANOVA with crop (OSR or linseed), N fertiliser rate and their interaction as fixed effects. Where relevant, linseed-only models were fitted to test genotypic effects and genotype × fertiliser interactions. Tukey HSD post-hoc tests were used for pairwise comparisons ($\alpha = 0.05$). Daily GHG fluxes (CO_2, N_2O, CH_4) were analysed using linear mixed models (LMMs; lme4 package), with genotype, fertiliser rate and their interaction specified as fixed effects and sampling date included to account for repeated measures over time. The approach captured fertiliser-driven emission pulses while controlling for temporal autocorrelation. Where residuals deviated from normality, flux data were log-transformed.

To synthesise relationships among plant traits and emissions, standardised plant growth variables and cumulative CO_2e emissions were ordinated with non-metric multidimensional scaling (NMDS; vegan::metaMDS) based on Bray-Curtis dissimilarities. Differences among crop x N fertiliser treatments were tested with PERMANOVA (vegan::adonis2, 9999 permutations). NMDS was used as a visual and integrative rool rather than for inference on individual variables. Structural equation modelling (SEM; lavaan package) was used to explicitly test whether dry plant weight mediated the interaction between crop type and N fertiliser rate on CO_2e emission intensity. Crop type (binary) and N fertiliser rate (continuous) were specified as exogenous predictors, dry plant weight as a mediator and CO_2e intensity as the response variable. A full-mediation model was evaluated by constraining the direct crop x N fertiliser path to zero. Model fit was assessed with the Fisher C statistic test of d-separation (χ^2), Akaike's Information Criterion (AIC) and the root mean square error of approximation (RMSEA). Model

assumptions of normality and homoscedasticity were assessed using Shapiro-Wilk and Levene's tests, with visual inspection of residuals. Significance was evaluated as $p < 0.05$.

Results

Plant growth responses to N fertilisation differed strongly between crops, with OSR showing consistently greater biomass, chlorophyll content, and dry weights than linseed (Table 1; Supplementary Fig. 2). These differences were primarily driven by crop type and N fertiliser rate, with two-way ANOVA showing significant main effects of crop and N alongside a strong crop × fertiliser interaction for dry plant weight ($p < 0.001$ for all; Table 2).

Table 1
Mean ± SE values for key plant growth traits by crop and nitrogen fertiliser rate, aggregated from replicates per crop-treatment combination. Asterisks appended to OSR values indicate significant differences vs linseed at each rate (*** $p < 0.001$), derived from two-way ANOVA and emmeans pairwise contrasts.

Fertiliser (kg N ha^{-1})	Biomass OSR (g)	Biomass Linseed (g)	Chlorophyll OSR (SPAD)	Chlorophyll Linseed (SPAD)	Dry Weight OSR (g)	Dry Weight Linseed (g)
0	59.33 ± 12.98	72.17 ± 7.17	10.3 ± 4.65	1.04 ± 0.03	9.53 ± 1.55	15.42 ± 1.86
40	261.33 ± 22.58 ***	132.5 ± 9.16	31.32 ± 3.91 ***	1.8 ± 0.24	67.4 ± 0.25 ***	33.67 ± 1.73
80	311.33 ± 7.51 ***	151.67 ± 5.13	59.33 ± 4.58 ***	1.72 ± 0.26	137.43 ± 9.79 ***	50.83 ± 2.15
120	266.0 ± 14.19 ***	167.33 ± 10.9	46.92 ± 5.56 ***	1.69 ± 0.18	156.77 ± 8.89 ***	47.85 ± 1.93

In contrast to crop and fertiliser effects, genotypic variation within linseed was limited. Nested and linseed-only models detected no consistent genotype effects on biomass-related traits once fertiliser rate was accounted for ($p > 0.05$ for primary traits; Supplementary Tables 1–2). Crop height and root length increased with N application rate (fertiliser $p < 0.001$ for both), but genotypic variation within linseed was non-significant when nested within crop ($p > 0.05$). Chlorophyll content was higher in OSR (mean 32–49 SPAD units) than linseed (1–4 SPAD units; crop $p < 0.001$). Post-hoc tests confirmed significant differences at all N fertilisation rates ($p < 0.001$; Supplementary Table 2).

Table 2
Summary of ANOVA p-values for key plant growth traits, comparing crop-level effects (OSR vs linseed) and genotypic effects within linseed. Crop model includes crop, fertiliser rate and their interaction; linseed-only model includes genotype (four varieties), fertiliser rate, and their interaction. Significant: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ns = not significant ($p > 0.05$).

Trait	Crop p-value	Fertiliser p-value (crop model)	Crop × Fertiliser p-value	Genotype p-value (linseed only)	Fertiliser p-value (linseed only)	Genotype × Fertiliser p-value (linseed only)
Harvest Biomass	< 0.001***	< 0.001***	< 0.001***	0.056 ns	< 0.001***	0.021*
Harvest Height	< 0.001***	< 0.001***	0.002**	0.015*	< 0.001***	0.043*
Harvest Chlorophyll	< 0.001***	< 0.001***	< 0.001***	0.002**	0.002**	0.793 ns
Dry Root Weight	< 0.001***	< 0.001***	< 0.001***	0.009**	< 0.001***	0.024*
Dry Plant Weight	< 0.001***	< 0.001***	< 0.001***	0.052 ns	< 0.001***	0.167 ns
Total Dry Weight	< 0.001***	< 0.001***	< 0.001***	0.008**	< 0.001***	0.046*

We found contrasting N response trajectories to increased N application rate (Fig. 2). OSR exhibited a strong increase in biomass across the N gradient whereas linseed showed a more modest and gradual response. Consistent with this visual pattern, the estimated biomass response to N was substantially steeper in oilseed rape than in linseed (emtrends: OSR = 1.279 g dry biomass kg^{-1} N, $p < 0.001$; linseed = 0.286 g dry biomass kg^{-1} N, $p < 0.001$), indicating a pronounced crop-level difference in N responsiveness.

