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Agriculture, Ecosystems and Environment 367 (2024) 108951

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

Regulating soil microclimate and greenhouse gas emissions with rye mulch in cabbage cultivation

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ARTICLE INFO

Keywords:
Nitrous oxide
Vegetable farming systems
Organic mulch
Climate change
IPCC

ABSTRACT

Agriculture is a major contributor to greenhouse gas (GHG) emissions and one of the sectors most vulnerable to climate change. Mulching, the application of an organic layer to an agricultural field, is one promising agricultural practice, with the aim of reducing evaporation, preventing soil erosion and stabilising yields. While mulching has become a popular research topic in recent years, little is known about its effects on climate change adaptation and GHG emissions. We conducted weekly measurements of nitrous oxide (N_2O) emissions and analyzed related soil parameters, including soil nitrate content, temperature, and moisture, in an organic cabbage field with mulching and fertilization as treatments. Fertilization increased N_2O emissions, but rye mulch had no significant effect on emissions. Soil microclimatic parameters changed substantially under mulch, with significantly higher soil moisture and lower, less fluctuating soil temperatures. At the same time, yields increased with fertilization and mulching combined. In conclusion, our findings suggest that rye mulching can aid in climate change adaptation via soil microclimatic buffering, while not increasing GHG emissions and without compromising cabbage yield, owing to the high C/N ratio of the rye mulch.

1. Introduction

Reducing atmospheric concentrations of greenhouse gases (GHG) to mitigate climate change and feed the world's rapidly expanding population is one of the most significant obstacles humanity faces in the twenty-first century (IPCC, 2022; Myers et al., 2017; Vermeulen et al., 2012). The consequences of climate change, such as prolonged droughts, heat waves and heavy rainstorms pose threats to the global food production and are predicted to occur more frequently with the ongoing and intensifying climate change (IPCC, 2022). Changes in precipitation patterns can result in water shortages and increased competition between different water uses. About 84% of annual water consumption is due to irrigation (Brauman et al., 2016). Most outdoor vegetable crops are grown and harvested during the vegetative or early stages of the propagation phases. The associated growth physiology during these developmental stages is exponentially correlated with water and nitrogen (N) availability (Feller and Fink, 2002; Meisinger et al., 2008). To avoid massive yield losses, vegetable production is usually irrigated (Bisbis et al., 2018). Additionally, the high tillage intensity common in vegetable production reduces aggregate stability, making the soils more susceptible to erosion, and reducing water holding capacity and soil fertility (Kasper et al., 2009). To successfully adapt to climate change, agricultural practices must be innovative as well as resilient to rapidly changing and adverse growing conditions (Bisbis et al., 2018; Howden et al., 2007).

Mulching, the application of organic or inorganic materials as a soil cover, offers numerous potential benefits for vegetable production compared to bare soil. By shading the soil, mulching reduces soil warming and evaporation and consequently enhances water use efficiency (WUE) (Kader et al., 2019; Yu et al., 2018). Additionally, the mulch layer protects the soil from rainfall-induced erosion and suppresses undesirable weeds, thus reducing the need for mechanical weeding and herbicide spraying in the growing period (Abouziena et al., 2008; Kader et al., 2017a; Oliveira Jr. et al., 2014). Ultimately, mulching improves WUE, N use efficiency (NUE) and enhances yields, especially under hot and dry conditions (Gao et al., 2019; Masarirambi et al., 2013; Qin et al., 2015).

The promising effects of mulch application can provide benefits in climate change adaptation and the practice is becoming more popular in Central Europe due to the numerous horticultural advantages and recent

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https://doi.org/10.1016/j.agee.2024.108951
Received 14 December 2023; Received in revised form 25 February 2024; Accepted 27 February 2024

technical innovations in mulch-planting machinery (Junge et al., 2020). There are, however, potential downsides of mulching. Plastic film mulches increase soil water contents and temperatures which may increase soil mineralization and thus GHG emissions while degrading soil organic matter (Cuello et al., 2015). Plastic mulch also contributes to plastic waste generation, as most plastic foils in use today are difficult to dispose and recycle (Zhang et al., 2021). Organic mulch materials, such as straw, are crop residues that remain on the field and are a potential source of GHG emissions (Abalos et al., 2022a). According to the IPCC (2006, 2019) estimates, about 1% of N from plant residues is emitted as N_2O. To suppress weeds on the field reliably, large quantities of mulched biomass of at least 12 Mg dry matter (DM) ha^{-1} are required (Abouziena et al., 2008; Oliveira Jr. et al., 2014). Often, much higher loads of mulch are applied in vegetable cropping systems, e.g. more than 20 Mg DM ha^{-1} of mulch in a potato cultivation (Junge et al., 2022). Such large amounts of biomass are associated with high nutrient loads. Thus, large quantities of N are at risk of being lost via leaching and gaseous emission, depending on different factors, such as crop type and biochemical composition of the mulch material, e.g. the C/N ratio, which influence the mobilization and immobilization of N (Abalos et al., 2022a; Lashermes et al., 2022). Gaseous N losses primarily consist of elemental N (N_2), ammonia (NH_3) and N_2O. N_2O is an ozone-depleting gas and one of the most potent greenhouse gases, with an estimated global warming potential of 273 (GWP_{100}) (Ravishankara et al., 2009; IPCC, 2021). About 66% of total global N_2O emissions arise from agriculture, primarily from N fertilizer usage (Davidson and Kanter, 2014). As vegetable production typically requires large quantities of fertilizer and leaves readily degradable crop residues on the field after harvest, vegetable cultivation is a hotspot for N_2O emissions (Abalos et al., 2022a; Pfab et al., 2011; Qasim et al., 2022).

Lowering N_2O emissions is one of the key goals to reduce the impact of agriculture on the climate (Smith et al., 2007). N_2O emissions are associated with a wealth of biotic and abiotic processes but typically linked to the biological activity of nitrifying and denitrifying organisms (Braker and Conrad, 2011; Butterbach-Bahl et al., 2013; Bremner, 1997). Under aerobic or semi-anaerobic conditions, N_2O may predominately be produced by nitrifying microorganisms in fertilized soils, while denitrification is the main N_2O-producing process at elevated soil moisture contents (Bremner, 1997; Butterbach-Bahl et al., 2013; Bateman and Baggs, 2005). In addition to soil moisture, temperature, pH and substrate availability play a crucial role in microbial N dynamics and gaseous N losses (Baggs et al., 2010; Butterbach-Bahl et al., 2013; Duan et al., 2019).

The effects of incorporating plant residues into the soil on N_2O emissions are well documented and explained (Abalos et al., 2022a; Lashermes et al., 2022). GHG emission patterns from organic material left on the soil surface as mulch, however, are not well understood. In their meta-analyses, Hu et al. (2019) and Wang et al. (2021b) found an increase in N_2O emissions by mulching of plant residues, without giving a classification of the mulch material. Larsson et al. (1998) and Nawaz et al. (2017) also reported increased N_2O emissions by mulching, however in non-vegetated soil, thus not including potential soil-plant interactions of the practice. Little is known about the impact of organic mulch material on GHG dynamics in open field vegetable production, especially in temperate climate. To fill this knowledge gap, we conducted a field experiment at an experimental farm in Central Germany with organic cabbage (*Brassica oleracea var. capitata f. alba*) cultivation, comparing mulched and non-mulched systems with and without fertilization. We measured GHG fluxes and related environmental parameters such as soil microclimate as well as the agronomic output.

