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Biodegradable plastic film mulch increased nitrous oxide emissions in organic leek but decreased emissions in organic cabbages

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Plastic film mulch (PFM) controls weeds and increases yields, making it attractive to vegetable growers; biodegradable PFMs potentially reduce the harms associated with conventional PFMs. PFMs increase soil biological activity, accelerating the decomposition of soil organic matter and potentially increasing emissions of some greenhouse gases (GHGs). Conversely, they are a barrier to rainfall infiltration and gas exchange, reducing harmful nitrate (NO_3^-) leaching and ammonia (NH_3) volatilisation. The effects of PFMs on the processes resulting in GHG emissions are not well explored outside conventionally grown commodity crops in major growing regions. To address this, we conducted a field experiment on an organic vegetable farm with a temperate maritime climate. We measured nitrous oxide (N_2O), methane (CH_4), carbon dioxide (CO_2) and potential NH_3 emission from the soil, growing leeks or cabbages, with or without biodegradable PFM and amended with poultry manure or green-waste compost. Averaged across both crops, yield was 26% higher with PFM; potential NH_3 emissions were 18% lower (43% on a yield-scaled basis) in mulched treatments than unmulched; CH_4 emissions were not significantly affected. Yield-scaled N_2O emissions were 62% higher in mulched leeks than unmulched but 56% lower in mulched cabbages than unmulched; this coincided with higher soil NO_3^- content in mulched leeks than either unmulched crop or mulched cabbages. Results were not obtained for CO_2 , so partial global warming potential (GWP) and greenhouse gas intensity (GHGI) were determined mainly by N_2O emissions. Overall, our results indicate that biodegradable PFM can potentially reduce harmful gaseous N emissions in organic horticulture.

KEYWORDS

sustainable plasticulture, organic farming, soil quality, PLA, nitrogen dynamics

1 Introduction

Enhancing crop yield has been the primary imperative of agronomists; however, it is increasingly recognised that this must be balanced against the harms caused to the environment and human health, particularly those associated with nitrogen (N) losses (Fowler et al., 2013). Recent years have seen a rapid expansion in the use of plastic film mulches (PFM) within agricultural production due to their ability to increase crop yields (Nachimuthu et al., 2017; Sun et al., 2020). These increases have been attributed to increased water and nutrient use efficiency, protection against soil erosion, the suppression of weeds and pests and thermal insulation of the soil (Gao et al., 2019; Kasirajan and Ngouajio, 2012; Lamont, 2005). They can act as a barrier to rainfall infiltration and gas exchange at the soil surface and affect the system's energy balance by regulating radiation, convection, and evaporation, which can influence soil moisture, temperature, and gas exchange (Li et al., 2013; Saglam et al., 2017; Tarara, 2000). These, in turn, may affect crop growth, soil biological processes and soil carbon (C) and N cycling in numerous ways (Supplementary Figure S1) (Liu et al., 2017; He et al., 2018; Sintim et al., 2021).

However, the problems of removal and disposal as well as the legacy of plastic left in the soil at the end of the cropping season and its potential to generate nano- and micro-plastics has led to significant concerns about the sustainability of plastic mulch film use in agriculture (Salama and Geyer, 2023; Steinmetz et al., 2016). One potential solution to this has been the adoption of biodegradable mulch films, which biodegrade in the soil at the end of the growing season (Kasirajan and Ngouajio, 2012). Recently, mesocosm-based experiments have suggested that biodegradable plastic mulch films may, however, negatively alter soil functioning and N dynamics, while others have shown minimal effect (Brown et al., 2023; Rauscher et al., 2023; Reay et al., 2023). The potential effect of residual micro-plastics is in contrast to the positive impact of using the films as a mulch in field experiments (Lee et al., 2021; Samphire et al., 2023). The relative importance of positive effects on N cycling and yield and the adverse effects of biodegradable PFM in long-term use are poorly explored. This has led to the call for more research to better understand how PFMs alter soil and plant functioning when used in the field, particularly with biodegradable mulch films (Qi et al., 2020; Salama and Geyer, 2023; Serrano-Ruiz et al., 2021).

Most previous studies have indicated that conventional LDPE-based PFMs can reduce NH_3 emissions despite the increases in soil temperature and NH_4^+ concentration under the film (Chae et al., 2022; Fang et al., 2022; Li et al., 2022; Mo et al., 2020). This has been ascribed to the PFM reducing gas exchange, increasing the partial pressure of NH_3 in the air under the mulch, preventing soil drying and tipping the equilibrium towards the retention of dissolved NH_4^+ . In contrast, there is no consensus on the effect of PFM on N_2O fluxes. Fang et al. (2022) found that PFM reduced N_2O emissions, while Nan et al. (2016) found the opposite effect. Three meta-analyses in China have also reported different results: (i) PFM reduces N_2O emissions under moderate N fertilisation rates but increases emissions at high N application rates (Mo et al., 2020);

(ii) PFM use increases N_2O emissions (Yu et al., 2021), but only in paddy fields or with non-biodegradable PFM; or (iii) PFM has no significant effect on N_2O emissions (Wei et al., 2022). The differences in these analyses were probably due to the inclusion of different crops, management practices and climate regimes, but all involved major staple crops under conventional conditions.

PFM often leads to increased microbial activity and, hence, respiration and breakdown of soil organic matter (SOM). This can lead to increased CO_2 emissions (Li et al., 2022) and a net loss of soil C. However, increased crop growth and C returns (e.g., rhizodeposition and crop residues) can mitigate this (Wang et al., 2016). A meta-analysis found that although PFM increased CO_2 emissions, it resulted in net C sequestration in dry upland areas (Mo et al., 2020). Several studies have also shown that PFM can increase CH_4 emissions which has been attributed to higher soil water content under the PFM (Cuello et al., 2015; Wang et al., 2021a; Yu et al., 2021), although occasionally, the opposite trend is found (Nan et al., 2016). As the use of PFM usually results in increased crop yields, it is important, however, to yield-scale greenhouse gas (GHG) emissions (Islam Bhuiyan et al., 2021), for example, the higher GHG emissions under PFM management were shown to be lower than the unmulched control when crop yield was taken into account (Li et al., 2022; Zhang et al., 2022).

Most previous studies on the effects of biodegradable PFM on GHG emissions have focused on major commodity crops, conventional farming using mineral fertilisers, and regions with drier or warmer climates. In contrast, there is very little information regarding their performance under organic management regimes, in vegetable crops, or in moist temperate climates, contexts which present particular challenges with yield-scaled environmental impacts from gaseous N emission (Hergoualc'h et al., 2021; Skinner et al., 2014; Tei et al., 2020). However, PFM may play a significant role in these conditions: it may speed up the breakdown of organic matter (Jin et al., 2018), reduce the impacts of high rainfall, such as leaching (Quemada and Gabriel, 2016) and waterlogging (Snyder et al., 2015), and increase N use efficiency (NUE) in vegetable crops, some of which are known to be poor in this respect (Samphire et al., 2023). Despite the functional similarities often observed (Tofaneli and Wortman, 2020; Wang et al., 2021c) biodegradable PFM has different physical properties including significantly higher different gas permeability (Briassoulis and Giannoulis, 2018) and smaller effects on temperature (Cozzolino et al., 2023) than PE which may be important in this context. However, the most significant difference between them is likely to be that of soil biology and chemistry after incorporation (Bandopadhyay et al., 2018), which will not be seen in a single-season experiment. While the effects of PFM on the soil microclimate (temperature and moisture), crop yield and N availability are relatively well studied, little is known about the effect of biodegradable PFMs on gaseous emissions, particularly with horticultural crops, in wetter climates, and the interaction with organic amendments.

To address this knowledge gap, we investigated the effect of biodegradable PFM on gaseous N fluxes in field-grown organic vegetables (N-efficient cabbages vs. N-inefficient leeks) under two

contrasting organic fertiliser regimes (poultry manure vs. green waste compost). We hypothesised that (i) PFM would increase crop growth and yield due to more consistent soil moisture availability and higher soil temperature; (ii) PFM would result in higher NH_4^+ and NO_3^- content due to greater rates of SOM turnover and reduced leaching; (iii) the increases in mineral N would result in higher gaseous losses of NH_3 and N_2O , but (iv) net GHG losses would be lower when expressed on a yield-scaled basis.

2 Materials and methods

2.1 Experimental site

The experimental field site was at a commercial organic horticultural farm in SW Wales, UK (51°47'N, 4°12'E; 130 m a.s.l.). The soil is classified as a free-draining, silty clay loam textured Eutric Cambisol developed on a carboniferous sandstone and shale parent material. The main soil chemical and physical properties ($n=5$) for the top 10 cm of soil at the start of the experiment are summarised in [Supplementary Table S1](#). Initial values for soil pH, P, K and Mg content were determined by NRM Laboratories, Cawood Scientific, Berkshire, UK ($n=5$). Olsen P content was determined by extraction with 0.5 M sodium bicarbonate ([Olsen and Sommers, 1982](#)), and extractable K and Mg were determined by extraction with 1 M ammonium nitrate ([Thomas, 1982](#)).