Daily GHG fluxes were driven primarily by N fertiliser timing, with pronounced post-application peaks in CO_2 and N_2O following split applications, while CH_4 showed a net uptake (Supplementary Fig. 3). LMMs indicated significant fertiliser effects ($p < 0.001$ for CO_2 and N_2O), escalating at 80-120kg N ha^{-1}, but no crop or interaction effects ($p > 0.05$; Supplementary Table 4). Consistent with this, post-hoc contrasts within each N rate showed no significant differences among genotypes (Supplementary Table 5). Cumulative GHG emissions increased stepwise with N application rate ($p < 0.001$ for CO_2 and N_2O; $p < 0.05$ for CH_4), rising from ~ 28 kg ha^{-1} CO_2 and 0.10 kg ha^{-1} N_2O at 0 kg N ha^{-1} to ~ 61 kg ha^{-1} CO_2 and 0.45 kg ha^{-1} N_2O at 120 kg N ha^{-1} (Fig. 3; Supplementary Table 6). Post-hoc tests confirmed these rate-specific increases (Supplementary Table 3), while crop type did not significantly influence cumulative emissions once N rate was accounted for.

NUE decreased with increasing N application across both crops, with OSR maintaining higher values across the fertiliser gradient (3–5 g biomass kg^{-1} N at 40 kg ha^{-1} vs 1–3 g at 120 kg ha^{-1}; crop $p < 0.001$, fertiliser $p < 0.001$, interaction $p < 0.001$; Fig. 4a). This decline in NUE with increasing N input contrasted with divergent crop-level responses in emission intensity. Emission intensity for CO_2e showed opposing trends between crops, with linseed showing relatively lower intensity at 0-40kg N ha^{-1} but increased positively with N application (0.00691 kg CO_2e kg^{-1} biomass per kg N ha^{-1}) and OSR decreasing in emission intensity with increasing N application (-0.01413 kg CO_2e kg^{-1} biomass per kg N ha^{-1}; Fig. 4b; Supplementary Table 7). Post-hoc comparisons confirmed these contrasting crop-level responses across fertiliser rates (Supplementary Table 8).

To integrate plant growth and emission responses across the nitrogen gradient, multivariate ordination and structural equation modelling were used to assess whether biomass mediated crop-specific patterns in emission intensity (Fig. 5). NMDS ordination of standardised plant traits and cumulative CO_2e emissions revealed clear separation along a productivity-emission gradient (stress = 0.062; Fig. 5a), with significant effects of crop, fertiliser and their interaction ($p < 0.001$ each; 81% variance explained; Supplementary Table 9). OSR clustered at high productivity/emission positions, linseed at lower-impact ones, aligned with significant vectors for dry plant weight, harvest chlorophyll, root length and cumulative CO_2e flux ($p = 0.001$), reflecting OSR's steeper growth response to increasing N rates. Post-hoc tests showed OSR-linseed differences ($p < 0.05$) but no significant genotypic contrasts within rates ($p = 1$; Supplementary Tables 10). SEM provided direct support for this interpretation, indicating full mediation of the crop x N interaction on CO_2e intensity by dry plant weight, with no remaining direct effects (ns; Fig. 5b). Additional plant physiological and soil traits did not explain significant residual variance ($p > 0.05$), and overall model fit was strong, underscoring biomass dilution as the primary mechanism offsetting emissions in OSR at higher N inputs.

Discussion

Our results demonstrate clear crop-level trade-offs in N response and GHG emission intensity between OSR and linseed. Across the fertiliser gradient, OSR consistently produced greater biomass than linseed (Tables 1–2) reflecting a strong responsiveness to N supply. However, this higher productivity was accompanied by steeper increases in absolute GHG emissions at elevated N rates (Fig. 3). In contrast, linseed exhibited more modest but stable growth responses at low-to-moderate N inputs (Fig. 2) and maintained lower emission intensity across much of the fertiliser range (Fig. 4), supporting its role as a lower-impact break crop in diversified rotations.

The dominance of fertiliser rate over genotype in determining plant growth and emissions was a consistent pattern throughout the study. Crop type and N rate explained the majority of variation in biomass-related traits (Tables 1–2; Fig. 2), while genotypic variation within linseed was negligible once analysed at the crop level. This aligns with recent syntheses showing that genotype-specific differences in NUE and emissions are often small relative to species-level traits and fertiliser management (Walthall

et al., 2025). Together, these results suggest that crop choice and N rate are more influential levers for mitigating emissions than within-crop genotype selection under controlled conditions.

Observed growth responses were consistent with known physiological and breeding differences between the two crops. OSR's steep biomass and root-weight responses to increasing N (Fig. 2) reflect breeding gains in photosynthetic capacity and N uptake (Bouchet et al., 2016; Stahl et al., 2017, 2019). In contrast, linseed's more uniform growth response across the N gradient suggests greater resilience under lower-input N regimes (Biradar et al., 2016). These differences translated directly into NUE, highlighting diminishing returns of high N application (Fig. 4).