Since the main drivers of N_2O emissions are N availability and environmental conditions benefiting microbial nitrification and denitrification, we hypothesize that N applied with mulch contributes to N_2O emissions. We further hypothesize that mulching has a considerable effect on soil microclimate, with potential effects on N_2O dynamics and positive implications for climate change adaptation.

2. Material and Methods

2.1. Experimental site

The field experiment was conducted at the Gladbacherhof teaching and experimental farm of the Justus Liebig University of Giessen in Hesse, Central Germany (50°23'55.43 "N 8°15'17.42 "E, 182 m a.s.l.). The Gladbacherhof has been managed organically for the past 30 years. The 8-year crop rotation prior to the experiment consisted of potato-winter triticale-field bean-spelt-spring wheat-alfalfa-alfalfa-winter rye. The average annual temperature is 9.7 C, and annual precipitation is 668 mm. The soils (0.30 m) are predominantly loess-rich luvisols, with a pH of 6.36 and bulk density of 1.37 g cm^{-3}.

2.2. Field management and experimental design

A randomized block design with four blocks and 20 experimental plots in total was established to investigate the influence of two factors in a 2×2 full factorial design: organic mulch [two treatment levels: with mulch (M+) and without mulch (M-)] and fertilization [two treatment levels: with fertilizer (F+) and without fertilizer (F-)] (Supplementary Material Fig. 1). Target variables were soil moisture, soil temperature and GHG emissions in cabbage cultivation (*Brassica oleracea var. capitata f. alba*, variety Korsuma RZ F1, planting density 0.45 ×0.45 m). Additionally, one plot per block was established where no cabbage was planted to observe the effect of each treatment without the influence of the planted crop (non-vegetated soil). These non-vegetated plots were only analysed descriptively and not included in statistical models. Consequently, each block consisted of five plots, i.e. four treatment plots with cabbage plants and one plot without plants. Each plot measured 12.81 m^2 (width: 1.72 m; length: 7.09 m).

The mulch treatment was implemented as the so-called combi-mulch approach (a combination of *in situ* mulch and transfer mulch). At the beginning of the experiment in June 2021, the mulch-providing crop, winter rye (including ears, prior to ripening), was mulched and removed from the field to allow soil preparation with a rototiller to 0.10 m depth. Subsequently, the winter rye (C/N ratio: 63) was applied as a mulch layer at a rate of 12.5 Mg DM ha^{-1} on the corresponding experimental plots. Cabbage seedlings were planted directly into the mulch material with a MulchTec Planter (live2give gGmbH, Dickendorf, Germany) on June 17 2021. With this newly developed planting technology, it is possible to plant vegetable seedlings mechanically in a closed mulch cover at larger scales. The mulch layer is cut open by a cutting device, followed by the planting coulter, which opens the soil. After the young plant is placed into the soil, the pressure rollers close the furrow. Simultaneously, an ammonium rich organic fertiliser (Phytoperls®-N, Provita) was applied as underfoot fertilization at a rate of 220 kg N ha^{-1}. During the growing period, the plots were irrigated four times with 4.7 l m^{-2} using watering cans. On two occasions (8th and 22nd of July 2021), the plots without mulch were manually weeded to a depth of about 20 mm to reduce weed competition. Following organic agriculture regulations, no synthetic herbicides, pesticides, fungicides, or fertilizers were used. After cabbage harvest on October 11 2021, crop residues were mulched down and, together with the remaining mulch in the corresponding treatments, incorporated into the soil by a rototiller (0.10 m depth). Afterwards, the soil was prepared with a rotary harrow (0.10 m depth) and a vetch-rye-pea ley was sown as cover crop. The experiment continued until March 2022 when the soil was prepared for potato planting. The observation period consisted of 267 days, which can be divided into two periods: The cabbage growing period from planting to harvesting (growing period: 06/17/2021–10/11/2021, 117 days); and the winter period from incorporation of crop residues and mulch followed by sowing of the cover crop (vetch rye-pea) until soil preparations for the following potato planting (winter period: 10/12/2021–03/10/2022, 150 days).

2.3. Soil, plant and mulch sampling and analyses

Weather data was recorded at the nearby weather station, about 300 m from the experimental field. Soil temperatures were measured weekly by a rod thermometer (AGTS03, Agreto electronics GmbH, Austria) in the test plots, at the soil surface, and in 0.10 m, 0.20 m and 0.30 m depths. After initiating the experiment, soil bulk density and pH in 0.30 m depth were determined (DIN, 1973, 2022). Soil samples to a depth of 0.30 m were taken weekly with a manual auger during the growing period, and monthly during the winter period. At the beginning of the experiment, at harvest, and at the end of the experiment, soil sampling was extended to 0.90 m depth, separated into 0–0.30 m, 0.30–0.60 m, and 0.60–0.90 m, to investigate the relocation of nitrate (NO_3^-) to deeper soil layers with the potential of leaching. Water-filled pore space (WFPS) in percent was calculated from gravimetric soil water contents, total porosity and bulk density. Soil nitrate content in the upper 0.30 m of soil was estimated following the common method used in German agriculture (DIN, 1998). Weekly nitrate sampling started one month after the experiment was set up. Mulch samples were collected in the beginning and at the end of the growing period (prior to incorporation) for carbon (C) and N quantification of the mulch material (DIN, 1995, 1998). Mulch mass loss, N and C composition were determined from litterbags with mulch, which were pre-weighed, and placed in the mulch at the establishment of the experiment and removed and analysed after harvest. The cabbage plants were harvested manually by cutting the stem 20 mm above the soil surface on October 11 2021. Both the total aboveground biomass and the marketable yield, defined as fully developed cabbage heads, were weighed and scaled up to tonnes per hectare. The yield was evaluated from the cabbage heads of the central plant row of each plot to exclude effects of neighbouring plots. After harvest, the water, C and N contents of the cabbage, separated into leaves and heads, were analysed (DIN, 1995, 1998).

2.4. Greenhouse gas (GHG) emission measurements

After cabbage planting, two circular chamber bases, made of polyvinyl chloride (PVC) (0.20 m height, 0.30 m diameter) were installed in each plot (40 total) to the depth of 0.15 m. Chamber bases were installed in the planting row, between plants. In the mulch treatments, mulch material was placed in the chamber base corresponding to the same rate present in the plots (12.5 Mg DM ha^{-1}).

GHG measurements were performed weekly utilizing a manual closed chamber system with circular, opaque chamber tops (PVC, 0.125 m height, 0.30 m diameter) placed on top of the fixed chamber bases. Short tubes (50 mm length, 2 mm diameter) passing through the chamber wall were used to equilibrate chamber pressure. Tubes of 20 m length were used to transport the chamber headspace air to the Picarro field lab, a mobile measurement device to determine concentrations of N_2O, CO_2 and CH_4 via high-resolution cavity ring-down laser absorption spectroscopy (PICARRO G-2508 CRDS Analyzer, Picarro Inc., Santa Clara, USA). Before the measurements, each tube was flushed with ambient air. Chambers were closed airtight on the chamber base one minute before the first measurement was initiated and kept closed for 41 minutes. During this period, the air from each chamber was measured in one-minute intervals for a total of five times per chamber. Ten chambers (two per plot, five plots per block) were measured in succession, resulting in 50 individual one-minute measurements per block per measurement day. The number and duration of measurements per plot and block were limited by the maximum chamber closure time insusceptible to lateral diffusion of N_2O below the chamber base (Rochette, 2011). After the measurement period of one block, the procedure was repeated in the following blocks. Chamber temperatures during gas measurements were estimated by additional chambers equipped with thermometers that were installed in plots of the same treatments within a different measuring block. GHG fluxes were calculated using the R-package gasfluxes (Fuß, 2023). Quality of flux measurements as assured based on R^2 of CO_2 concentration increase over time since leaking tubing or improper chamber attachment on the collar was associated with $R^2 < 0.95$. To account for gas transport time through the tubes (1 m s^{-1}), the first 20 seconds of each measurement were discarded. Cumulative emissions were estimated by linear interpolation between weekly measurements and subsequent aggregation of all observation events.

