INTRODUCTION

Oilseed rape (Brassica napus L.) is a major oil crop in Europe, and the harvested area doubled from 2001 to 2018 (FAOSTAT, 2020) following the rise in biodiesel production (Hamelinek, De Loveinfosse, & Koper, 2014). The cultivation of oilseed rape demands high amounts of nitrogen (N) fertilizer, to gain sufficient yield (Hegewald, Koblenz, Wensch-Dorendorf, & Christen, 2016). The harvest index of oilseed rape is low, which results in high N surpluses post-harvest (Sieling & Kage, 2010). The straw residues of wheat or oilseed rape crops are commonly left in fields after the autumn harvest.

Straw amendments did not induce high N₂O emissions in non-frozen wintertime conditions: A study in northern Germany

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Abstract

An increasing area of oilseed rape cultivation in Europe is used to produce biodiesel. However, a large amount of straw residue is often left in the field in autumn. Straw mineralization provides both carbon (C) and nitrogen (N) sources for emission of soil nitrous oxide (N₂O), which is an important greenhouse gas with a high warming potential. Some studies have focused on soil N₂O emissions immediately post-harvest; however, straw mineralization could possibly last over winter. Most field studies in winter have focused on freeze-thaw cycles. It is still not clear how straw mineralization affects soil N₂O emissions in unfrozen wintertime conditions. We carried out a field experiment in northern Germany in winter 2014, adding straw and glucose as a source of C with three rates of N fertilizer (0, 30, and 60 kg N ha⁻¹). During the 26 days of observation, cumulative N₂O emission in treatments without C addition was negative at all N fertilizer levels. Straw addition produced –3.2, 11.2, and 5.0 mg N₂O-N m⁻² at 0, 30, and 60 kg N ha⁻¹, respectively. Addition of glucose surprisingly caused –1.5, 74.6, and 165 mg N₂O-N m⁻² at 0, 30, and 60 kg N ha⁻¹, respectively. This study demonstrates that oilseed rape straw does not cause high N₂O emissions in wintertime when no extreme precipitation or freeze-thaw cycles are involved, and soil organic C content is low. However, N₂O emission could be intensively stimulated, when both easily available organic C and nitrate are not limited and the soil temperature between 0 and 10°C. These results provide useful information on potential changes to N₂O emissions that may occur due to the increased use of oilseed rape for biodiesel combined with less severe winters in the northern hemisphere driven by global warming.

KEYWORDS

glucose, nitrate, nitrous oxide, straw, winter
in wheat-barley-oilseed rape rotation systems in Germany. Mineralization of the straw residues can increase the availability of both soil organic carbon (C) and nitrate (NO$_3^-$) and, in turn, nitrous oxide (N$_2$O) emissions (Senbayram, Chen, Budai, Bakken, & Dittert, 2012; Wu et al., 2018). N$_2$O is a potent greenhouse gas with a warming potential 300 times higher than that of carbon dioxide (CO$_2$) (Intergovernmental Panel on Climate Change, 2013) and is also the most important chemical species in the depletion of atmospheric ozone (Ravishankara, Daniel, & Portmann, 2009).

Several studies have researched how straw residues affected soil N$_2$O emissions in autumn (Carmo et al., 2013; Köbke, Senbayram, Pfeiffer, Nacke, & Dittert, 2018; Pitombo, Cantarella, Packer, Ramos, & do Carmo, 2017). However, straw decomposition is a slow process and possibly lasts over winter (Mary, Recous, Darwis, & Robin, 1996). The behavior of straw decomposition in wintertime is still not clear, especially its effect on soil N$_2$O emission. Soil temperature is a key factor in soil enzyme activity (Shi, Reddy, Chen, & Ge, 2017) and a main cause of fluctuations in nitrification and denitrification processes (Ryden, 1983). Positive correlations between the soil temperature and the emission of N$_2$O have been reported by a number of researchers (Schaufler et al., 2010; Skiba, Sheppard, Macdonald, & Fowler, 1998; Smith, Thomson, Clayton, Mettaggart, & Conen, 1998). Some researchers have linked lower soil temperatures during winter with a lower rate of denitrification (de Klein, van Logtestijn, van de Meer, & Geurink, 1996; Ryden, 1986), although there have been other reports of higher rates of denitrification in winter (Luo, Tillman, & Ball, 2000; Saggar et al., 2004, 2013). Most studies found that pulsed emissions of N$_2$O in winter were linked with distinct freeze-thaw cycles (Flessa, Dörsch, & Beese, 1995; Groffman, Hardy, Driscoll, & Fahey, 2006; Wolf et al., 2010; Yu et al., 2007). However, as a result of global warming, the mean number of frost days in Germany dropped from 97 days in 1951–1960 to 83 days in 2008–2018, while the mean annual temperature increased from 8.2°C (1951–1960) to 9.5°C (2008–2018) (DWD, 2020); thus, northern Germany is more likely to experience non-frozen winters in the future. Most previous studies on straw residues have been carried out at soil temperatures $>10^\circ$C. Microbial respiration and therefore denitrification show different patterns in winter when diurnal temperatures fluctuate below $10^\circ$C (Butterbach-Bahl, Baggs, Dannenmann, Kiese, & Zechmeister-Boltenstern, 2013).