GHG dynamics were driven overwhelmingly by N fertiliser timing and application rate rather than crop type. Daily N_2O and CO_2 fluxes showed pronounced post-application peaks following split fertiliser inputs (Supplementary Fig. 3), and cumulative emissions increased stepwise with N rate (Fig. 3). The absence of crop or genotype effects on daily fluxes, and the lack of crop influence on cumulative emissions once N rate was accounted for indicate that soil microbial processes responded similarly across treatments under these controlled conditions. Net CH_4 uptake across all treatments further suggests dominance of aerobic methanotrophy in well-aerated pot soils (Lidstrom, 2024).

The clearest divergence between crops emerged when emissions were normalised by productivity. While NUE declined with N in both crops, CO_2e intensity increased in linseed but decreased in OSR (Fig. 4), revealing biomass dilution as the key mechanism in OSR at higher rates (Paut et al., 2025). Integrated multivariate analysis (Fig. 5a) and SEM (Fig. 5b) confirmed that dry plant weight fully mediated the crop x N interaction on emission intensity, with no remaining direct effect. This provides strong mechanistic support for biomass dilution as the primary driver of declining emission intensity in OSR at higher N inputs, whereas linseed's lower absolute productivity constrained dilution potential despite lower overall emissions.

Although the controlled glasshouse design allowed clear isolation of crop and N fertiliser effects, it inevitably limits extrapolation to field heterogeneity, soil biota and long-term rotation dynamics (Limpens et al., 2012; Poorter et al., 2012). The short experimental duration also precludes assessment of carry-over effects, residue-mediated N cycling or multi-year emission responses (Arndal et al., 2013; Isbell et al., 2021; Lei et al., 2025). Nevertheless, the consistency of crop-level patterns across traits, fluxes and integrative analyses (Figs. 2–5) provides a robust mechanistic foundation for targeted field validation. This field validation could be achieved with a multi-year, multi-site study across diverse UK soil types and climates, employing a randomised complete block or split-plot design. Studies should integrate crop rotations to capture carry-over effects from residues and soil N cycling.

Taken together, our results indicate that substituting OSR with linseed, or reducing N inputs to linseed relative to OSR, have the potential lower farm-scaled N_2O emissions by approximately 15–25% based on observed differences in emission intensity (Fig. 4) while maintaining acceptable productivity under reduced N regimes. Genotype selection within linseed appears less critical than crop choice when

observing the four genotypes used within this study, although broader genetic panels should be evaluated under field conditions to assess full real-world potential. Integrating lower-emission break crops such as linseed into UK arable systems has the potential to contribute to climate mitigation targets, while supporting rotation diversity and reduced reliance on high-input crops. Future work should extend these findings to the field scale, incorporate microbial metagenomics and evaluate economic outcomes of genotype-fertiliser pairings under real-world conditions.

Declarations

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Author Contribution

C.W. wrote the main manuscript. C.W. and H.W. collected the data necessary for the paper's creation. C.W. and A.S.J conducted data analysis and modelling. All authors reviewed the manuscript and provided editorial changes and recommendations.

Data Availability

The datasets used and generated for this paper can be found at the following repository: https://doi.org/10.6084/m9.figshare.31424462

References

1. Ahmed, N. et al. ‘Root exudate-mediated plant–microbe interactions and next-generation strategies for sustainable nitrogen management in agricultural soils’, *Applied Soil Ecology*, 219, p. 106758. (2026). Available at: https://doi.org/10.1016/j.apsoil.2025.106758
2. Angus, J. F. et al. ‘Break crops and rotations for wheat’, *Crop and Pasture Science*, 66(6), pp. 523–552. (2015). Available at: https://doi.org/10.1071/CP14252
3. Arndal, M. F. et al. ‘Root growth and N dynamics in response to multi-year experimental warming, summer drought and elevated CO2 in a mixed heathland-grass ecosystem’, *Functional plant biology: FPB*, 41(1), pp. 1–10. (2013). Available at: https://doi.org/10.1071/FP13117
4. Biradar et al. ‘Prospects and challenges in linseed (Linum usitatissimum L.) production: A review: PROSPECTS AND CHALLENGES IN LINSEED (LINUM USITATISSIMUM L.) PRODUCTION: A REVIEW’,

Journal of Oilseeds Research, 33(1). (2016). Available at: https://doi.org/10.56739/jor.v33i1.139028