2.5. N_2O emissions according to IPCC methodologies

To compare our results with the emission potential estimated by IPCC for political stakeholders, and to validate those estimates with measured data, we calculated the expected N_2O emissions from our field trial applying two approaches: The first approach (Eq. 1) reflects the general Tier 1 approach by the IPCC that is used for national inventories (IPCC, 2006, 2019). In this approach, the so-called activity data, i.e. the quantity of the source material, i.e., the amount of fertilizer N, mulch N or crop residue N ($N_{fert}, N_{mulch}, N_{cr}$ in kg N ha^{-1}, respectively) is multiplied with the related emission factors ($EF_{fert}, EF_{mulch}, EF_{cr}$) to obtain the amount of GHG that is emitted in the process (N_2O_{T1}). Both for fertilizer and crop residues, the Tier 1 emission factor is 1% (0.1–1.8%) of applied N (Novoa and Tejeda, 2006).

$$N_2O_{TI} = N_{fert} * EF_{fert} + N_{mulch} * 0.01 + N_{cr} * 0.01 \quad (1)$$

Additionally, N_2O emissions were calculated following an IPCC Tier 2 approach (N_2O_{T2}), using updated fertilizer emission factors that take the different pedo-climatic zones in Germany into account (Eq. 2) (Mathivanan et al., 2021). According to this approach, the N_2O emission factor for fertilizer and crop residue N at the experimental site Gladbacherhof is 0.385% (0.172–0.660%).

$$N_2O_{T2} = N_{fert} * EF_{fert} + N_{mulch} * 0.00385 + N_{cr} * 0.00385 \quad (2)$$

In order to ease comparability to other direct N_2O emission communications and to follow IPCC methodology, expected N_2O-N emissions were converted to N_2O by using the equation:

$$N_2O = N_2O - N * 44/28 \quad (3)$$

2.6. Statistical analysis

Linear regression analyses were conducted to investigate the effect of soil environmental conditions and properties (soil temperature, WFPS, soil nitrate) on N_2O emissions. Additionally, two-way analyses of variance (ANOVA) were used to examine the effect of the treatments (mulching x fertilization) on soil properties and N_2O emissions. As the growing and winter period had very different experimental conditions, one with mulch material on top of the soil, the other with mulch incorporated into the soil, the analyses were conducted separately for both periods. To account for temporal variance, measuring week was held fixed within the models. Target variables were log-transformed when necessary to meet the requirements of normality. The measurement block was introduced as a random factor when identified as significant in prior analyses. When significant effects were identified, least square means were explored using the Tukey HSD method to make specific comparisons among the different treatments.

Data pre-processing, computation of GHG fluxes, calculation of cumulative emissions and all statistical analyses and data visualisation were carried out using a custom made R script in Rstudio (RStudio Team, 2023) and R (R Core Team, 2023) and the packages dplyr, lme4, emmeans, ggplot2 and gasfluxes (Bates et al., 2015; Fuß, 2023; Lenth, 2023; Wickham, 2016; Wickham et al., 2023).

3. Results

3.1. N_2O fluxes

N_2O-N fluxes exhibited temporal variation during the growing period (Fig. 1D). The largest observed flux rate was 0.149 mg N_2O-N $m^{-2}h^{-1}$ in the fifth week (fertilized treatment without mulch), while the lowest was 0.002 mg N_2O-N $m^{-2}h^{-1}$ in week seventeen (non-fertilized treatment with mulch). Following the establishment of the experiment, with tillage, fertilization and planting, peak emissions occurred. During this time, fertilized treatments exhibited higher fluxes than unfertilized treatments. In both, fertilized and unfertilized treatments, mulch suppressed the fluxes by 37 and 63%, respectively. In the second week, fluxes decreased in all treatments, followed by a large peak event from weeks three to week five. In this period, higher emissions were observed in all treatments, more pronounced in fertilized treatments, and higher emissions coincided with high summer precipitation and highest observed levels of nitrate concentrations in the soil (Fig. 1A, B, C). After six to eleven weeks, emissions decreased across all treatments, with occasional smaller peak events. After 12 weeks, flux rates stabilized close to zero. During the growing period, fertilized treatments emitted significantly more N_2O-N than non-fertilized ($p<0.01$) while mulching did not influence emissions significantly ($p=0.69$). N_2O-N fluxes were significantly and positively correlated with the amount of nitrate (kg NO_3^--N ha^{-1}) in the soil ($p<0.01$). Increased WFPS and soil temperatures also enhanced N_2O-N flux rates in fertilized treatments ($p<0.01$). For non-fertilized treatments, only WFPS had a significant effect during the growing period.

The winter period started after harvest with soil tillage and sowing of cover crop in October, which made up the main peak event (maximum of 0.056 mg N_2O-N $m^{-2}h^{-1}$ in the non-fertilized treatment with mulch). Observed flux rates remained low for most of the winter period, with smaller peaks occurring at different time points. These trends were observed over all treatments, albeit at different magnitudes. The amounts of soil nitrate significantly enhanced N_2O-N emissions ($p<0.01$). When comparing between fertilized treatments, no environmental factor had a significant effect when fertilizer was present, while between non-fertilized treatments, soil temperature increased emissions ($p<0.05$). Fertilization increased emissions only of the non-mulched treatment ($p<0.01$), and mulching reduced emissions of the fertilized treatment. ($p<0.01$).

Overall, mulch slightly increased the emissions in fertilized treatments by 2% in the growing period, but reduced said emissions by 30% in the winter period. In total, mulch reduced the N_2O emissions by 4% in the fertilized treatments.

3.2. Cumulative and yield-scaled N_2O emissions

Cumulative N_2O-N emissions over the 267-day measurement period did not exceed 1.61 kg N_2O-N ha^{-1} (Fig. 2A). The majority of emissions occurred during the growing period in all treatments. Fertilization significantly increased cumulative emissions regardless of mulching, while mulching did not influence N_2O-N emissions during the growing period. During winter, mulching reduced emissions in fertilized treatments.

Yield and biomass production were primarily influenced by fertilization (Table 1). Marketable yield ranged between 13.9 Mg ha^{-1} in the unfertilized but mulched treatment (M+F-) and 41.7 Mg ha^{-1} in the fertilized mulched treatment (M+F+). Due to high variability between plots, the effect was not significant for most comparisons. Only M+F- and M+F+ were significantly different with regard to yields. Without fertilization, mulch decreased the yield further, while when fertilizer was applied, mulch tended to increase the yield compared to the non-mulched counterpart. The average cabbage head weight was 1151.8 g in M+F+, 1140.6 g in M-F+, 417.1 g in M+F- and 456.4 g in M-F-. The same trends were observed for total aboveground biomass. N uptake in aboveground biomass differed between the treatments. Although the non-mulched fertilized treatment produced less biomass overall, the total N uptake was higher, due to higher N concentrations in the plant material (Table 1). Cabbage from non-fertilized treatments took up less N than in fertilized treatments.