The mean annual rainfall (1981–2010) is 1380 mm, and the annual mean air temperature is 10.4°C ([Met Office, 2021](#)). During the experimental period (June 1st to Sept. 10th, 2022), daily temperature and precipitation data were measured at a nearby weather station (within 2 km), giving a mean air temp of 16.5°C and total rainfall of 355 mm ([The Weather Company, 2022](#)).

The experimental site has been under commercial organic horticulture since 2010, growing mixed vegetable crops in rotation with green manures. In the previous season, the experimental plot had been planted with a mixed ley of grass, clovers, and herbs. This was incorporated by ploughing in January, and the seedbed was prepared by secondary cultivation and rolling to create beds running across the slope. Irrigation is not usually necessary in this region and was not used in this experiment.

2.2 Experimental treatments

The experiment consisted of two crops, namely leeks (*Allium ampeloprasum* L. cv. Jolant) and cabbages (*Brassica oleracea* L. var. *capitata* cv. Stanton). These were chosen to represent typical horticultural crops with contrasting N uptake profiles, with cabbages being faster growing with a more extensive root system, producing more biomass and having the ability to use a greater portion of plant available N from the soil than leeks ([D'Haene et al., 2018](#); [Everaarts, 1993](#); [Karic et al., 2005](#); [Thorup-Kristensen and Sorensen, 1999](#)). Cell-grown transplants raised by a commercial nursery (Delfland Nurseries Ltd. Doddington, March,

Cambridgeshire, UK) were used. The mulch film was a 15 μm thick, black biodegradable polylactic acid (PLA)-based PFM, Gro-clean Bio-Mulch® (Gromax Industries Ltd., Hadleigh, Suffolk, UK).

Two organic fertilisers were used: pelleted organic fertiliser based on sterilised poultry manure (Greenvale Farms Ltd., Middleton Tyas, North Yorkshire, UK) spread at 100 g m^{-2} (total N 4.4 g m^{-2}) which is the rate recommended by the manufacturer and municipal green waste and food waste compost (Cwm Environmental Ltd., Nantycaws, Carmarthenshire, UK) applied at a rate of 2.5 kg m^{-2} (total N 16.3 g m^{-2}) which is a typical rate for compost use in organic horticulture ([Eva Erhart and Wilfried Hartl, 2010](#)); the equivalent field spreading rate was 0.8 and 20 t ha^{-1} respectively as fertilisers were only applied on the beds and not the wheelings between beds. The nutrient analysis of these amendments is shown in [Supplementary Table S2](#).

2.3 Experimental design

A randomised block design was used with 32 plots and four blocks with all combinations of the three treatments in each block. Beds were created by rolling on 2nd July, and the biodegradable PFM was laid on the plots on 4th July 2022. The main treatments consisted of plots with and without biodegradable PFM. Cabbages were planted at 40 × 40 cm spacing (6.25 plants m^{-2} on the bed, 50,000 plants ha^{-1} on field scale including wheelings) and leeks at 30 × 30 cm spacing (11.1 plants m^{-2} on the bed, 88,000 plants ha^{-1} on field scale including wheelings) on 5th June 2022, the size and layout of these plots are shown in [Supplementary Figure S2](#). These planting densities are typical for commercial organically grown cabbages and leeks ([Davies and Lennartson, 2005](#)). The subplots used two treatments: poultry manure and green waste compost. To avoid sampling affecting subsequent results, all measurements were taken at least 20 cm from holes made in the PFM for previous observations. When multiple samples were taken on a single occasion (for soil mineral N analysis), these were taken from a defined area rather than the whole plot; this requirement determined the size of the plots required.

2.4 Plant measurements

During the experiment, rows of plants (three cabbages or four leeks) were harvested 54 days and 97 days after planting, and their fresh weight was determined before oven-drying (80°C, 8 h). The dried samples were ground using a Retsch stainless steel ball mill and then analysed for total C and N using a TruSpec® CN analyser (Leco Corp., St Joseph, MI). Only above-ground parts were analysed; we did not test the N content of the roots, but amounts are likely to be small for these crops ([Huett and Dettmann, 1991](#)). The yield was calculated as fresh and dry matter yield per plant and economic yield, which was the weight of the fresh plants trimmed of outer leaves and stems to the standard of the farm on which the experiment was conducted and scaled per hectare. Mid-season measurements were taken from plants adjacent to the gas

sampling area, but at harvest, measurements were taken from plants both within and adjacent to this area.

2.5 Soil measurements

Soil temperature and volumetric moisture sensors (TDT-SDI-12; Acclima Inc., Meridian, ID) were installed at a depth of 5 cm. One sensor was placed within the gas sampling area and one in an adjacent area of the plot (Supplementary Figure S2). Readings were recorded hourly using SDI-12 DataSnap data loggers (Acclima Inc.). Volumetric soil moisture content was converted to gravimetric soil water content and then to Water-Filled Pore Space (WFPS) as follows (Equation 1):

$$\text{WFPS} = \theta_v / \Phi \quad (1)$$

where θ_v is volumetric soil water content, and Φ is total soil porosity. Φ was calculated by (Equation 2):

$$\Phi = (1 - \rho_b / \rho_p) \quad (2)$$

where ρ_b is soil bulk density, and ρ_p represents soil particle density (2.47 g cm^{-3}) (Sumner, 2000).

The tea bag method of Keuskamp et al. (2013) was used to estimate soil biological activity. For this, the mass loss of the relatively easily degraded 'green' tea (C: N of 12) and the more recalcitrant rooibos ('red') tea (C: N of 60) were measured to determine the rate of decay k (the exponential rate of decay calculated from the proportion of mass lost from the 'red' tea), and stabilisation factor S (the proportion of the mass of green tea remaining relative to the fraction thought to be degradable estimated from chemical hydrolysis) (Duddigan et al., 2020). The equations to calculate k and S are (Equations 3, 4):

$$k = \ln(a_r / (W_{(t)} - (1 - a_r))) / T \quad (3)$$

$$S = (1 - (a_g / H_g)) \quad (4)$$

where a_r = the decomposable fraction of red tea assumed to be the same fraction of hydrolysable material as that calculated for green tea so (Equation 5):

$$a_r = H_r(a_g / H_g) \quad (5)$$

where T = length of time buried in days, $W_{(t)}$ = fraction of red tea remaining after burial for time T , a_g is the fraction of green tea lost, and H_g and H_r are the easily degradable fractions of green and red tea, respectively, determined by hydrolysis ($H_r = 0.522$, $H_g = 0.842$; (Keuskamp et al., 2013).

Three pairs of Lipton Green Sencha ('green' tea) or Lipton Rooibos and Hibiscus tea bags ('red' tea) (Unilever Ltd., London, UK) were buried at a soil depth of 5 cm, spaced 20 cm apart (Supplementary Figure S2). These were recovered at the end of the experiment. The mass loss relative to the starting weight was determined after oven-drying the remaining tea in the litter bags at 60°C until constant weight.

To assess soil available NH_4^+ and NO_3^- content, five soil cores (0–10 cm) were taken every 14 days from between the plants in each subplot. After sample homogenisation, 5 g of soil was extracted with 25 ml of 1 M KCl (200 rev min^{-1} , 1 h), the extracts filtered, and the filtrate stored at -18°C prior to analysis. Soil moisture was determined by oven drying (105°C , 12 h). NO_3^- and NH_4^+ in the KCl extracts were measured colourimetrically using the vanadate methods of Miranda et al. (2001) and the salicylic acid method of Mulvaney (1996), respectively. To avoid damaging the PFM within the gas sampling area, samples were taken from adjacent areas during the growing season, but at the end of the experiment, samples were taken from both within the gas sampling area and adjacent to it.

2.6 Measurement of gaseous fluxes

Measuring gaseous emissions through a PFM under field conditions has several challenges. Gases may escape through planting holes or damaged film and by diffusion through the film or from the edge of the bed. Gas may build up in spaces under the film and be concentrated in the soil profile. Any penetration of the film to place a measuring chamber could measure a release of the accumulated gases rather than the steady state flux from the soil. Placing a chamber for a prolonged period may also affect soil conditions (Rochette and Hutchinson, 2005). If a hole in the film is made for one set of observations, the conditions may be changed for the following observations. To deal with these challenges, the static chamber method described by Li et al. (2022) was modified as follows. The apparatus for sampling gases is shown in Supplementary Figure S3. Before mulch and fertility treatments were applied, a UPVC collar was pushed into the soil so the rim was flush with the soil surface. Adhesive tape was then used to fix the mulch film to the collar. A UPVC sampling chamber (internally $390 \text{ mm} \times 390 \text{ mm} \times 300 \text{ mm}$) was placed on the collar and sealed using wet clay for each sampling occasion. The chambers were removed from the collars after each GHG and potential NH_3 emission measurement to prevent any differences in the microclimate in the area when the chamber was not in use.