5. Bouchet, A. S. et al. 'Nitrogen use efficiency in rapeseed. A review', *Agronomy for Sustainable Development*, 36(2), p. 38. (2016). Available at: https://doi.org/10.1007/s13593-016-0371-0
6. Cassman, K., Dobermann, A. R. & Walters, D. 'Agroecosystems, Nitrogen-use Efficiency, and Nitrogen Management', *Department of Agronomy and Horticulture: Faculty Publications* [Preprint]. (2002). Available at: https://digitalcommons.unl.edu/agronomyfacpub/356
7. DEFRA. *Agri-climate report 2022*, *GOV.UK*. (2022). Available at: https://www.gov.uk/government/statistics/agri-climate-report-2022/agri-climate-report-2022 (Accessed: 1 August 2023).
8. Eddy, R. et al. 'Optimizing Greenhouse Rice Production: What Is the Best Pot Size?', *Purdue Methods for Rice Growth* [Preprint], (9). (2016). Available at: http://docs.lib.purdue.edu/pmrg/9 (Accessed: 12 January 2026).
9. Eory, V. et al. 'Greenhouse gas abatement in UK agriculture, 2024–2050'. (2022).
10. Girkin, N. & Cooper, H. 'Nitrogen and ammonia in soils', *Reference Module in Earth Systems and Environmental Sciences*. (2022). Available at: https://doi.org/10.1016/B978-0-12-822974-3.00010-0
11. Govindasamy, P. et al. 'Nitrogen use efficiency—a key to enhance crop productivity under a changing climate', *Frontiers in Plant Science*, 14, p. 1121073. (2023). Available at: https://doi.org/10.3389/fpls.2023.1121073
12. Guo, C., Liu, X. & He, X. 'A global meta-analysis of crop yield and agricultural greenhouse gas emissions under nitrogen fertilizer application', *Science of The Total Environment*, 831, p. 154982. (2022). Available at: https://doi.org/10.1016/j.scitotenv.2022.154982
13. IPCC. *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 1st edn. Cambridge University Press. (2023). Available at: https://doi.org/10.1017/9781009157896
14. Isbell, S. A. et al. 'Nitrogen dynamics in grain cropping systems integrating multiple ecologically based management strategies', *Ecosphere*, 12(2), p. e03380. (2021). Available at: https://doi.org/10.1002/ecs2.3380
15. Kirkegaard, J. et al. 'Break crop benefits in temperate wheat production', *Field Crops Research*, 107(3), pp. 185–195. (2008). Available at: https://doi.org/10.1016/j.fcr.2008.02.010
16. de Klein, E. C. & Harvey, M. 'Nitrous Oxide Chamber Methodology Guidelines', p. 146. (2013).
17. Kokubun, K. 'Decoupling in Global Agriculture: Productivity Growth, Emission Intensity and Persistent Inequality', *Sustainability*, 18(1133). (2026). Available at: https://doi.org/10.3390/su18021133
18. Lassaletta, L. et al. '50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland', *Environmental Research Letters*, 9(10), p. 105011. (2014). Available at: https://doi.org/10.1088/1748-9326/9/10/105011
19. Lei, S. et al. 'Long-term legacy impacts of nitrogen fertilization on crop yield, nitrate accumulation, and nitrogen recovery efficiency', *European Journal of Agronomy*, 164, p. 127513. (2025). Available

at: https://doi.org/10.1016/j.eja.2025.127513

20. Li, J. et al. ‘Synergistic effect of nitrogen and potassium on seed yield and nitrogen use efficiency in winter oilseed rape (Brassica napus L.)’, *European Journal of Agronomy*, 148, p. 126875. (2023). Available at: https://doi.org/10.1016/j.eja.2023.126875
21. Liang, H. et al. ‘Systematic trait dissection in oilseed rape provides a comprehensive view, further insight, and exact roadmap for yield determination’, *Biotechnology for Biofuels and Bioproducts*, 15(1), p. 38. (2022). Available at: https://doi.org/10.1186/s13068-022-02134-w
22. Lidstrom, M. E. ‘Direct Methane Removal from Air by Aerobic Methanotrophs’, *Cold Spring Harbor Perspectives in Biology*, 16(7), p. a041671. (2024). Available at: https://doi.org/10.1101/cshperspect.a041671
23. Limpens, J. et al. ‘Glasshouse vs field experiments: do they yield ecologically similar results for assessing N impacts on peat mosses?’, *New Phytologist*, 195(2), pp. 408–418. (2012). Available at: https://doi.org/10.1111/j.1469-8137.2012.04157.x
24. Maurer, D. et al. ‘Interactive regulation of root exudation and rhizosphere denitrification by plant metabolite content and soil properties’, *Plant and Soil*, 467(1), pp. 107–127. (2021). Available at: https://doi.org/10.1007/s11104-021-05069-7
25. O’Neill, M. et al. ‘Greenhouse Gas Emissions and Crop Yields From Winter Oilseed Rape Cropping Systems are Unaffected by Management Practices’, *Frontiers in Environmental Science*, 9. (2021). Available at: https://doi.org/10.3389/fenvs.2021.716636
26. Ortiz-Bobea, A. & Pieralli, S. ‘Unpacking the growth of global agricultural greenhouse gas emissions’, *Science Advances*, 12(3), p. eaeb8653. (2026). Available at: https://doi.org/10.1126/sciadv.aeb8653
27. Paut, R. et al. ‘Critical nitrogen dilution curves for winter oilseed rape (Brassica napus L.) along the whole crop cycle: A Bayesian analysis’, *European Journal of Agronomy*, 168, p. 127642. (2025). Available at: https://doi.org/10.1016/j.eja.2025.127642
28. Poorter, H. et al. ‘The art of growing plants for experimental purposes: a practical guide for the plant biologist’, *Functional Plant Biology*, 39(11), pp. 821–838. (2012). Available at: https://doi.org/10.1071/FP12028
29. Premium Crops. *The largest buyer of Linseed in the UK*, *Premium Crops*. (2022). Available at: https://www.premiumcrops.com/spring-linseed/agronomy (Accessed: 20 February 2026).
30. R Core Team. ‘R: A language and environment for statistical computing.’ Vienna, Austria: R Foundation for Statistical Computing. (2025). Available at: https://www.R-project.org/
31. Regent Instruments. *WinRHIZO is a complete plant root measurement and analysis systems for agricultural and forestry research.* (2025). Available at: https://regentinstruments.com/assets/winrhizo_mostrecent.html (Accessed: 26 February 2026).
32. Roobroeck, D. et al. ‘Assessing and understanding non-responsiveness of maize and soybean to fertilizer applications in African smallholder farms’, *Agriculture, Ecosystems* & *Environment*, 305, p. 107165. (2021). Available at: https://doi.org/10.1016/j.agee.2020.107165