Non-significantly lower yield-based N_2O-N emissions were observed in fertilized treatments compared to non-fertilized treatments (Fig. 2B). Mulching reduced emissions per yield in fertilized treatments but increased emissions in non-fertilized treatments in a non-significant way.

3.3. N_2O emissions according to IPCC Tier 1 and 2 methods

The expected N_2O emissions based on IPCC Tier 1 estimations were higher than the measured emissions (Table 2). For all treatments with external inputs (M+F+, M+F-, M-F+), the measured N_2O emissions were within the uncertainty range, but well below the expected mean. For the treatment without external inputs (M-F-), the measured emissions were higher than the expected. The Tier 2 approach underestimates the emissions of all treatments. For all treatments with external inputs (M+F+, M+F-, M-F+), the measured N_2O emissions were within the uncertainty range of the Tier 2 approach, but above the expected mean. The treatment without external inputs (M-F-) emitted far more N_2O than the uncertainty range of expected N_2O emissions.

3.4. Soil environmental conditions and soil nutrients

Soil temperatures during daytime showed large fluctuations during both the growing and winter periods (Supplementary Material Fig. 2). Soil temperatures increased and decreased with ambient air temperature, most prominent on the soil surface. Mulching had a buffering effect on the soil temperature during the growing period. Especially on hot days, mulching reduced soil temperatures at the surface, in 0.10 and 0.20 m depth. In 0.30 m depths, the effects were less pronounced. Overall, soil temperatures were lower under mulch and showed less temporal variation (Table 3). During the winter period, after the mulch was incorporated, no differences in soil temperatures between the treatments could be discerned (data not shown).

WFPS varied throughout the growing period, increasing after rainfall events and reducing after periods of little rain (Fig. 1B). The highest WFPS was observed in week five in the M+F- treatment (62.35%) and the lowest in the 13th week in the M-F+ treatment (34.37%). WFPS were low at the beginning of the experiment and increased continuously until they reached the peak on the fifth week after a rainfall event. Overall, the mulched treatments (averages for M+F- and M+F+ were 54.0 ± 0.6 and 44.3 ± 1.1%, respectively) had significantly higher WFPS compared to the non-mulched counterparts (averages for M-F- and M-F+ were 47.2 ± 0.3 and 41.4 ± 0.5%, respectively) throughout the growing season. Fertilization had a significant decreasing effect on WFPS ($p<0.01$).

In week 17, prior to harvest and crop residue incorporation, unfertilized treatments had higher WFPS than fertilized treatments. This effect was observed until week 28. During the winter period, WFPS was higher in mulched treatments.

Soil nitrate content in the upper 0.30 m was mostly determined by fertilization (Fig. 1C). Unfertilized treatments had low levels of nitrate throughout the entire measurement period. Fertilized treatments had significantly larger amounts of soil nitrate during the growing season. Within fertilized treatments, on the first measurement instance, five weeks after the initiation of the experiment, the mulched treatment had considerably higher nitrate levels than its non-mulched counterpart. Nitrate levels decreased from the first measurement in week five over the following five weeks to a level similar to unfertilized treatments. During the winter period, little difference of soil nitrate was observed between either treatment.

The amounts of nitrate in 0.60 m and 0.90 m depth did not change

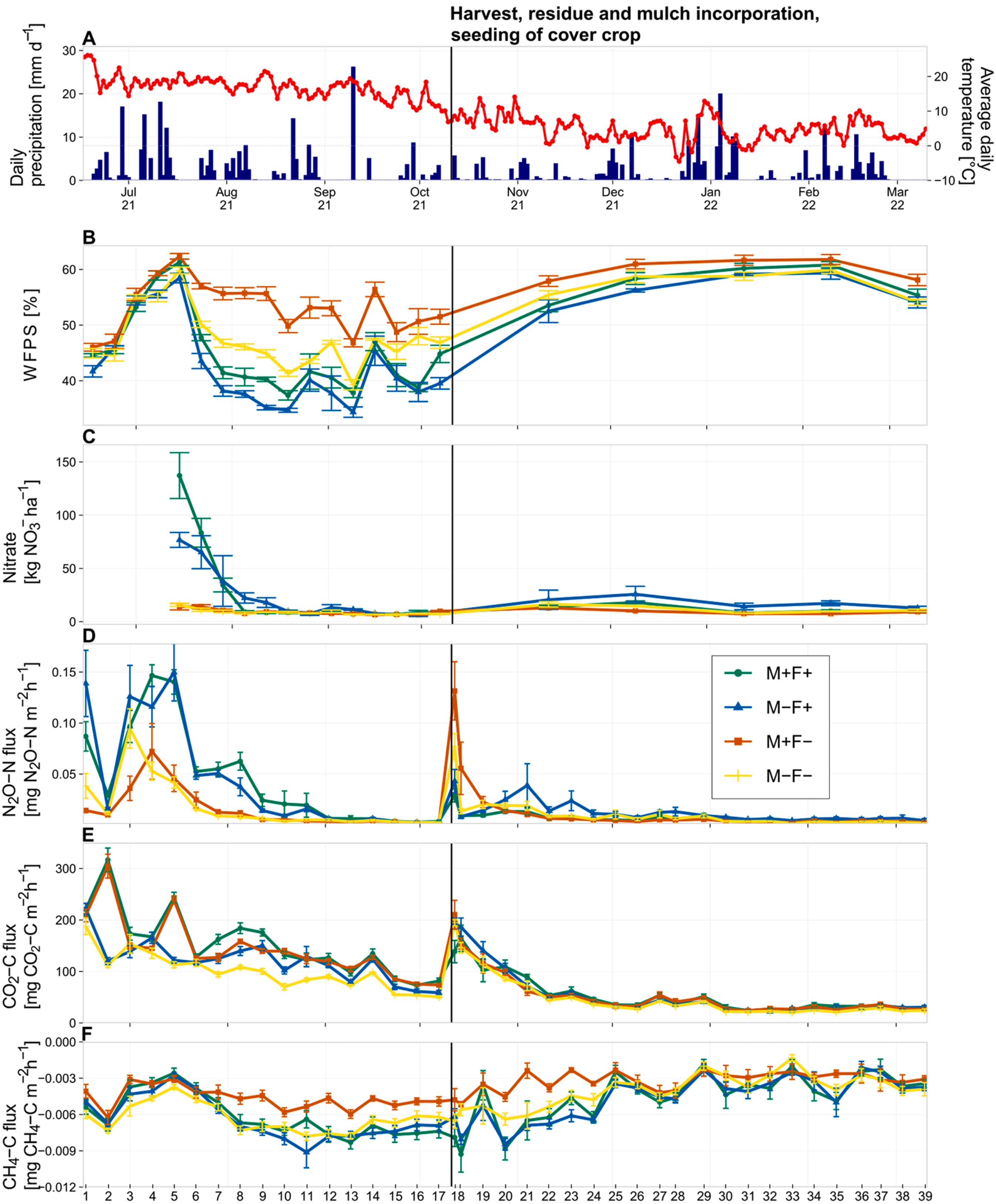

Fig. 1. Course of meteorological parameters, soil environmental conditions and GHG fluxes during the field experiment. The x-axis indicates measurement week during experimental period. Mean daily temperature [°C] (red line) and daily precipitation [mm] (A). Mean WFPS [%] and nitrate-N (0–30 cm depth) (B-C) and mean N_2O-N, CO_2-C and CH_4-C fluxes (D-F). Error bars indicate standard errors. The vertical line indicates the end of growing period, with harvest, residue and mulch incorporation and seeding of cover crop (October 12th 2021). Colors indicate treatments: M+F+ (green) = with mulch and fertilization (n=4); M-F+ (blue) = without mulch and with fertilization (n=3); M+F- (red) = without mulch and with fertilization (n=4); M-F- (yellow) = without mulch and without fertilization (n=4).