GHG sampling was conducted at least weekly at first, but after mid-season, the frequency was reduced to approximately every two weeks; in all, there were 11 sampling occasions over the course of the experiment. Unfortunately, the cabbages grew too large for the chambers in August, so the two penultimate observations were for leeks only. The final GHG flux measurements were taken immediately after the crop harvest so all plots could again be sampled.

Gas samples were withdrawn through the rubber septum using a 25 ml syringe and injected into pre-evacuated 20 ml vials. GHG flux was calculated from the change in concentration in the headspace gases between initial samples and samples taken after 60 min. Additional samples were taken from one randomly selected chamber on each occasion, at 15, 30, and 45 mins, to check for linearity of change in headspace gas concentrations; these were

satisfactory. Samples were analysed on a Perkin Elmer 580 Gas Chromatograph with a TurboMatrix 110 auto sampler (PerkinElmer, CT, USA). Gas samples passed through two Elite-Q mega bore columns via a split injector, with one connected to a ^{63}Ni electron-capture detector for N_2O determination and the other connected to a Flame Ionisation Detector for CH_4 and CO_2 determination. Fluxes were estimated using the slope of the linear regression between 0 min and 60 mins, considering the temperature and the ratio between chamber headspace volume and soil surface area. Cumulative GHG fluxes were estimated by linear interpolation between sampling points.

Potential ammonia emission was measured using the same chamber on different occasions. A sponge ($80 \times 80 \times 10$ mm) was soaked with 10 ml of 1 M H_2SO_4 mixture containing 5% glycol (Shigaki and Dell, 2015). This was suspended from the lid of the gas chamber and left in the closed chamber for 4 h. The sponge was kept in a closed vessel before and after collection to avoid absorption of background atmospheric NH_3 . After being returned to the laboratory, the sponges were shaken with 40 ml 1 M KCl for 20 min, and the extract was subsequently stored at -18°C . Subsequently, 10 ml of the extract was placed in a 50 ml polypropylene tube, and an excess of 1 M NaOH was added to promote NH_3 release. The NH_3 released was trapped in 0.015 M H_3PO_4 over 16 h, and the NH_4^+ in the traps was determined colourimetrically using the salicylic acid method of Mulvaney (1996).

Yield-scaled emissions were calculated by (Equation 6):

$$E_{ys} = E_t / Y_{ec} \quad (6)$$

where E_{ys} is the yield-scaled emissions, E_t is total emissions, and Y_{ec} is the economic yield.

To investigate the effect of PFM on nitrification and denitrification rates, we examined the relationship between soil NO_3^- and NH_4^+ content and N_2O efflux. N_2O efflux as a proportion of soil NO_3^- and NH_4^+ content was calculated by (Equation 7):

$$E_{nn} = E_n / C_n \quad (7)$$

where E_{nn} is the N_2O efflux as a proportion of soil NO_3^- and NH_4^+ content, $E_n = \text{N}_2\text{O}$ efflux, and C_n is the content of either NO_3^- and NH_4^+ in the top 10 cm of soil at the nearest sampling period (10 out of 12 of these where within 24 h, the other two within 48 h of N_2O efflux measurement).

As nitrification dominates N_2O in drier soils, switching to denitrification at between 60% and 70% soil moisture (Wang et al., 2023), we also analysed the relationship between soil NO_3^- and NH_4^+ content and N_2O efflux separately for drier and wetter soil conditions.

Global Warming Potential (GWP) over a 100-year period was calculated by Equation 8 (Forster et al., 2021):

$$\text{GWP} = 273(\text{N}_2\text{O flux}) + 27(\text{CH}_4\text{ flux}) + \text{CO}_2\text{ flux} \quad (8)$$

and Greenhouse Gas Intensity (GHGI) was calculated by (Equation 9):

$$\text{GHGI} = \text{GWP} / Y_{ec} \quad (9)$$

2.7 Statistical analysis

Data were analysed in R (The R Foundation for Statistical Computing, 2020). Mixed effects modelling was carried out using the Lme4 package (Bates et al., 2015). The best-fit model was determined by a comparison of models using the experimental variables (mulch, crop density and fertility treatments) as fixed effects and the block and bed, and where relevant (in analysis of time series data) date, as random effects in random intercept models. The anova function from the R 'stats' package was used to determine the best fit model by comparison of log-likelihood (Chambers and Hastie, 1992). A summary of coefficients and significance levels was extracted with the lmerTest package (Kuznetsova et al., 2017). Results are assumed to be significant where $p < 0.05$, but some results are presented where terms in the best fit model have $p < 0.1$ but > 0.05 .

3 Results

3.1 Effect of biodegradable mulch film on crop yields and N content

Fresh and dry matter yield per plant (for both leeks and cabbage) was significantly higher when grown with biodegradable PFM (30% and 26%, respectively; Figure 1). The interaction of PFM with poultry manure fertiliser increased cabbage yield further. The economic yield of cabbage was more affected by PFM than leeks (Figure 1). Poultry manure resulted in slightly higher yields when used with PFM and lower without PFM compared to compost in the same combination; however, this was not statistically significant. The fresh and dry yield per plant was not significantly different between the GHG monitoring areas and the other areas of the plot.

Cabbages had significantly higher N content and a lower C: N ratio at harvest (Table 1); this, combined with higher yield, resulted in N uptake that was three to five times higher than that of leeks (Table 2). Biodegradable PFM increased crop N content (15%, $p < 0.001$) and reduced the C: N ratio (18%, $p < 0.001$), but the effect was smaller in cabbages than in leeks ($p < 0.005$). The choice of organic amendment did not significantly affect these metrics.

3.2 Effect of biodegradable mulch film on soil gas fluxes

On most occasions, measured fluxes of N_2O were significantly higher from PFM plots with leeks, but the magnitude of the difference varied (Table 2, Figure 2). There was a notable emission peak for all treatments three days after the start of the experiment. Over the growing season, PFM resulted in significantly higher cumulative N_2O emissions than unmulched treatments for

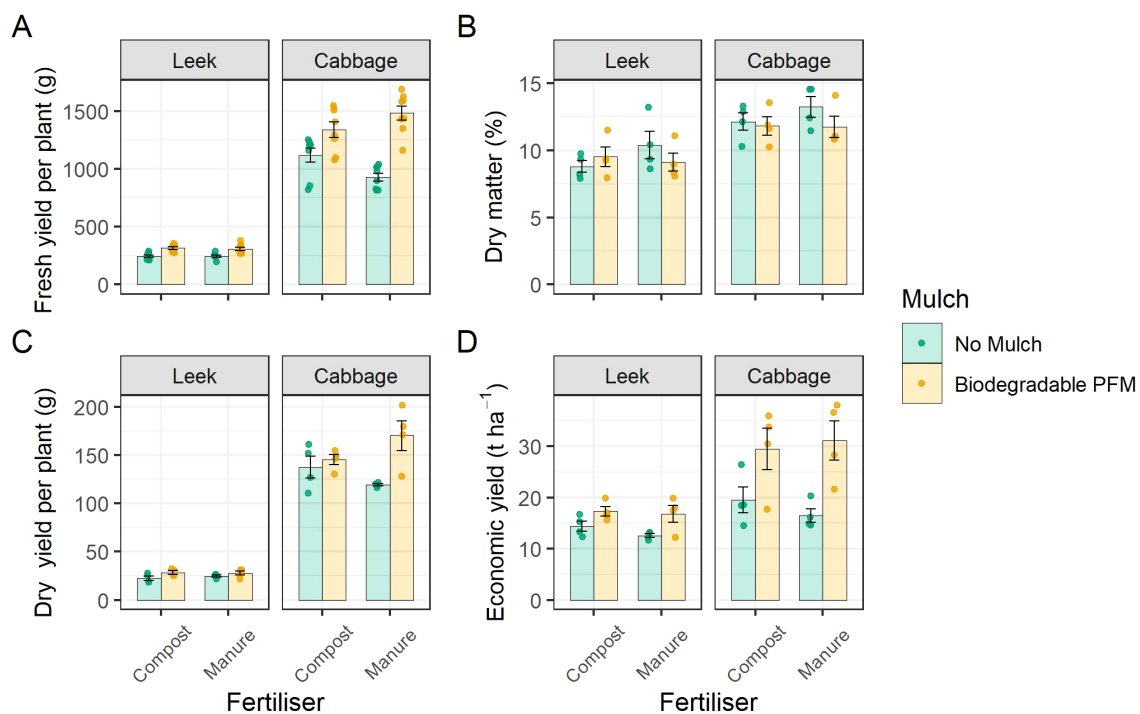


FIGURE 1

Yield characteristics of cabbages (6.25 plants m^{-2}) and leeks (11.1 plants m^{-2}) grown with or without a biodegradable plastic film mulch (PFM) and with green waste compost (2.5 kg m^{-2}) or pelleted poultry manure (100 g m^{-2}). Panel (A) shows the total fresh weight of above-ground plant material; (B) dry matter content; (C) the total fresh weight of above-ground plant material; and (D) the total marketable yield when trimmed to the standard of the farm where the experiment was conducted and taking account of planted area and the unplanted area between beds (4:1). Values represent means $\pm$ SEM ($n=8$) and dots represent individual data points.

leeks (111% higher, $p<0.005$); however, for PFM with cabbages, this situation was reversed (4% lower, $p<0.05$) (Table 2, Figure 3). Crop type did not affect cumulative N_2O emissions from the unmulched plots. The organic amendment did not significantly impact N_2O emissions.