To understand whether oilseed rape residues induce high soil N$_2$O emission and the factors constraining N$_2$O emission from denitrification in non-frozen wintertime, we conducted a field trial and monitored gas fluxes in northern Germany from February 1, to March 4, 2014, with the addition of different C sources (straw and glucose) and three N levels (no added N and 30 and 60 kg KNO$_3$-N). Glucose was applied as a rapid organic C source (Blagodatskaya, Blagodatsky, Anderson, & Kuzyakov, 2007) compared to slowly decomposing oilseed rape straw. We also included different N fertilizer levels for the following reasons: (a) to create different C:N ratios with the additions, because this ratio is an important factor for denitrifying bacteria, and thus for soil N$_2$O emission (Senbayram et al., 2012; Wu et al., 2018); (b) to investigate whether nitrate is a constraining factor on soil N$_2$O emission in non-frozen wintertime; and (c) to avoid N limitations on straw decomposition; it has been reported that mineral N availability is an important factor controlling plant residue decomposition under field conditions (Mary et al., 1996). Our hypotheses were as follows: (a) the addition of glucose would increase CO$_2$ and N$_2$O emissions sharply and (b) the addition of straw would increase CO$_2$ and N$_2$O emissions more slowly and continuously.

2 | MATERIALS AND METHODS

2.1 | Site and soil description

The field experiment was conducted at the Reinhof agricultural research station, University of Göttingen, Lower Saxony, Germany (51°29′50.3″N, 9°55′59.9″E). The mean annual precipitation at this site is 651 ± 24 mm, and the mean annual temperature is 9.2 ± 0.1°C (1981–2010, Göttingen meteorological station, station ID 1691, German Meteorological Service). The soil is classified as a Luvisol (IUSS, 2015), and the topsoil (0–25 cm) consists of 61% silt, 23% sand, and 16% clay (Römer, Hilmer, Claassen, Nöhren, & Dittert, 2015). The bulk density of the soil is 1.29 kg/L, and the soil pH is 7.1 ± 0.1. The total N concentration in the soil is 0.13%, and the total C concentration is 1.3%. The main crops at this site consist of a winter wheat (Triticum aestivum L.)—winter barley (Hordeum vulgare L.)—oilseed rape (Brassica napus L.) rotation system. The previous crop was oilseed rape in 2013, and 180 kg N ha$^{-1}$ urea was applied in spring 2013. During the study period in the winter of 2014, the standing crop was winter wheat at BBCH stage 13–16, when three to six leaves are unfolded.

2.2 | Experimental setup

The main objective was to investigate soil N$_2$O emission in winter, and therefore, the experiment was carried out from February 6, to March 4, 2014. There were three replicate blocks $3 \times 7$ m in size. Each block included nine randomly distributed treatment areas each of a size $1 \times 1$ m. In each block, the treatments included three N fertilizer levels (no fertilizer and 30 and 60 kg potassium nitrate (KNO$_3$)-N ha$^{-1}$) multiplied by three different sources of C (no source of C, straw and glucose). An additional chamber was installed in the adjacent grassland as a reference (ie, the grassland treatment). A sketch map of the plot
distribution and size is presented in Figure 1. The amounts of C and N added for each treatment are detailed in Table 1. The N fertilizers and C sources were added on February 11, 2014.

2.3 | Gas sampling and measurement

The gas samples were collected using the static closed chamber method. A ring frame (diameter 0.35 m, height 0.1 m) was inserted into the soil in each plot, and a cylindrical chamber (diameter 0.35 m, height 0.35 m) was capped onto the ring frame during the measurement. A rubber loop was used to keep the ring frame air-tight. A silicon septum was inserted into the top of the chamber, and a syringe was used to extract the gas samples. The collected gas samples were injected into a 12-ml vacuum Exetainer tube (Labco). The gas samples were collected 0, 20, and 40 min after the chambers were sealed. Gas samples were taken once before fertilizer application, daily after fertilization for 1 week, and every 2 or 3 days in the later periods. Gas samples were therefore collected on 15 occasions.

The gas samples were analyzed in a Model 456 SCION™ gas chromatograph (Bruker), and the concentration of N₂O was determined using an electron capture detector. A thermal conductivity detector was used to determine the concentrations of CO₂. The flux rates were calculated using linear regression of the gas concentration over time (Parkin, Venterea, & Hargreaves, 2012; Wang et al., 2013). Linear interpolation was used to estimate the cumulative N₂O and CO₂ emissions.