33. Sieling, K. et al. ‘Differences in N use efficiency, N translocation and N immobilization capacity of their residues of oilseed rape varieties due to N fertilization’, *Archives of Agronomy and Soil Science*, 69(14), pp. 3300–3313. (2023). Available at: https://doi.org/10.1080/03650340.2023.2228257
34. Smith, P. et al. ‘Agriculture’, Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. (2007).
35. Somers, C. et al. ‘The effects of urine nitrogen application rate on nitrogen transformations in grassland soils’, *The Journal of Agricultural Science*, 157(6), pp. 515–522. (2019). Available at: https://doi.org/10.1017/S0021859619000832
36. Stahl, A. et al. ‘Recent Genetic Gains in Nitrogen Use Efficiency in Oilseed Rape’, *Frontiers in Plant Science*, 8, p. 963. (2017). Available at: https://doi.org/10.3389/fpls.2017.00963
37. Stahl, A. et al. ‘Effect of breeding on nitrogen use efficiency-associated traits in oilseed rape’, *Journal of Experimental Botany*, 70(6), pp. 1969–1986. (2019). Available at: https://doi.org/10.1093/jxb/erz044
38. Sun, W. & Huang, Y. ‘Synthetic fertilizer management for China’s cereal crops has reduced N2O emissions since the early 2000s’, *Environmental Pollution*, 160, pp. 24–27. (2012). Available at: https://doi.org/10.1016/j.envpol.2011.09.006
39. Sutton, M. A. (ed) *Our nutrient world: the challenge to produce more food and energy with less pollution ; [global overview on nutrient management]* (Centre for Ecology & Hydrology, 2013).
40. UNFCCC. ‘The Paris Agreement | UNFCCC’. *Paris Climate Change Conference - November 2015* (COP 21). (2018). Available at: https://unfccc.int/process-and-meetings/the-paris-agreement (Accessed: 10 September 2025).
41. Walter, K. et al. ‘Direct nitrous oxide emissions from oilseed rape cropping – a meta-analysis’, *GCB Bioenergy*, 7(6), pp. 1260–1271. (2015). Available at: https://doi.org/10.1111/gcbb.12223
42. Walthall, C. et al. ‘A Global Synthesis of Genotypic Variation in Crop Greenhouse Gas Emissions Under Variable Nitrogen Fertilisation’, *Frontiers in Agronomy*, 7. (2025). Available at: https://doi.org/10.3389/fagro.2025.1669002
43. You, L. et al. ‘Optimized agricultural management reduces global cropland nitrogen losses to air and water’, *Nature Food*, 5(12), pp. 995–1004. (2024). Available at: https://doi.org/10.1038/s43016-024-01076-w
44. Zhang, X. et al. ‘Managing nitrogen for sustainable development’, *Nature*, 528(7580), pp. 51–59. (2015). Available at: https://doi.org/10.1038/nature15743