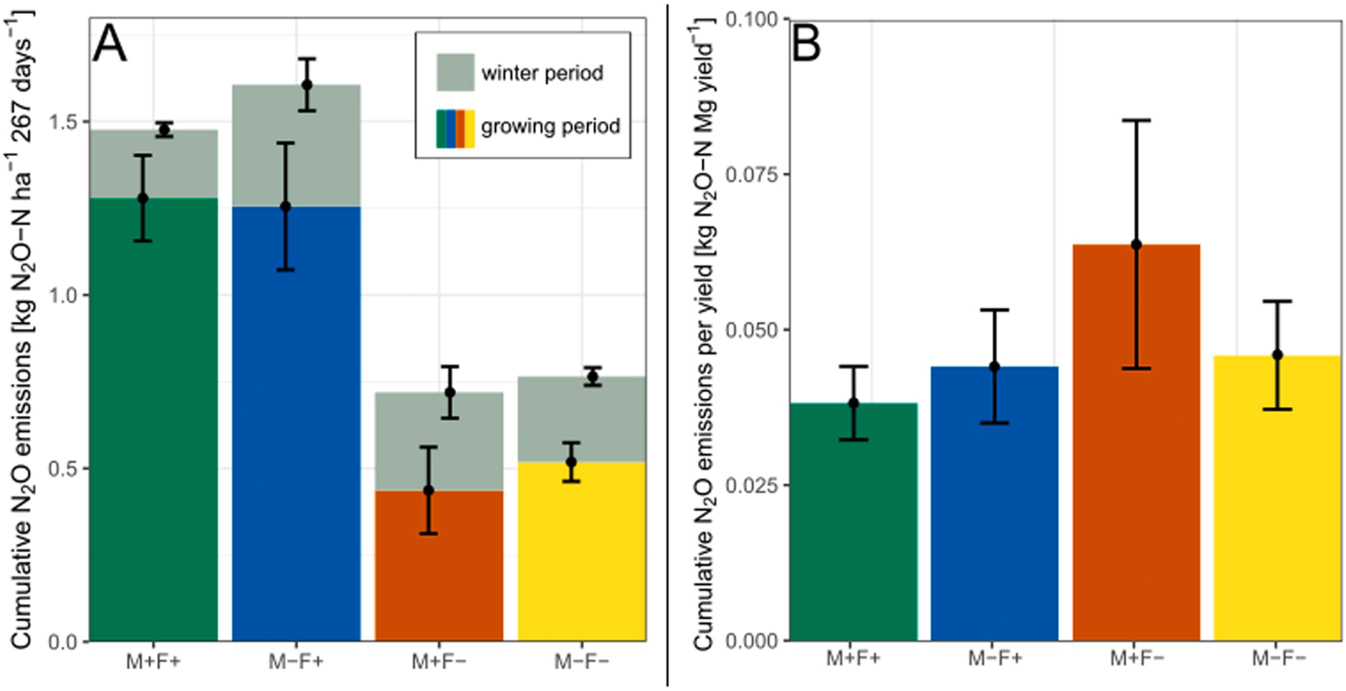

Fig. 2. A: Cumulative N_2O-N emissions from each treatment over the experimental period, separated for growing and winter period. B: N_2O-N emissions per kilogram of marketable cabbage yield. Error bars indicate standard error. M+F+ = with mulch and fertilization (n=4); M-F+ = without mulch and with fertilization (n=3); M+F- = without mulch and with fertilization (n=4); M-F- = without mulch and without fertilization (n=4). Marketable cabbage yield defined as fully developed cabbage heads.

Table 1
N inputs, aboveground biomass, yields and N in aboveground biomass.

	Input		Output		
Treatment	*Fertilizer N* (Phytoperls®-N) *[kg ha^{-1}]*	*Mulch material N [kg ha^{-1}]*	*Total aboveground biomass [Mg ha^{-1}]*	*Cabbage yield [Mg ha^{-1}]*	*Total N in aboveground biomass [kg ha^{-1}]*
M+F+	220	82.3	70.6 ± 22.7^{a}	41.7 ± 15.6^{a}	145.16
M-F+	220	0	67.5 ± 26.6^{ab}	39.7 ± 15.9^{ab}	172.95
M+F-	0	82.3	30.0 ± 11.6^{b}	13.9 ± 6.7^{b}	81.8
M-F-	0	0	33.0 ± 11.2^{ab}	18.5 ± 7.3^{ab}	73.72

Note: M+F+ = with mulch and fertilization; M-F+ = without mulch and with fertilization; M+F- = without mulch and with fertilization; M-F- = without mulch and without fertilization. Values are mean ± standard deviation (n= 4 for M+F+, M+F-, M-F-; n=3 for M-F+). Significances ($p<0.05$) are indicated with letters.

Table 2
Measured and expected N_2O emissions. Data are mean of four replicates ± standard deviation.

	Measured N_2O emissions	Expected N_2O emissions	
Treatment	*Measured N2O emissions [kg N_2O ha^{-1} 267 days^{-1}]*	*Tier 1 [Exp. kg N_2O ha^{-1}]*	*Tier 2 [Exp. kg N_2O ha^{-1}]*
M+F+	2.33 ± 0.35	5.86 (0.59–10.54)	2.25 (1.01–3.86)
M-F+	2.53 ± 0.33	4.79 (0.48–8.63)	1.85 (0.82–3.16)
M+F-	1.13 ± 0.44	2.07 (0.21–3.73)	0.80 (0.36–1–37)
M-F-	1.19 ± 0.24	0.57 (0.06–1.03)	0.22 (0.10–0.38)

Note: The expected N_2O emissions are based on emission factors for N fertilizers, mulch and crop residues. For Tier 1, the factor is 0.01 for fertilizer, mulch and crop residue N. For Tier 2 the factor is 0.00385 for fertilizer, mulch and crop residue N. Brackets indicate uncertainty range. Treatments: M+F+ = with mulch and with fertilizer; M+F- = with mulch and without fertilizer; M-F+ = without mulch and with fertilization; M-F- = without mulch and without fertilization. Values transformed from N_2O-N to N_2O.

Table 3
Soil temperatures during the growing period (June-October 2021) between mulched (M+) and non-mulched (M-) treatments.

	M+		M-	
Soil depth [cm]	*Temporal mean [° C] ± SD*	*Temporal variance*	*Temporal mean [° C] ± SD*	*Temporal variance*
0	17.08 ± 2.5	6.68	19.43 ± 4.4	20.5
10	16.17 ± 4.4	5.29	17.21 ± 3.3	11.86
20	16.11 ± 1.9	3.98	16.35 ± 2.7	7.51
30	16.15 ± 1.7	3.13	16.40 ± 2.2	5.22

Note: Soil temperatures were measured with an auger placed on the soil surface, at 10, 20 and 30 cm.

between the start of the experiment in June 2021 and harvest in October 2021 (Supplementary Material Figure 3). Over the winter period, some nitrate was allocated to the deeper soil layers (between October 2021 and March 2022). Non-mulched treatments had significantly larger amounts of nitrate than mulched treatments in March 2022 (0.60 m $p<0.01$; 0.90 m $p<0.05$). Fertilized treatments showed higher levels of nitrate than unfertilized at 0.60 m ($p<0.01$). The largest amount of nitrate at 0.60 m was recorded in the M-F+ treatment, with 17.44 ± 3.98 (SD) NO_3^- ha^{-1}, the lowest level was recorded in the M+F-, with 7.69 ± 1.77 NO_3^- ha^{-1}. At 0.90 m, the highest nitrate content was recorded in the M-F+ treatment (22.07 ± 6.57 NO_3^- ha^{-1}) the lowest value was recorded in the M+F- (13.01 ± 3.82 NO_3^- ha^{-1}).