On most occasions, the measured daily CH_4 fluxes were very low and not significantly different between treatments. Despite a peak in emissions in the second week of the experiment, the cumulative effect was a net CH_4 consumption. However, there was no significant difference between the treatments.

Measured potential NH_3 fluxes were higher overall in the unmulched than in the PFM treatments, but the significance was marginal ($p=0.055$); daily NH_3 fluxes significantly differed in the first week and at the end of the experiment but not at other times (summary data and MLM analysis not presented). This resulted in cumulative seasonal emissions, which were also numerically higher in the unmulched plots, but again with marginal significance (Table 2, $p=0.07$). However, cabbages resulted in a significant increase in cumulative emissions compared to leeks, and the use of poultry manure with cabbages led to an additional increase compared to cabbages with compost. On a yield-scaled basis, PFM led to significantly lower NH_3 emissions (Figure 4).

N_2O emission as a proportion of NO_3^- content in the topsoil (0–10 cm) was significantly lower in mulched plots ($p<0.05$); the occasions when there was a significantly higher proportion of emissions in unmulched plots appear to coincide with peaks of %

WFPS (Figure 5). In contrast, N_2O emission as a proportion of the soil NH_4^+ content was significantly higher in mulched plots ($p<0.05$).

Analysis of the relationship between N_2O efflux and soil NH_4^+ and NO_3^- content at higher and lower WFPS revealed different trends with biodegradable PFM than without (Supplementary Table S3 shows the best fit MLMs). When WFPS was $<60\%$, there was a significant positive correlation between N_2O flux and soil NH_4^+ content in PFM plots which was significantly reduced by biodegradable PFM ($p<0.001$), and PFM increased the rate of emission ($p<0.001$); on the other hand, there was no relationship between N_2O flux and soil NO_3^- . In contrast, when WFPS was $>60\%$, PFM did not significantly affect the relationship between N_2O flux and soil NH_4^+ content. However, there was a strong positive correlation between N_2O flux and soil NO_3^- content, which was significantly reduced by biodegradable PFM ($p<0.05$).

3.3 Effect of biodegradable mulch film on soil mineral N dynamics

There was an initial peak in soil NH_4^+ content in the first 4 weeks, after which the content remained low. This pattern was the same in all treatments, but this initial peak was higher in the poultry manure amended plots (Figures 6A, B). Overall, MLM analysis of the time-series data revealed PFM and poultry manure significantly

TABLE 1 Crop N content, C/N ratio and N uptake in response to the presence or absence of a biodegradable plastic film mulch and the application of either compost or poultry manure.

Mulch	Crop	Fertiliser	Crop N content at harvest (%)	Crop C/N ratio at harvest	Crop N uptake mid-season (g m ⁻²)	Crop N uptake at harvest (g m ⁻²)
No Mulch	Leek	Compost	3.59 ± 0.35	11.75 ± 0.94	0.27 ± 0.03	9.06 ± 1.47
		Poultry Manure	3.68 ± 0.41	11.82 ± 0.68	0.21 ± 0.04	10.10 ± 0.44
	Cabbage	Compost	5.29 ± 0.35	7.61 ± 0.08	3.65 ± 1.08	45.59 ± 4.59
		Poultry Manure	4.92 ± 0.23	8.13 ± 0.21	2.45 ± 0.49	36.61 ± 1.24
Biodegradable PFM	Leek	Compost	4.70 ± 0.41	8.98 ± 0.39	0.45 ± 0.06	14.79 ± 0.63
		Poultry Manure	4.72 ± 0.46	8.79 ± 0.19	0.40 ± 0.04	14.59 ± 1.20
	Cabbage	Compost	5.31 ± 0.22	7.45 ± 0.34	3.45 ± 0.22	48.35 ± 3.44
		Poultry Manure	5.43 ± 0.31	7.14 ± 0.14	3.06 ± 0.42	57.56 ± 4.82
Statistical analysis						
Mulch			***	***		
Fertiliser			ns	ns		
Crop			***	***		
Mulch*Fertiliser			ns	ns		
Mulch*Crop			**	***		
Crop*Fertiliser			ns	ns		
Mulch*Crop*Fertiliser			ns	ns		

ns - not significant; Significant differences: * $p < 0.05$, ** $p < 0.005$, *** $p < 0.001$. Values represent means ± SEM (n=4).

increased soil NH_4^+ content. Initially, soil NO_3^- content was also high but decreased after four weeks in all treatments other than PFM with leeks, which had a substantial surplus by harvest of $99 \pm 18 \text{ mg NO}_3^- \text{N kg}^{-1}$ (Figures 6C, D). The unmulched plots had the lowest soil NO_3^- content at harvest, averaging $2.4 \pm 0.4 \text{ mg NO}_3^- \text{N kg}^{-1}$. The soil in mulched cabbage plots ($8.2 \pm 3 \text{ mg NO}_3^- \text{N kg}^{-1}$) was higher than that in unmulched plots but less than 10% of that of mulched leeks. Table 3 shows the measured N inputs and outputs and the changes in soil mineral N content over the course of the experiment: mulched leeks resulted in an increase in soil mineral N content, but unmulched plots and mulched cabbages all resulted in a loss. Cabbages had significantly higher crop N uptake due to their higher yield and N content; PFM increased N uptake in both crops because of increased yield and N content.

3.4 Effect of biodegradable mulch film on soil biological activity

The teabag biodegradation assay showed that biodegradable PFM caused a significantly higher rate of decay, k , and a significantly lower stabilisation index, S (Figure 7). These parameters were not significantly affected by organic amendment or crop type.

3.5 Effect of biodegradable mulch film on soil microclimate

Biodegradable PFM moderated temperature and moisture fluctuations, resulting in lower soil moisture and higher average soil temperature relative to the unmulched soil over the growing period (Supplementary Table S4, Supplementary Figure S4). Cabbages resulted in drier and cooler soil on average than leeks; these differences were larger than those for the mulch treatments (Supplementary Table S4, Supplementary Figure S4).

4 Discussion

4.1 Soil microclimate

Applying a PFM resulted in relatively small overall changes in soil microclimate (0.6°C and 0.8% WFPS); however, it effectively reduced fluctuations in soil moisture and prevented extremes of both soil temperature and moisture. This contrasts with previous studies where black PFMs are often found to raise mean soil temperatures by 2°C or more (Locher et al., 2005; Schonbeck and Evanylo, 1998a). This is possibly due to less film-soil contact and the insulating effect of air gaps between mulch and soil (Liakatas

TABLE 2 Cumulative seasonal emissions and yield-scaled emissions of N₂O, CH₄ and NH₃ from soils with PFM mulch or No mulch combined with a crop of cabbages or leeks and fertilised with poultry manure or green-waste compost.

Mulch	Crop	Fertiliser	Seasonal N ₂ O emission (mg N m ⁻²)	Yield-scaled N ₂ O emission (kg N Mg ⁻¹)	Seasonal CH ₄ emission (mg m ⁻²)	Seasonal GHGI (N ₂ O +CH ₄) (g CO ₂ eq m ⁻²)	Yield-scaled GHGI (N ₂ O +CH ₄) (kg CO ₂ eq Mg ⁻¹)	Seasonal NH ₃ emissions (mg N m ⁻²)	Yield-scaled NH ₃ emissions (kg N Mg ⁻¹)
No Mulch	Leek	Compost	71.5 ± 15.7	0.065 ± 0.017	-75.0 ± 25.0	17.5 ± 4.9	16.0 ± 5.0	336.1 ± 64.8	0.291 ± 0.056
		Poultry Manure	77.1 ± 22.6	0.076 ± 0.021	-65.7 ± 23.7	19.3 ± 6.1	19.0 ± 5.7	299.6 ± 58.2	0.299 ± 0.058
	Cabbage	Compost	53.5 ± 23.5	0.038 ± 0.016	-91.8 ± 16.5	12.2 ± 6.7	8.9 ± 4.3	423.0 ± 38.9	0.282 ± 0.037
		Poultry Manure	88.7 ± 15.2	0.070 ± 0.014	-70.2 ± 29.9	22.3 ± 4.0	17.8 ± 3.8	598.4 ± 147.3	0.480 ± 0.126
Biodegradable PFM	Leek	Compost	149.5 ± 51.9	0.109 ± 0.040	-64.0 ± 31.0	39.1 ± 14.6	28.5 ± 11.2	242.1 ± 86.5	0.178 ± 0.066
		Poultry Manure	163.4 ± 30.7	0.121 ± 0.017	-44.8 ± 41.6	43.4 ± 8.7	33.4 ± 5.2	239.6 ± 39.0	0.178 ± 0.022
	Cabbage	Compost	51.6 ± 18.5	0.023 ± 0.007	-25.1 ± 47.9	13.4 ± 4.7	5.8 ± 1.7	368.3 ± 48.8	0.173 ± 0.044
		Poultry Manure	85.8 ± 8.5	0.036 ± 0.006	-80.6 ± 28.2	21.2 ± 2.0	8.9 ± 1.2	546.5 ± 58.6	0.236 ± 0.051
Statistical analysis									
Mulch			**	*	<i>ns</i>	**	*	**	0.07
Fertiliser			<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>
Crop			<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	*
Mulch*Fertiliser			<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>
Mulch*Crop			*	**	<i>ns</i>	*	**	<i>ns</i>	<i>ns</i>
Crop*Fertiliser			<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	*	*
Mulch*Crop*Fertiliser			<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>	<i>ns</i>

ns -not significant; Significant differences: **p*<0.05, ***p*<0.005, ****p*<0.001, numerical values given for marginal cases. Values represent means ± SEM (*n*=4).