Figures

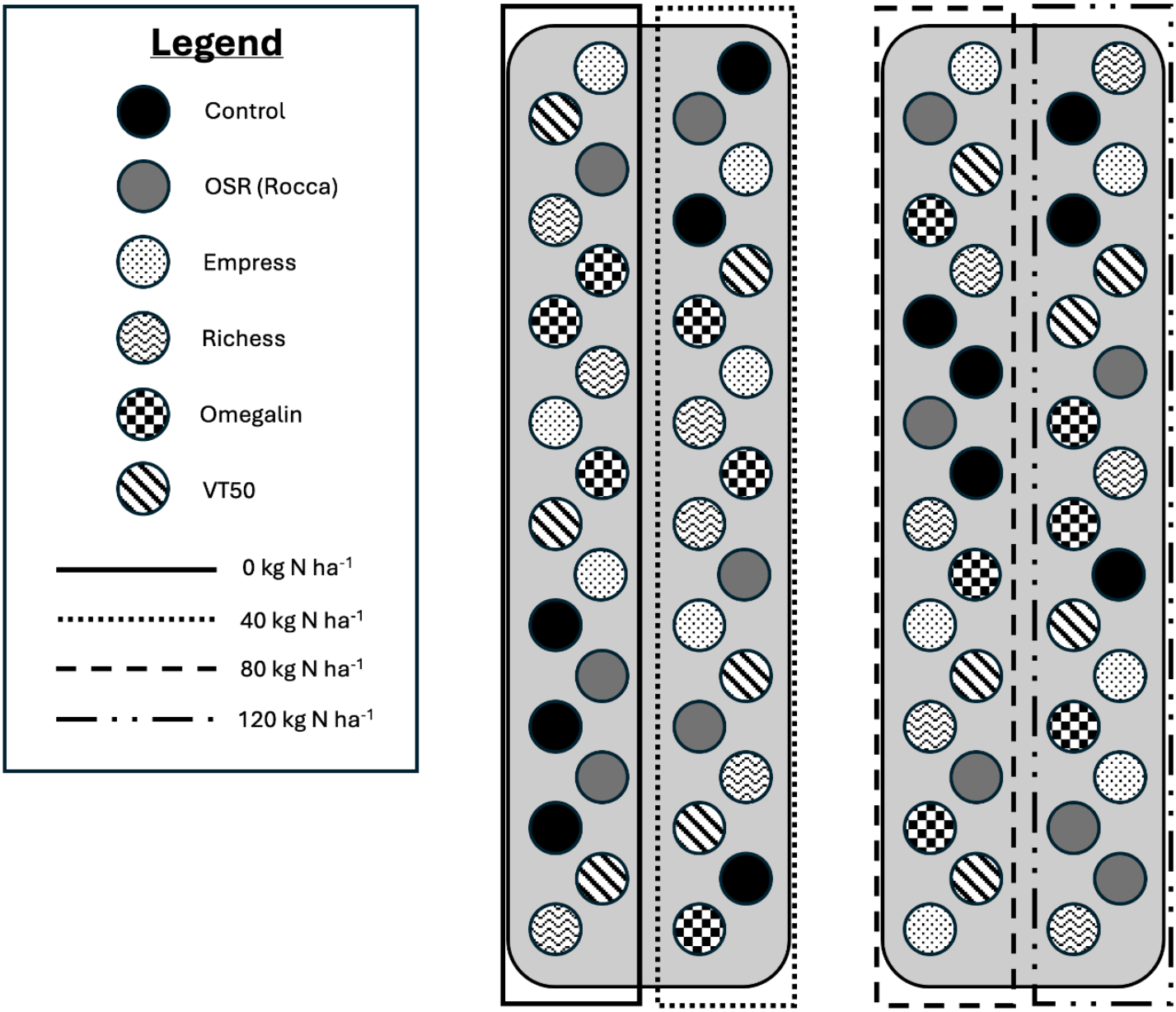


Figure 1

Experimental layout of pots in the glasshouse, illustrating the randomised arrangement of four linseed genotypes and one OSR genotypes across four nitrogen fertiliser rates. Pots were organised in a randomised complete block design with three replicates per genotype-treatment combination, ensuring spatial uniformity and minimising edge effects.

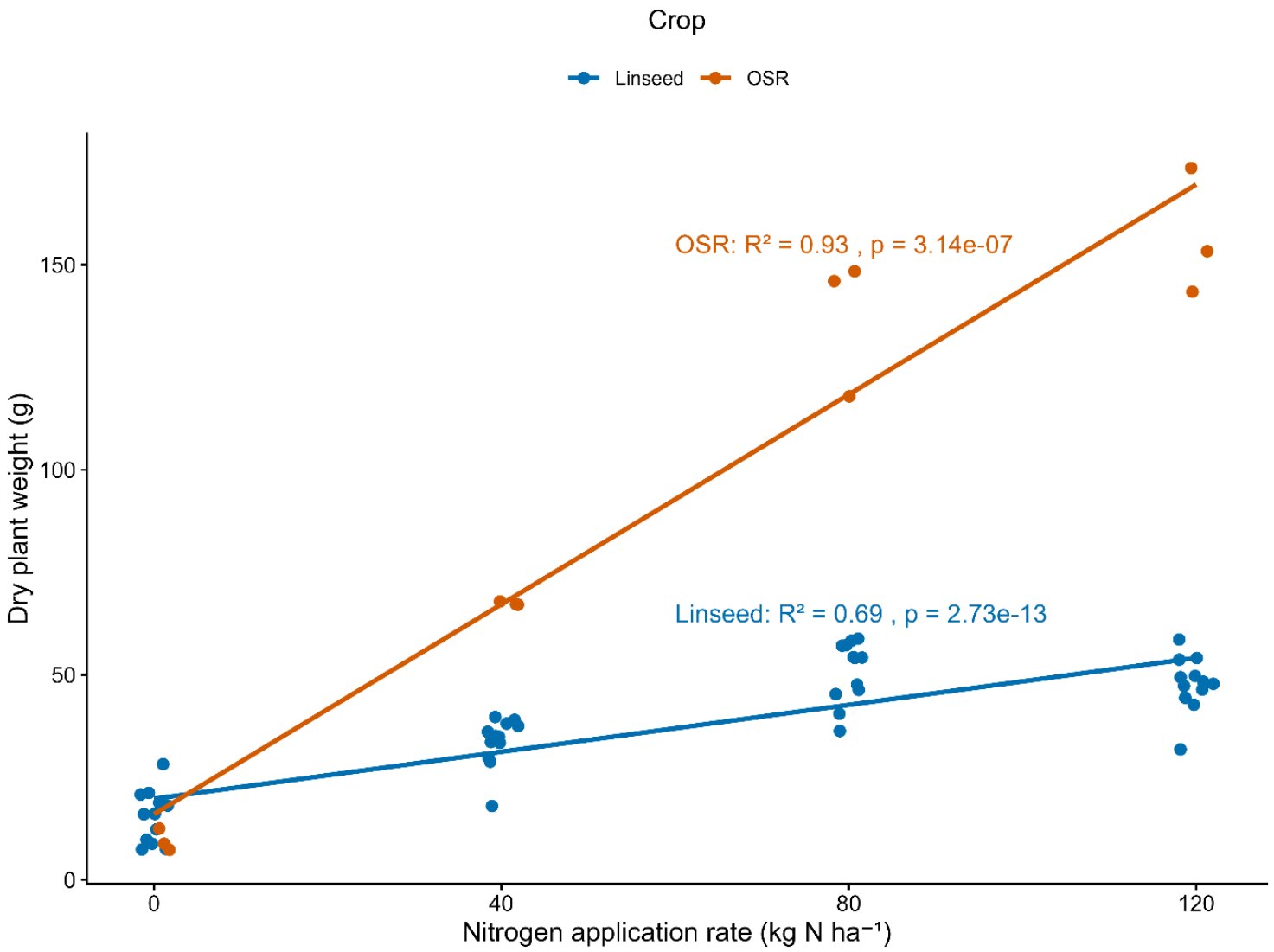


Figure 2

Dry plant weight response to N fertiliser application rate (kg N ha^{-1}) for OSR and linseed in a controlled glasshouse experiment. Points represent individual replicates (n=3 per crop-treatment combination), with linear regression lines showing crop-level trends derived from two-way ANOVA and emtrends analysis.