3.5. Loss of nutrients from mulch material

The mulch material had N and C contents of 82.3 ± 1.5 kg N ha^{-1} and 5149.4 ± 11.4 kg C ha^{-1} at the beginning of the experiment. After the growing season but before incorporation, the N contents in the mulch had reduced to 61.3 ± 3.6 kg N ha^{-1} for the fertilized and 69.5 ± 7.9 kg N ha^{-1} for the unfertilized treatments. In the fertilized treatments, the mulch material lost 21 kg N ha^{-1}, and 12.8 kg N ha^{-1} in the unfertilized treatments. The C contents reduced to 3343.5 ± 143.2 kg C ha^{-1} in the fertilized and 3391.3 ± 34.7 kg C ha^{-1} in the unfertilized treatments, resulting in C losses of 1805.9 and 1758.1 kg C ha^{-1} for the fertilized and unfertilized treatments, respectively. The C/N ratio of the mulch changed from 63 at the start of the experiment to 55 in the fertilized and 49 in the unfertilized treatment.

3.6. Ecosystem respiration and methane fluxes

During the growing period, ecosystem respiration (R_{eco}) ranged from 50.4 mg CO_2-C m^{-2} h^{-1} in week 17 (M-F-), to 316.7 mg CO_2-C m^{-2} h^{-1} in week two (M+F+). After the initiation of the experiment, R_{eco} was similar in all treatments (Fig. 1E). In the second week, a major peak event occurred in the mulched treatments while CO_2-C fluxes dropped in the non-mulched treatments. A stabilisation of CO_2-C fluxes occurred in week three and four over all treatments. In week five, similar to week two, a peak was observed in the mulched treatments, while emissions from non-mulched treatments decreased. From the seventh until the ninth week fertilized treatments emitted more CO_2-C than unfertilized treatments, with mulched treatments emitting more than non-mulched. From week ten until harvest, emissions were similar over all treatments. During the winter season, a post-harvest peak event was observed. CO_2-C fluxes decreased from that point on, with occasional smaller peaks. Overall, higher emissions were recorded during the growing period, with the highest CO_2-C fluxes occurring in the mulched treatments. The lowest flux rates were observed in the M-F- treatment. Cumulatively over 267 days, M+F+ emitted 6212.2 kg CO_2-C ha^{-1}, M-F+ emitted 5177.0 kg CO_2-C ha^{-1}, M+F- emitted 5805.9 kg CO_2-C ha^{-1}, and M-F- emitted 4340.9 kg CO_2-C ha^{-1} (Supplementary Material Figure 4).

CH_4-C was not emitted but consumed in the soil throughout the entire experimental period (Fig. 1F). Methane fluxes showed some temporal variation, but mostly remaining between −0.001 and −0.009 mg CH_4-C m^{-2} h^{-1}. In week two after initiating the experiment, consumption rates increased across all treatments. After a reduction of consumption rates in weeks three to five, starting from week six, methane consumption increased for all treatments but M+F-. During winter, weekly fluctuations can be observed, with all treatments consuming similar amounts from December on. Cumulatively over 267 $days^{-1}$, methane C sequestration was 0.33 kg CH_4-C ha^{-1} in M+F+, 0.34 kg CH_4-C ha^{-1} in M-F+, 0.25 kg CH_4-C ha^{-1} in M+F- and 0.32 kg CH_4-C ha^{-1} in M-F- (Supplementary Material Figure 5).

3.7. Non-vegetated treatments (descriptive results)

The results from non-vegetated plots cannot be assessed statistically and have to be interpreted with caution as they were established in single repetition only. Although we did not identify a block effect for the main treatments, the spatial heterogeneity of the experimental field could have influenced the results and cannot be taken into account in the control treatments. The lack of plants had a large effect on N_2O emissions (Supplementary Material Figure 6). With 9.4 kg N_2O-N in M+F+, 6.87 in M-F+ and 1.35 kg N_2O-N ha^{-1} 267 $days^{-1}$ in M+F-, most treatments emitted far more N_2O when no plants were present. The treatment with bare soil (no plants, fertilizer or mulch) emitted less than its counterpart with plants (0.54 kg N_2O-N ha^{-1} 267 $days^{-1}$).

CO_2-C emissions increased in the mulched treatments when no plants were present (Supplementary Material Figure 7). Especially the mulched treatments without fertilizer showed increased emissions overall.

Less CH_4 was consumed when no plants were present compared to the same treatments with plants (Supplementary Material Figure 8). Only when mulch but no fertilizer was present did the non-vegetated treatments consume slightly more CH_4-C.

4. Discussion

4.1. Mulching does not enhance N_2O emissions

We hypothesized that the N applied with mulch would enhance N_2O emissions. Mulching did not increase the emissions during the experimental period, despite the application of 82.3 kg ha^{-1} N through the mulch material, however.

This may have several possible reasons: It is most likely that N immobilization after mulch incorporation contributed most to N_2O emission reduction. In a meta-analysis by Abalos et al. (2022a), the application and incorporation of crop residues resulted in lower or higher N_2O emissions depending on environmental conditions, residue type, and amount of added material. Crop residue composition influences N and C mineralization in the soil, which affects soil NO_3^- and NH_4^+ concentrations and consequently the N_2O emissions (Lashermes et al., 2022). Immature material can be decomposed quickly, leads to N mobilization and consequently stimulates microbial processes of nitrification and denitrification that produce N_2O, while more mature material is more difficult to decompose and emits less N_2O (Lashermes et al., 2022). Especially the C/N ratio has a considerable effect on microbial activity regarding N-metabolising processes, with a C/N ratio of 30:1 being considered the threshold for immobilization to become more prevalent (Lashermes et al., 2022). The rye mulch material used in our experiment had a high C/N ratio (63:1 after mulching and 48:1 before soil incorporation) akin to mature material used by Lashermes et al. (2022), likely retarding mineralization and reducing mineral N available for substrate-driven microbial N turnover processes. Microbial N metabolism is highly dependent on available C and N, and due to the different levels of available C between the treatments with and without mulch, plant available mineral N was likely used by microorganisms to release organically bound C in the incorporated mulch, resulting in less N being lost as N_2O. Despite the lack of microbial community estimates in our experiment, we assume that rye mulch with a high C/N ratio increased the fungi-to-bacteria ratio in the soil, affecting N transforming processes (De Vries et al., 2006). Along that line, previous studies revealed that arbuscular mycorrhizal fungi (AMF) may reduce N_2O emissions from soil (Bender et al., 2014; Storer et al., 2018). While the underlying mechanisms remain uncertain, there are indications that AMF-induced changes in the soil microbial community regulate N_2O emissions. Recently, Li et al. (2023) found that AMF and hyphae-associated microbes may cooperate, influencing N_2O emissions from residue patches, similar to the mulch system used in our experiment. In their study, carboxylates exuded by hyphae act as attractants for *Pseudomanos fluorescens* and also as stimulants triggering *nosZ* gene expression which in return catalyses the terminal step in denitrification from N_2O to N_2 (Li et al., 2023).