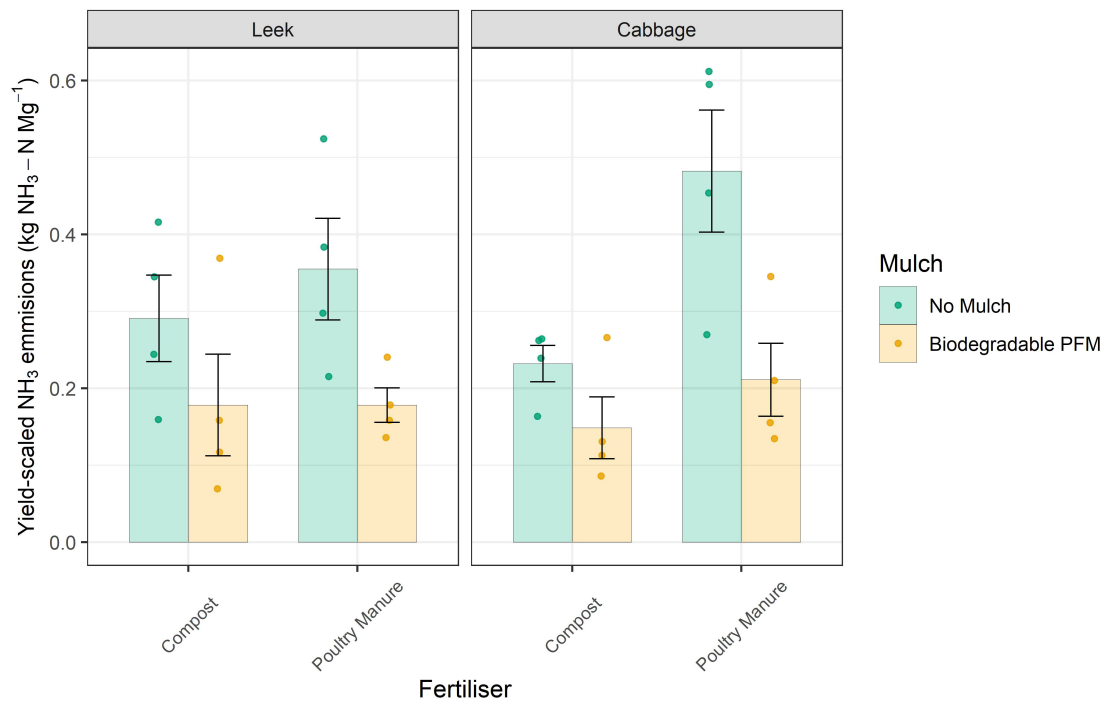


FIGURE 2 Nitrous oxide flux from soil (across both fertiliser treatments) covered with biodegradable plastic film mulch (PFM) or un-mulched and with a crop of leeks or cabbages. Values represent means $\pm$ SEM ($n=8$). The cabbage treatment was not sampled on the two dates in August.