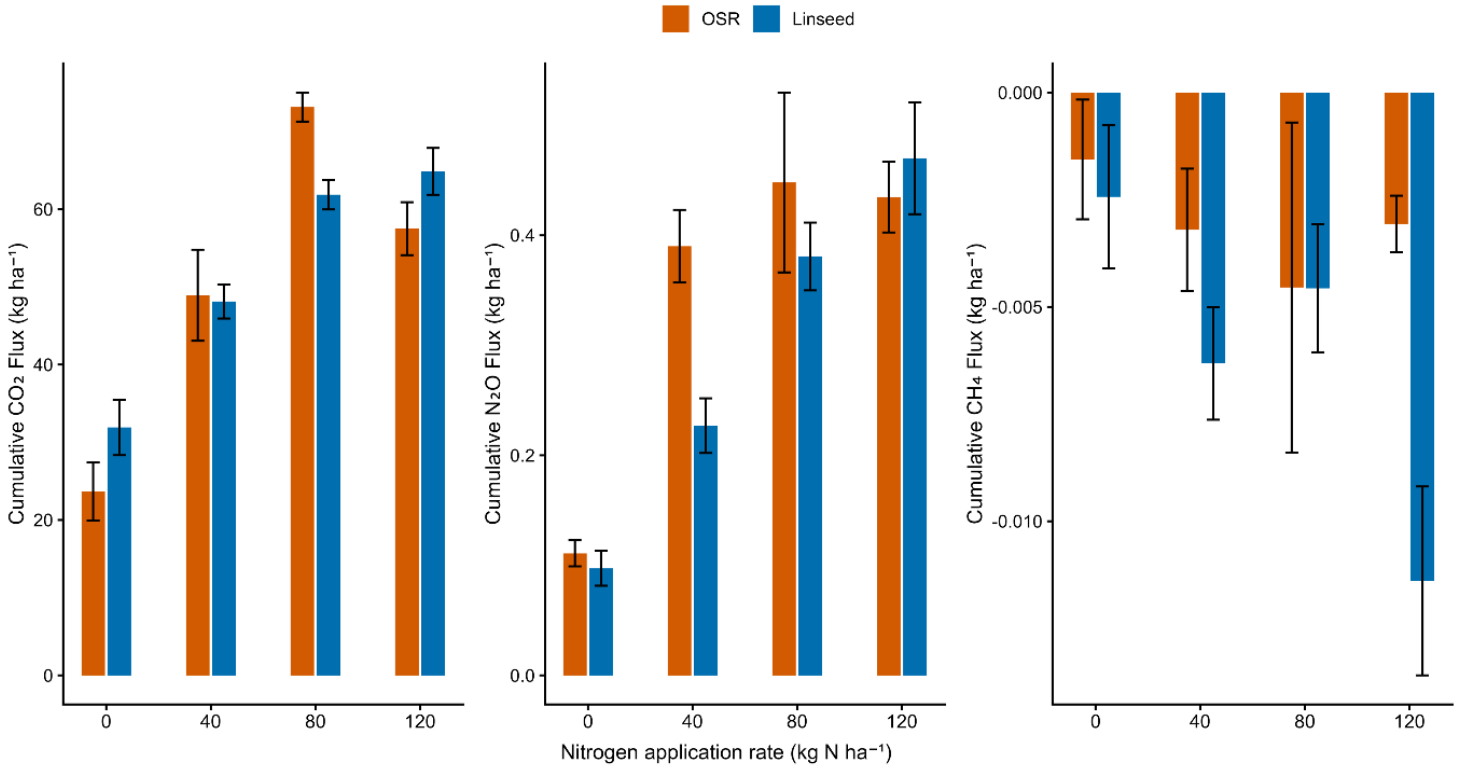


Figure 3

Mean cumulative GHG emissions (± SE) over the glasshouse experiment period for OSR and linseed across N fertiliser rates. GHG emissions were aggregated from respective linseed (n=12) and OSR (n=3) per crop-treatment combination, reflecting the experimental design with multiple linseed genotypes and a single OSR comparator.