4.2. Mulch regulates soil N_2O drivers

Soil NO_3^-content is a key driver of N_2O emissions. In our experiment, NO_3^- contents (0–0.30 m) were primarily dependent on fertilization. After ten weeks, nitrate levels aligned between fertilized and non-fertilized treatments, suggesting that excess NO_3^- was taken up by plants, immobilized by microorganisms or lost in form of NH_3, N_2O, N_2 or NO_3^- by that point. During winter, no differences were observed between the non-fertilized treatments nitrate levels in 0.30 m. Within the fertilized plots the non-mulched treatment had higher NO_3^- contents than the mulched during winter season. This suggests that when incorporating senescent rye mulch with large loads of cabbage plant residues, the high C/N ratio has an influence on the soils winter nitrate levels due to microbial N immobilization. Additionally, we found an increased amount of NO_3^- in the deeper soil layers (0.60 and 0.90 m) after the winter period in March, compared to the starting values in June and at harvest in October (Supplementary Material Figure 3). Whereas fertilization increased nitrate levels in deeper soil layers, mulching had a reducing effect. N-enriched agricultural soils can contribute to NO_3^- leaching and have a negative impact on the water quality of estuaries and underground aquifers (Di and Cameron, 2002). Our results suggest that rye mulch does not contribute to an increased nitrate leaching risk and may even reduce that risk, which validates the N-immobilization of senescent rye mulch incorporation.

Due to the lower soil temperature, the soil shading and the physical barrier, soil evaporation is reduced under mulch (Kader et al., 2019). As increased WFPS tends to increase N_2O emissions (Butterbach-Bahl et al., 2013), the increased WFPS under mulch would suggest higher N_2O emission from this treatment. The soil cooling effect of the mulch, however, may have compensated for this effect thus not increasing emissions. N_2O emissions are highly dependent on soil temperatures (Signor and Cerri, 2013; Wang et al., 2021a), with higher temperatures resulting in higher emissions due to increased microbial activity (Maag and Vinther, 1996). Lower temperatures under mulch during the growing period likely repressed microbial N turnover compared to non-mulched treatments. This effect was apparent after the establishment of the experiment, where mulch significantly reduced the N_2O flux. Additionally, increased water availability improves plant growth and thus plant N uptake which reduces the amount of residual soil N prone to be transformed to N_2O (Ullah et al., 2019). Our results of plots without plants support that conclusion, as these treatments emitted considerably more N_2O than their vegetated counterparts. The growing season of the experimental year was characterized by frequent rainfall events, which provided a sufficient amount of water for the cabbage, so that the mulch could not fully achieve its water saving advantages.

Improved soil water and N availability could potentially benefit crop growth and yields. In our experiment, however, only slightly higher yields and production of biomass were realized with mulch in the fertilized treatments (non-significant). An increased NUE from mulching could not be detected, as the treatment with fertilizer and without mulch showed the largest amounts of N in total aboveground biomass. In other studies, increased yields of brassicaceous vegetables were recorded under organic mulch materials with high C/N ratios, but the mulch showed best effects under dry conditions (Masarirambi et al., 2013; Noertjahyani et al., 2019). In a meta-analysis by Qin et al. (2015), mulching significantly increased corn and wheat yields, WUE and NUE compared to uncovered soil. An additional benefit of mulch is the CO_2 emitted from the mulch layer being utilized for photosynthesis by the planted crop, resulting in enhanced biomass production (Bisbis et al., 2018). In our experiment, the increased C contents of the cabbage grown in mulch may be attributable to this phenomenon.

4.3. Drivers for low N_2O emissions at the experimental site

Compared to other field vegetable studies, cumulative N_2O emissions in this experiment were low (Pfab et al., 2011; Rezaei Rashti et al., 2015). Especially cumulative emissions during the winter season were much lower in our results, with a maximum of 0.35 kg N_2O-N ha-1 (M-F+) compared to other studies, with between 1.3 and 4.8 kg N_2O-N ha-1 (Pfab et al., 2011). When comparing our results over the growing period to other cabbage cultivations with similar fertilization levels (~220 kg N ha-1) and similar number of growing days (119), our emissions (maximum at treatment M+F+ with 1.28 kg N_2O-N ha-1) were either much lower (6.8 and 2.8 kg N_2O-N ha^{-1} in Mu et al. 2013) or higher (0.48 kg N_2O-N ha^{-1} in Pang et al. 2009). Soils under intensive vegetable cultivation are often characterized by high mineral N concentrations (Rezaei Rashti et al., 2015). At the start of our experiment, the initial nitrate concentrations were low (6.15 kg NO_3-N ha-1) due to the previous N uptake from the soil by rye cultivation.

The fertilizer used in this experiment may also have contributed to the generally low level of emissions: Phytoperls®-N is an organic fertilizer, consisting mostly of ammonium (NH_4^+) that was applied to a depth of 0.10 m, beneath the seedlings, not on the soil surface. This closely resembles a Controlled Uptake Long Term Ammonium Nutrition (CULTAN) procedure (Deppe et al., 2016), which aims to slowly releasing ammonium, thereby decrease the nitrification rate of ammonium from the N source, and thus resulting in lower N_2O emissions. Consequently, excess N levels in soils may have been balanced out by microbial N immobilization and plant N uptake instead of excessively stimulating nitrification and denitrification processes. However, this expected suppression of emissions was, thus far, not confirmed in field trials (Deppe et al., 2016).

Reduced tillage also contributes significantly to reduction of N_2O emissions. We observed N_2O peaks after tillage operations before and after the growing season. In other field studies, tillage also plays a crucial role in agricultural N_2O emissions (Chatskikh et al., 2005; dos Reis Martins et al., 2022; Krauss et al., 2017). Soil tillage leads to mineralization of soil organic matter by breaking of soil aggregates and aerating the soil, which increases mineral N in the soil, resulting in N_2O emissions via nitrification and denitrification (Li et al., 2015; Parton et al., 2001). In this experiment, no mechanical weed control was carried out throughout the growing period for any of the treatments, potentially reducing overall emissions. In mulched fields, mechanical weed control with cultivators typical in organic vegetable production is not possible due to the mulch layer on top of the soil, which would clog the machinery. This reduces the frequency and overall number of tillage events during the growing period compared to a typical vegetable production system.

Another potential explanation for the overall low cumulative emissions during winter, regardless of treatment, is the weather dynamics during the measurement period. Freeze-thaw events can be a major source of winter N_2O emissions (Maljanen et al., 2007). During the experimental period, the winter was mild, with soil temperatures below 0°C occurring only on two individual measurement days (12/21/2021, 03/03/2022).

Our results align with the scientific consensus, but without knowing the further relevant N species and the microbial communities involved, we cannot determine the underlying N_2O forming pathways from our experiment (Krauss et al., 2017).