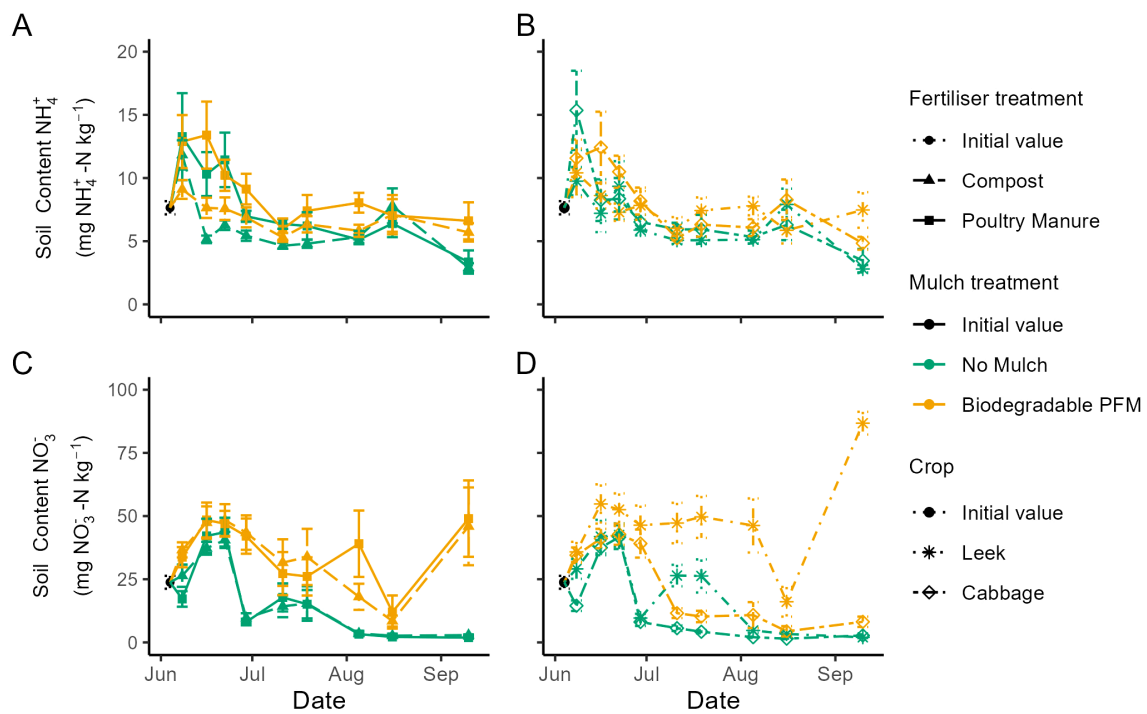
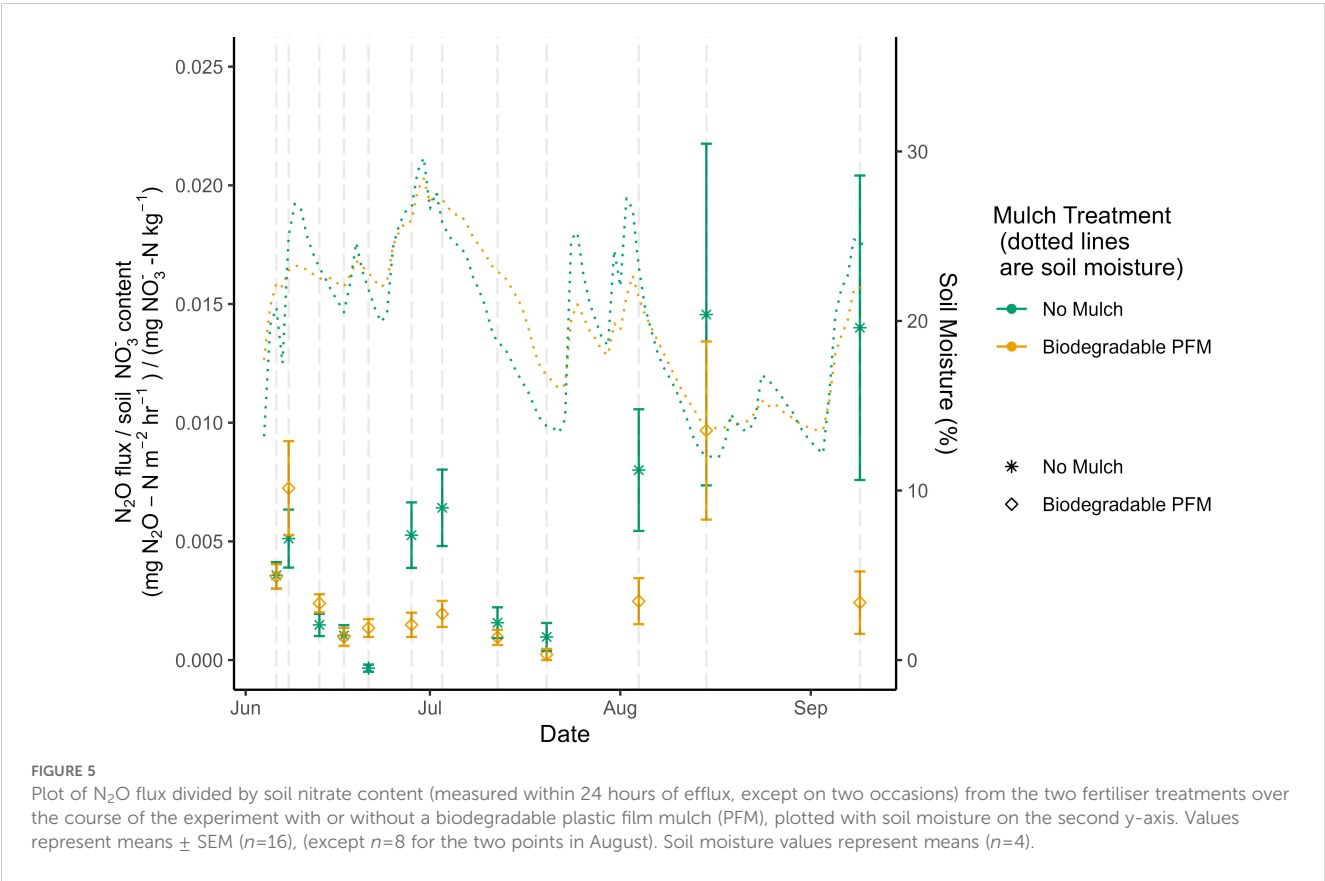
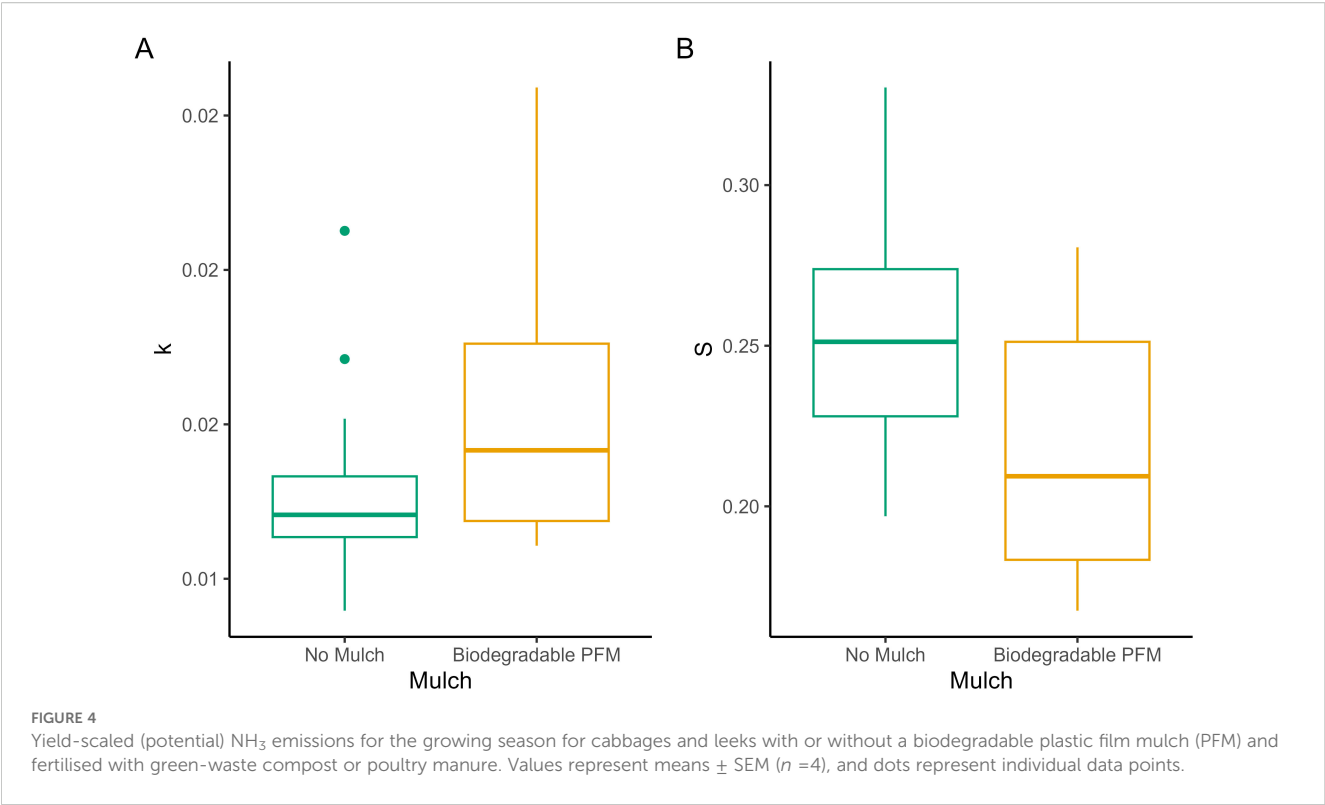
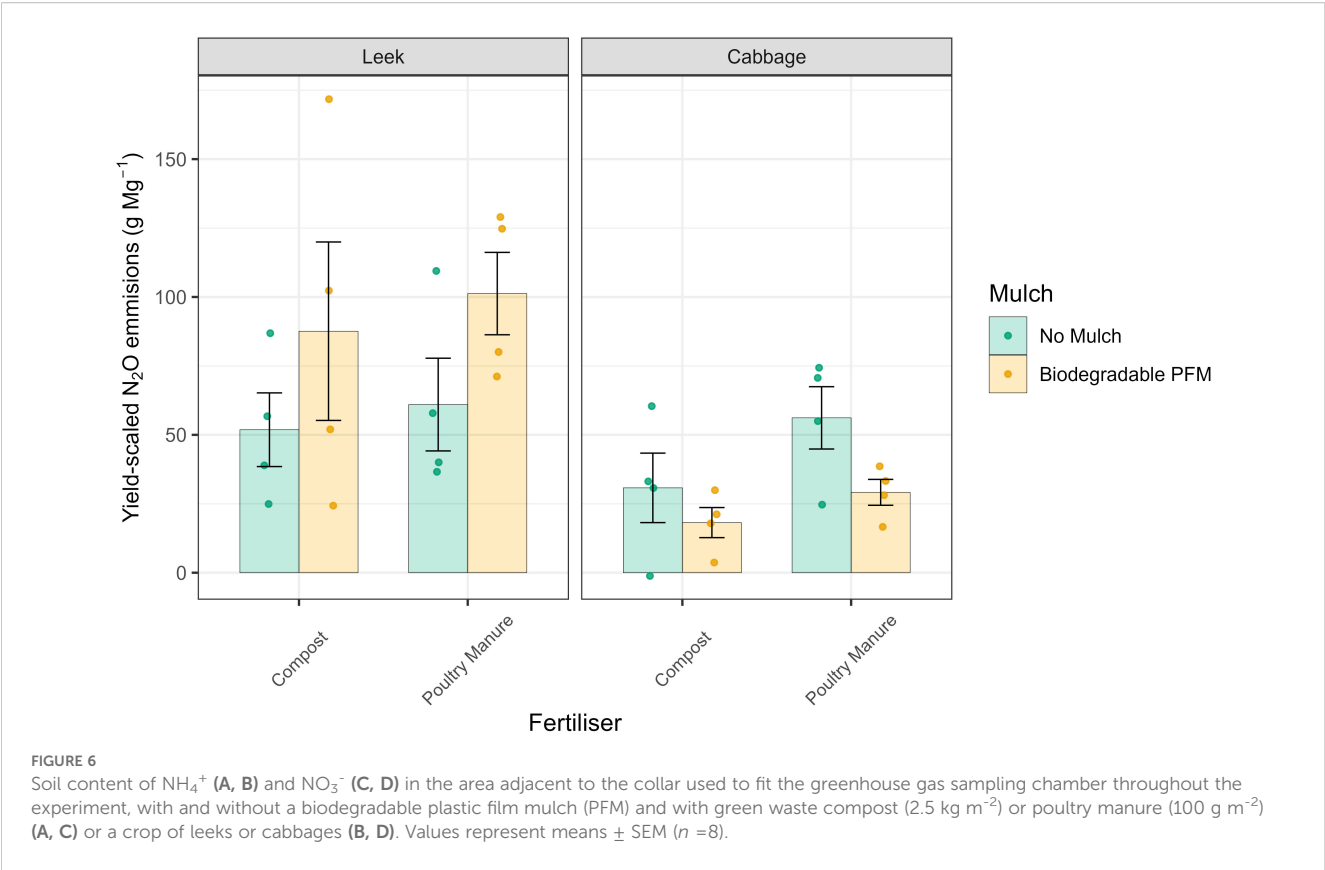


FIGURE 3 Yield-scaled N_2O emissions for the growing season for cabbages and leeks with or without a biodegradable plastic film mulch (PFM) and fertilised with green-waste compost or poultry manure. Values represent means $\pm$ SEM ($n=4$) and dots represent individual data points.





et al., 1986; Tarrara, 2000), as well as reduced sunlight hours and, thus, incident UV radiation in the maritime climate. PFM reduces evaporation and rainfall infiltration, reducing the rate of both wetting and drying (Snyder et al., 2015; Tarara, 2000). The effects of PFM on soil moisture are likely to vary spatially with both depth and distance from the planting holes (Chen et al., 2018; Saglam et al., 2017). It is likely that at shallower depths, the differences that PFM causes to soil wetting and drying will be more pronounced than those measured in deeper soil layers. The difference in soil moisture between cabbages and leeks was larger than between

mulch treatments; we ascribe this to the greater relative leaf area of cabbages, which resulted in shading and increased transpiration. Further, the mulched cabbage plots had fewer planting holes as they were planted less densely than the leeks, and it is possible that the canopy architecture of cabbages directed rainfall away from the planting holes (Chen et al., 2018; Haraguchi et al., 2003; Li et al., 2005). This heterogeneity of soil moisture response to wetting and drying is likely to have influenced the highly moisture-dependent biotic (e.g., plant N uptake, microbial N cycling) and abiotic (e.g., N leaching, NH₃ volatilisation) processes in this study. This is

TABLE 3 Changes in soil mineral nitrogen (N) content and known N inputs and outflows.