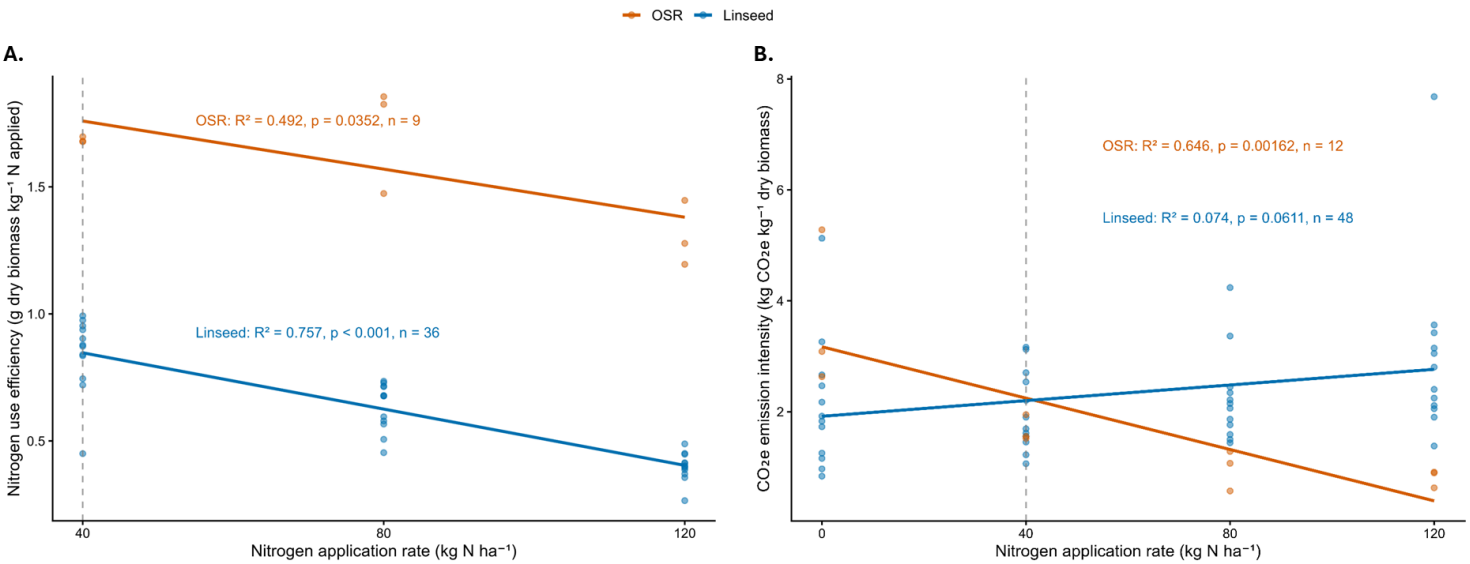


Figure 4

NUE(A) and CO_2e emission intensity (**B**) response to N fertiliser application rate for OSR and linseed in a controlled glasshouse experiment. Points represent individual replicates (n=3 per genotype-treatment combination), with linear regression lines showing crop-level trends derived from two-way ANOVA and emtrends analysis.

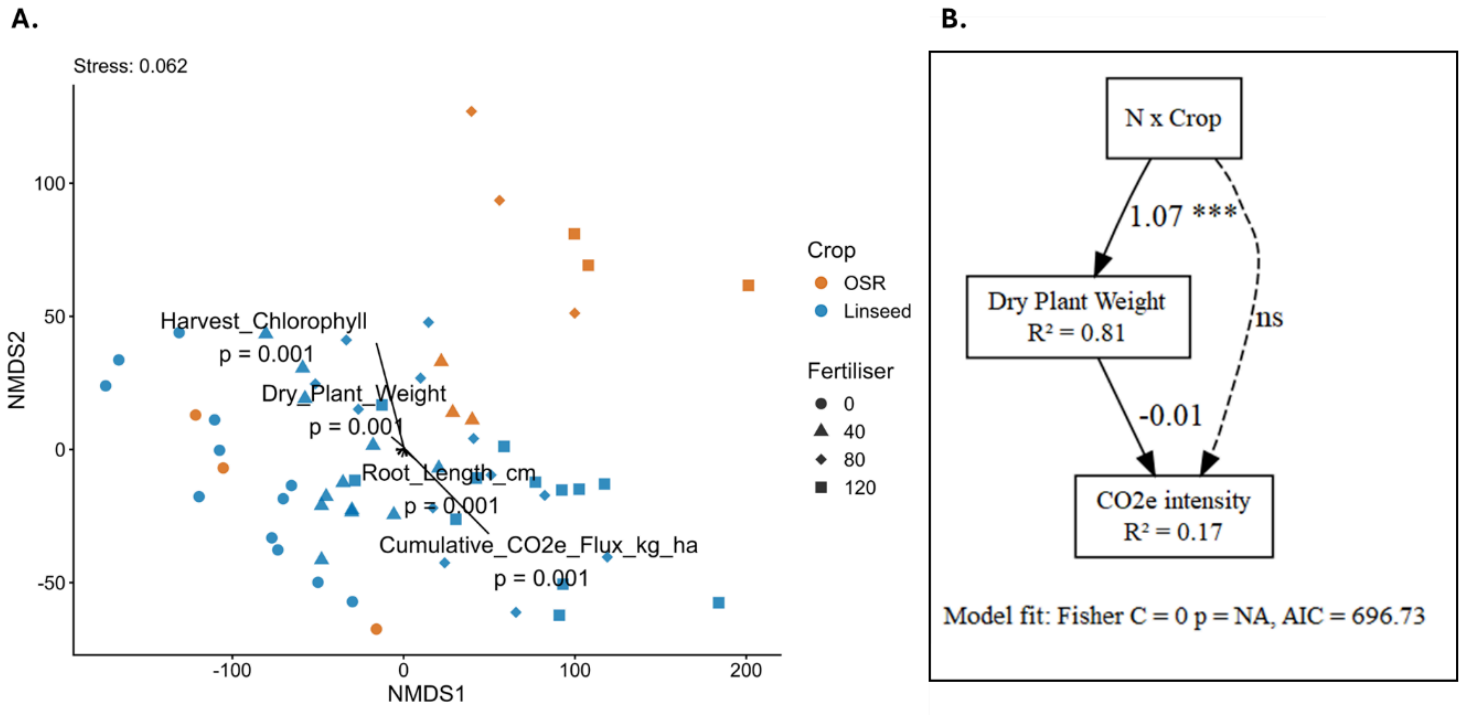


Figure 5

Integrated analysis of plant growth and GHG emissions in OSR and linseed across N fertiliser rates. NMDS ordination of standardised plant traits and cumulative CO_2e emissions **(A)** with points coloured by crop and shaped by N rate. Vectors denote significant variables (p = 0.001); stress = 0.062. SEM depicting mediation of Crop x N interaction on CO_2e emission intensity by dry plant weight **(B)**. Standardised coefficients shown for significant paths (** p < 0.01; *** p < 0.001); non-significant (ns) direct path dashed. Model fit: Fisher C p = 0.52, AIC = 696.73.

Supplementary Files

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