4.4. Evaluation of the IPCC emission estimates

N_2O emissions according to IPCC Tier 1 approach were considerably higher than the measured ones. This is remarkable since the presented field measurements include the natural background emissions from soil, which are not considered by the IPCC approach, as it was designed to calculate anthropogenic emissions. Consequently, the actual emissions due to fertilizer addition, mulching and crop residues are even lower than the values given in Table 2. Discrepancies between Tier 1 approach of the IPCC and measurements may be due to the general character of the approach which does not take into consideration different types or application methods of fertilizer (IPCC, 2019). It also does not include soil properties or local climatic conditions in the calculation. The considered emission enhancing N inputs largely stem from the fertilizer. Next to the fertilizer, the mulch material carries large N loads, but the expected N_2O emissions are much higher than the actual emissions for the treatment with mulch, regardless of fertilizer. The composition of the mulch material plays a crucial role in its emission profile (Abalos et al., 2022a, 2022b; Lashermes et al., 2022), which is not considered in IPCC Tier 1 calculations (IPCC, 2006; IPCC, 2019). The treatment without mulch and fertilizer (M-F-) was the only one exceeding the expected N_2O emissions, likely because the estimation model does not include emissions from natural vegetation or the (unfertilized) soil itself that result from soil inherent N sources. For this reason, the entire growing season of the M-F- treatment had an estimated N_2O emission of zero. The emissions from the winter period, with the incorporation of plant residues, were overestimated compared to the actual emissions, however (winter period M-F-: expected: 0.57 kg N_2O ha^{-1}, actual 0.39 kg N_2O ha^{-1}). In commercial practice, there is no cabbage cultivation without some external input of N. Our results indicate that assessing the emission profile of a mulch vegetable system solely on Tier 1 estimates is not sufficient and can vastly overestimate actual emissions from such a system. The IPCC Tier 2 approach is based on national inventories and uses adjusted emission factors based on local climatic conditions and takes previous peer-reviewed publications into account (Mathivanan et al., 2021). Here, the Tier 2 estimated N_2O emissions were lower than the measured N_2O emissions, but closer to the actual value than the Tier 1 approach. The emissions from the treatment with fertilizer and mulch (M+F+) were very close to the expected emissions from the Tier 2 approach. The other treatments had higher measured emissions than expected. Despite basing on more elaborate and local background information, the Tier 2 approach is also a general emission factor, still not considering different crops, fertilizer types, mulch properties and specific local weather conditions. Expected N_2O emissions based on the general IPCC approaches (Tier 1 and 2) are designed to be applicable to all fertilized agricultural land. Considering the importance of fertilizer type, application method, mulch type and composition, as well as climatic conditions such as temperature and rainfall, the IPCC approaches are not suitable to correctly estimate mulch vegetable systems, although the Tier 2 approach is an improvement over the Tier 1 approach. More elaborate approaches including management and environmental factors exist (Novoa and Tejeda, 2006), the practice of mulching, however, is still not properly included in estimation models resulting in over or underestimation of emissions from mulch. More complex models that include type of mulch material and related plant physiological properties are needed to accurately assess the potential emissions from a mulch vegetable system.

4.5. Mulching as a tool to adapt to changing growing conditions

In our experiment, mulching formed a protective organic layer, which effectively buffered soil temperature, through shading and insulation. Temperature regulation can help to create optimal conditions for the plants (Kader et al., 2019). In addition, mulch helped to reduce soil evaporation, which in turn increased WUE. This is crucial for plant health and growth, especially during dry periods when moisture retention is important. Mulching provided a stable environment, resistant to weather fluctuations in which plants can thrive. These benefits could become exceedingly important with the intensifying climate change (Bisbis et al., 2018).

4.6. Ecosystem respiration and methane fluxes

Both fertilization and mulching increased CO_2 emissions. Emissions from mulch are due to the large quantities of C in the material used (5149 kg ha^{-1}). A great portion of CO_2 emissions are produced by indigenous microflora respiration present on mulch material (Flessa et al., 2002). The large quantities of CO_2 emitted from mulch should not be considered a climate threat, as the C released was previously fixed by the preceding crop, thus remaining in the cycle of already present atmospheric CO_2. Fertilization tends to repress CO_2 emissions, rather than increase them (Kowalenko et al., 1978; Wilson and Al-Kaisi, 2008). We found the opposite, potentially due to the type of fertilizer used in this experiment, and the difference in soil water contents due to enhanced plant growth. Soil conditions, such as water contents, temperature and pH are drivers of CO_2 emissions from the soil (Kowalenko et al., 1978).

Soil conditions, such as water contents, also play a crucial role in methane dynamics (Yang et al., 2017). Methane consumption was similar between all treatments, with the treatment with mulch and without fertilizer taking up less than the other treatments. This was also the treatment with the highest soil moisture levels during the growing period, which may have reduced the methane consumption by reducing diffusion of atmospheric methane into the soil (Chen et al., 2011). As the differences were small between treatments, the methane fluxes from mulch as a contribution to climate change can be neglected.

4.7. Shortcomings of this study

We studied greenhouse gas (GHG) fluxes in high resolution, but only weekly, potentially missing peak events. Single freeze-thaw events and resulting emissions may have been missed in the recording, possibly leading to underestimated overall emissions. We measured only during the day, extrapolating emissions for 24 hours, possibly overestimating for nightly emissions. While treatment protocols were consistent, these limitations must be considered when comparing to other studies.

Gas chambers were placed on the fertilization strip, encapsulating more emission prone fertilizer than the rest of the field. This discrepancy could overestimate per-hectare N_2O emissions during the growing period, but relative differences between treatments remain unaffected.

We documented N inputs from fertilizer, mulch, and soil. While we studied various aspects of N dynamics, some parameters like root N, soil organic matter, and specific gaseous emissions were not investigated. A comprehensive understanding requires additionally analyzing these parameters in the mulch vegetable system.

In this study, rye straw with a high C/N ratio was used as mulch material. Our results can therefore not be translated to the practice of mulching as a whole. Other common mulch materials with narrow C/N ratios like clover or other legume species are likely to show different results (Lashermes et al., 2022). Further studies should incorporate several mulch materials with different properties. Our experiment spanned one year. To assess long-term effects, multi-year experiments are necessary.

5. Conclusions

This study investigated the impact of mulching in combination with fertilization on GHG emissions. We found that mulching with material characterized by a high C/N ratio, such as rye, has not only increased soil moisture and cooled the soil, but also did not increase the emissions of N_2O as previously expected from organic mulch material. In the winter, incorporated mulch even reduced fertilizer emissions. Our research suggests that organic mulching, as an innovative but practical application in vegetable cropping, has the potential to adapt to climate change without increasing the negative contributions of agriculture to a changing climate. Further studies are necessary to confirm these findings in other vegetable crops and with other organic mulch materials with different C/N ratios over longer periods of time and in different climatic zones. Additional research is also needed to determine whether mulch has a fertilizing effect and how it affects soil microbial communities. We also conclude that current tools used to inform political stakeholders about GHG emissions from cropping systems must be adjusted to accurately predict N_2O emissions. They should include information on mulch characteristics, such as C/N ratio and material maturity, as well as environmental and soil characteristics.

Funding

We thankfully acknowledge the funding by the 'Europäische Innovationspartnerschaft' (EIP Agri) program and the 'Entwicklungsplan für den ländlichen Raum Hessen 2014 – 2020 (EPLR) for the project 'Mulching vegetables - Economic vegetable cultivation in a natural mulching system'. Further funding was also received by Fachagentur Nachwachsende Rohstoffe (FNR) through the IBAN project (2220NR083A, 2220NR083B). We also thankfully acknowledge the funding by the LOEWE priority program 'GreenDairy – Integrated Livestock-Plant-Agroecosystems' of Hesse's Ministry of Higher Education, Research, and the Arts, grant number LOEWE/2/14/519/03/

07.001-(0007)/80.

CRediT authorship contribution statement

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Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Acknowledgements

Special thanks to Johannes Storch, Maria Barfels, Yannick Salomon, Franz Schulz, Klaus-Peter Franz and the live2give gGmbH for technical assistance and support. We also thank all involved student assistants.

Author contribution

Bryan A. Dix and Michael E. Hauschild contributed equally to this manuscript. All authors have read and agreed to the published version of the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.108951.

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