Mulch	Crop	Fertiliser	Change in soil mineral N conc. (0–10 cm) (g N m ⁻²)	Crop N uptake (g N m ⁻²)	Measured losses of N ₂ O and NH ₃ (g N m ⁻²)	Added N in fertiliser (g N m ⁻²)
No Mulch	Leek	Compost	-2.56 ± 0.04	9.06 ± 1.47	0.41 ± 0.03	16.5
		Poultry Manure	-2.77 ± 0.07	10.10 ± 0.44	0.38 ± 0.03	4.4
	Cabbage	Compost	-2.57 ± 0.03	45.59 ± 4.59	0.48 ± 0.02	16.5
		Poultry Manure	-2.48 ± 0.25	36.61 ± 1.24	0.69 ± 0.07	4.4
Biodegradable PFM	Leek	Compost	6.17 ± 0.23	14.79 ± 0.63	0.39 ± 0.05	16.5
		Poultry Manure	6.39 ± 1.14	14.59 ± 1.20	0.40 ± 0.02	4.4
	Cabbage	Compost	-2.13 ± 1.85	48.35 ± 3.44	0.42 ± 0.03	16.5
		Poultry Manure	-1.56 ± 0.30	57.56 ± 4.82	0.63 ± 0.03	4.4

Values represent means ± SEM (n=4).

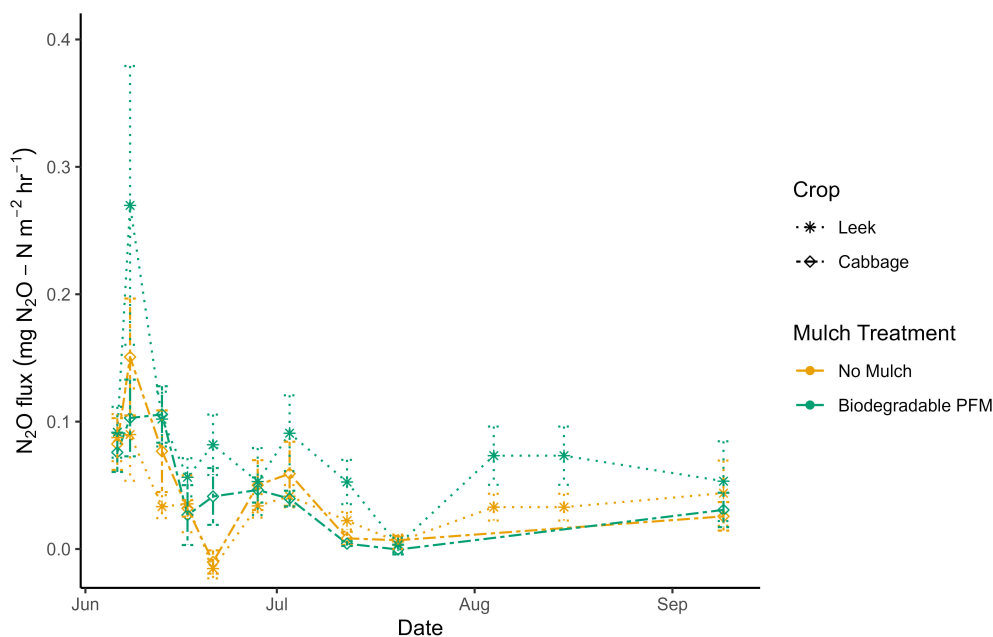


FIGURE 7

Tea bag index (across both fertiliser treatments) in the presence or absence of biodegradable plastic film mulch (PFM): A) early decay rate constant k , and B) stabilisation index S . The centre line is the mean value; lower and upper hinges are the first and third quantile; and the whiskers represent 1.5 times the inter-quartile range ($n=16$).

supported by Berger et al. (2013), who observed lower N₂O emissions in dry soil away from planting holes and higher emissions in the wetter areas around the planting holes, resulting in an insignificant net effect of PFM.

4.2 Crop yield

The average economic yield of cabbages was slightly lower than the standard benchmark for UK organic producers but higher than expected for leeks (Lampkin et al., 2017), possibly reflecting the slightly shorter growing period for the cabbages. Economic yield showed bigger differences between the treatments than yields per plant; this probably reflects enhanced maturity of the crops in mulched plots, resulting in lower leaf-to-head or leaf-to-pseudostem ratio, which comprise the marketable product.

PFM increased dry matter yield per plant by 26%, which is in the range typically found for horticultural crops grown with PFM for leeks (10 – 40%) (Benoit and Ceustermans, 2002; Golian and Anyszka, 2015), cabbages (5 – 36%) (Ponjičan et al., 2021; Trdan et al., 2008) and other horticultural crops (Nachimuthu et al., 2017; Samphire et al., 2023; Wojciechowska et al., 2007). The yield differences are often attributed to the effect of PFM on soil temperature or moisture; however, in this experiment, the differences in these are relatively small, suggesting that other factors were more important (e.g., higher soil NH₄⁺ and NO₃⁻ content).

In the unmulched plots, there was no significant difference between the effect of organic amendment type on the yield between the two crops; however, the use of PFM and poultry manure caused

a significant increase in yield, particularly for leeks (> 48%). This effect was not detected with compost. This is perhaps related to the relative growth rate of the two crops, leeks being slow to establish (Davies and Lennartson, 2005) and perhaps unable to take advantage of the initial short-lived higher available N.

4.3 Soil microbial activity

The Tea Bag Index results indicate that biodegradable PFM causes significantly higher rates of SOM turnover. This replicates previous findings on the same site (Samphire et al., 2023). The effect is large, given the relatively small changes in mean soil moisture and temperature. However, the relative stability of soil moisture may also be a factor affecting SOM turnover. It is commonly observed that PFM increases soil microbial activity with consequent increases in mineralisation and soil DOC (Bandopadhyay et al., 2018; Han et al., 2020; Kim et al., 2017; Zhang et al., 2023). This may be relevant to our soil mineral N and N₂O emissions findings.

4.4 Soil mineral N

PFM increased both soil NO₃⁻ and NH₄⁺ content. However, we are not able to attribute this to increased mineralisation or N losses (e.g. NO₃⁻ leaching and gaseous N₂ from denitrification), as these were not measured in this experiment. Overall, the content of soil NH₄⁺ were low, indicating a high soil nitrification rate, which is commonly found in cultivated soils with high C and N content when temperature and pH are not limiting (Elrys et al., 2021). The

highest content was found in the initial period following poultry manure amendments, indicating rapid hydrolysis of readily available N compounds such as urea. PFM also had the largest effect at this time, probably partly by reducing N volatilisation losses.

Soil NO_3^- content was higher in the first month for all treatments but became very low in the unmulched plots towards the end of the experiment. This pattern was also present in the mulched cabbages but to a lesser extent, although it was still twice that of the unmulched plots by the end of the experiment. Soil NO_3^- content in mulched plots with leeks were several times higher than in other treatments. Crop uptake was the largest measured factor affecting soil mineral N in this experiment; as it significantly exceeds the total N in inputs from the organic amendments, there must have also been significant mineralisation of SOM. The soil in the mulched leek plots increased in soil mineral N content; all other treatments resulted in losses. The greater crop N uptake can explain the difference between this and mulched cabbages; the difference between this and unmulched leeks is consistent with biodegradable PFM causing increased mineralisation and reducing unmeasured losses. We only measured mineral N content in the top 10 cm of soil, and it is likely that the crops took up N from deeper soil profiles. This may have been a bigger factor in cabbages than leeks as they are significantly deeper-rooting (Thorup-Kristensen and Sorensen, 1999). Nevertheless, as there is no obvious reason to believe that more N was mineralised in the cabbage plots, it looks like there were substantially higher losses in leek plots, particularly those that were unmulched.

The small differences in soil temperature and moisture suggest that mineralisation is unlikely to account for the very low NO_3^- content in unmulched plots with both crops. Considering the lower N uptake caused by lower yield, it must be concluded that there were substantially higher losses in unmulched crops. The measured losses of N_2O and NH_3 cannot explain these losses. Given the high rainfall events at various times in the experiment, it is likely that leaching was responsible for substantial N loss (Chen et al., 2020; Schonbeck and Evanylo, 1998b).

Excess soil mineral N in leeks grown with PFM could be lost by leaching or denitrification. Steps could also be taken to mitigate these losses after harvest, such as growing a green manure or incorporating a high C: N ratio organic material (Constantin et al., 2010; Kang et al., 2022; Xie and Kristensen, 2017). However, it is likely that mineral N, equivalent to a significant portion of this, was lost from unmulched leeks through the growing period. This loss cannot be mitigated without reducing N input with a probable consequential reduction in yield, and is likely to contribute to environmental impacts elsewhere, for example, eutrophication in aquatic environments (Nixon et al., 1996) and N_2O emissions from aquatic systems (Pätsch and Kühn, 2008), negating the lower on-farm emissions. Thus, the lower on-farm emissions may not represent the overall environmental impact. It should be noted that leeks would often be grown later in an organic horticultural rotation than cabbages when there is less available N in the soil (Thorup-Kristensen, 1999).

Other than initially higher soil NH_4^+ content with poultry manure, there was little difference in soil mineral N content between the two organic amendments despite total N inputs from the compost being nearly four times as much as that from poultry manure. Up to 50% of N from poultry manure is estimated to be available to the crop in the same season, but the N supply from compost is deemed negligible (AHDB, 2021); however, this does not take into account any possible effect of PFM (Han et al., 2020). The total amount of mineral N in the top 10 cm of soil and crop was significantly greater than the total added by either amendment, suggesting that the contribution of N accumulated from the previous ley was an important source. The ploughing-in of a two-year-old grass and red clover ley may have an N fertiliser replacement value of about 100 kg N ha^{-1} (Eriksen et al., 2006).

4.5 Gaseous emissions

4.5.1 Methane emissions

Net CH_4 flux did not appear to be affected by the treatments. In all treatments, there was a small peak in CH_4 fluxes one week after the start of the experiment; however, this was balanced by net consumption at other times. It is likely that our results are due to the relatively small difference in soil microclimate between the treatments. Cuello et al. (2015) found that PFM significantly increased CH_4 production in maize cultivation, reflecting the higher soil moisture in their study. Our study found no difference between different organic amendments, but this may be because native SOM and inputs from the ley were much larger. Similarly, the crop grown had no significant effect, which is more unexpected given the significant differences this caused to soil moisture.

4.5.2 Carbon dioxide emissions

Unfortunately, equipment failure resulted in no CO_2 emissions data from the soil. Hence, we can only provide a partial GHG intensity of production ($\text{N}_2\text{O} + \text{CH}_4$, expressed as CO_2 equivalent). However, soil emissions would reveal little about the net global warming contribution because, while they give us useful information about respiration of soil organisms, they miss the effects of changes in crop photosynthesis, return of crop residues and rhizodeposition. Future experiments to calculate Net Ecosystem Exchange could quantify these (Oertel et al., 2016).

4.5.3 Nitrous oxide emissions

N_2O emissions were increased by PFM when the crop was leeks but decreased when the crop was cabbages. The higher emissions in mulched leeks are likely partly due to higher soil NH_4^+ and NO_3^- content. Soil microclimate could also have contributed as the differences between cabbages and leeks were greater than those between mulched and unmulched treatment, particularly later in the growing season.

The only research on PFM mulch and N_2O emissions in a related climate examined the establishment of *Miscanthus* for biofuel production (Holder et al., 2019). They found that PFM

caused no significant difference in N_2O emissions over two years compared to the other establishment methods. PFM resulted in greater soil NO_3^- content and drier soil, and these two factors may have had opposite effects of a similar magnitude, resulting in no significant overall effect on N_2O fluxes. In our study, the differences in mean soil moisture were minor. Two studies in South Korea (which has a similar but warmer climate) were conducted using organic inputs (Cuello et al., 2015; Kim et al., 2017; Lee et al., 2019). Both found that PFM significantly increased N_2O emissions and emission factors for organic amendments. These studies found a positive correlation between emissions and soil NO_3^- and soil NH_4^+ content. In their experiments, differences in soil mineral N were smaller than ours. However, differences in soil microclimate (that were more significant than in our experiment) and significantly higher DOC likely played an important role. We did not measure DOC, although indications of increased SOM breakdown rate from the TBI assay suggested it might also have been greater.

Our finding that PFM had a positive interaction with soil NH_4^+ content at WFPS < 60% and a negative interaction with soil NO_3^- content at WFPS > 60% indicates that PFM positively affects the nitrification rate and the denitrification process when soil moisture conditions are favourable. It is known that nitrification is the dominant process where the average WFPS is < 60%, and denitrification is the dominant process where the average WFPS is > 60–70% (Wang et al., 2023). Nitrification is favoured by higher temperatures (Sahrawat, 2008). The difference in mean soil temperature in our study was only 0.6°C, but this may be a factor. On the other hand, when the % WFPS suggests that denitrification is dominant, higher emissions from unmulched soils could be due to higher peaks and increased amplitude of the fluctuations in soil moisture during heavy rainfall, reducing saturation and ‘hot moments’ not represented in the averaged figures (Barrat et al., 2021, 2022; Dobbie et al., 1999; Song et al., 2022). Our results tend to confirm the speculation of Berger et al. (2013) that the rainfall-shedding effect of PFM can reduce N_2O emissions by reducing micro-sites with conditions that favour denitrification in the covered bed areas. Another study showed that biodegradable PFM increased the abundance and diversity of genes associated with ammonia-oxidising bacteria while simultaneously reducing emissions of N_2O (Wang et al., 2021b). As we made no observations to discriminate between these microbial pathways, further research would be needed to confirm this effect.

The different organic amendments did not significantly affect N_2O emissions. This is unsurprising as the effects on mineral N content were small and not significant for NO_3^- . Other characteristics of organic fertilisers, such as the C: N ratio, can be significant in determining the N_2O emission factor (Charles et al., 2017). Soil C content and the probable larger contribution to soil mineral N from residues from the ley may have obscured any differences.

4.5.4 Potential ammonia emissions

Although we did measure a reduction in potential NH_3 emissions from the PFM treatments, this was not significant, and the reduction

was smaller than reported in other studies (Chae et al., 2022; Li et al., 2021). However, the reduction was more significant when expressed on a yield-scaled basis due to the higher yield. We ascribe the relatively low rates of NH_3 loss to the slightly acidic and relatively moist soil (Whitehead and Raistrick, 1990; Hargrove, 1988).

Poultry manure was expected to have higher potential NH_3 emissions than compost because it contains ammoniacal compounds, uric acid and urea, which are readily hydrolysed (Sommer and Hutchings, 2001). However, this response was only observed in the plots with cabbages. The reason for this is not apparent. Peaks of emissions occurred in the first few days, during a warm, dry period in mid-July and immediately after harvest in early September. The potential NH_3 emission results should be viewed with some caution. Whilst useful for comparative purposes between treatments, the emissions measured should not be considered absolute fluxes for comparison with other studies that have used flow-through chamber methods, as the lack of air movement would have limited emissions (Wang et al., 2004). Also, the extra step in our method for measuring NH_3 emissions may have introduced additional uncertainty. Condensation on the walls of the collection chamber and the crop leaves, caused by high humidity in the closed chamber, may have absorbed ammonia; higher measurements post-harvest could be because the crop leaves were no longer present (Chae et al., 2022).

5 Conclusions

As we hypothesised, PFM increased crop yield and resulted in higher soil NH_4^+ and NO_3^- content. However, this did not result in higher gaseous losses of NH_3 . Although N_2O losses were higher in mulched leeks than unmulched, this was not the case in mulched cabbages despite higher soil NH_4^+ and NO_3^- content. Our results also revealed that biodegradable PFM can reduce the yield-scaled emissions of both N_2O and NH_3 without a negative impact on CH_4 emissions. N_2O fluxes were positively related to soil NH_4^+ and NO_3^- content, but without knowing the relative contributions of mineralisation and leaching to the differences observed, it is not possible to fully understand the wider environmental impacts of PFM use. These results indicate that the use of PFM to moderate soil moisture fluctuations may be beneficial in reducing GHG emissions in climates with extreme rainfall events that are predicted to become more frequent and widespread with climate change. Developing a static chamber method that allows the chamber to be removed between sampling occasions and allows PFM to shed rainfall away from the mulched area could be an important development. Adopting micrometeorological GHG measurement approaches, e.g. eddy covariance, would allow fluxes to be measured at a larger scale without interfering with the integrity of the mulch film, although measurements from replicated treatments would be limited. However, these methods would have the additional advantage of taking into account the effect of PFM not just on the beds but also on the unmulched areas between beds, where it has very different effects on soil moisture. also PFM may reduce denitrification associated with

high rainfall, which is an encouraging observation that deserves further investigation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MS: Methodology, Writing – original draft, Conceptualization, Investigation, Formal Analysis, Visualization, Data curation. DJ: Project administration, Writing – review & editing, Supervision. DC: Supervision, Writing – review & editing, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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