2.4 | Soil sampling and measurement

Topsoil (0–15 cm) samples were collected each week for a total of 26 days to determine the soil concentrations of ammonium (NH₄⁺) and NO₃⁻. A Göttinger auger was used to collect the soil samples, with four drills in each plot. Soil samples

![Figure 1: Distribution and size of each block. A chamber was installed as reference in the adjacent grassland. Each number represents the sequence of treatments. See Table 1 for details of the treatment descriptions. The standing crop of the experimental area was winter wheat at BBCH stage 13–16.](image)

| Nr. | Treatments                  | C (kg C ha⁻¹) | N (kg N ha⁻¹) | C:N ratio |
|-----|-----------------------------|--------------|--------------|-----------|
| 1   | No added C                  | 0 N          | 0            | n.a.      |
| 2   | 30 kg KNO₃-N/ha             | 0            | 30           | 0         |
| 3   | 60 kg KNO₃-N/ha             | 0            | 60           | 0         |
| 4   | Added straw (200 kg/ha)     | 0 N          | 864          | 18.6      | 46.5      |
| 5   | (43.2% C and 0.93% N)       | 30 kg KNO₃-N/ha | 864        | 48.6      | 17.8      |
| 6   |                             | 60 kg KNO₃-N/ha | 864        | 78.6      | 11.0      |
| 7   | Added glucose               | 0 N          | 700          | 0         | n.a.      |
| 8   |                             | 30 kg KNO₃-N/ha | 700        | 30        | 23.3      |
| 9   |                             | 60 kg KNO₃-N/ha | 700        | 60        | 11.7      |

Note: n.a.: not applicable; number of replicates = 3.
weighing 50 g were dissolved into 200 ml of 0.0125 M calcium chloride (CaCl$_2$) solution, and the samples were shaken for 1 hr before filtering (MN615 ¼, pore size 4–12 µm; Macherey-Nagel) into small bottles and were then stored at −20°C until analysis. About 50 g of soil was weighed and air-dried to determine the soil water content. The concentrations of NH$_4^+$ and NO$_3^-$ in the extracts were determined on a San++ continuous flow analyzer (Skalar Analytical). To determine the soil pH, 10 g of air-dried soil was dissolved in 50 ml of 0.01 M CaCl$_2$ solution with stirring and the pH was measured directly using a pH meter (Sartorius).

### 2.5 Statistical analysis

All data analyses were performed using the IBM SPSS Statistics 21.0 software package. Cumulative CO$_2$ and N$_2$O emissions were calculated by linearly interpolating the values of CO$_2$ and N$_2$O emissions. For cumulative CO$_2$ and N$_2$O emissions, the homogeneity of variances (Levene's test) and normal distribution (Shapiro-Wilk test) was tested; then, one-way ANOVA was performed to compare the mean values of each treatment and after that Tukey's honestly significant difference (HSD) post-hoc test for pairwise comparison of the treatments with a statistical difference at $p < .05$ and marginal difference at $p < .1$.

### 3 RESULTS

#### 3.1 Climatic conditions

No freeze-thaw cycle occurred in the soil during the period of the experiment. The lowest soil temperature at 5 cm depth was 0.4°C on February 6, 2014, and the highest temperature was 10.9°C on March 4, 2014 (Figure 2a). There was no heavy rainfall, although small amounts of precipitation were recorded on about 60% of the days (Figure 2b). The highest precipitation was 6.2 mm on February 13, 2014. The measured water-filled pore space during the experimental period was 45%–52% (Figure 2b).

#### 3.2 Soil NH$_4^+$-N and NO$_3^-$-N concentrations

The addition of fertilizer increased the soil NO$_3^-$-N concentrations in the 0–15-cm soil profile (Figure 3a,c,e). The soil NO$_3^-$-N concentration in the unfertilized soil (without C, or with the addition of straw or glucose) increased from 3 to 8 kg N ha$^{-1}$ as a result of mineralization. The addition of 60 kg N ha$^{-1}$ fertilizer increased the soil NO$_3^-$-N of the plots with added straw ($p < .03$), and it remained at > 20 kg N ha$^{-1}$ for 1 month after fertilization (Figure 3c), whereas the soil NO$_3^-$-N contents in the plots with added glucose (Figure 3e) were quickly reduced to < 20 kg N ha$^{-1}$ after 10 days and remained lower than the concentrations in the plots without added C ($p < .1$) (Figure 3a) and with added straw ($p < .06$) (Figure 3c) for the full period of the experiment. The peak concentrations of soil NO$_3^-$-N in each group were 42 kg N ha$^{-1}$ (Figure 3a, 60 kg N ha$^{-1}$, without added C, on February 20, 2014), 42 kg N ha$^{-1}$ (Figure 3c, 60 kg N ha$^{-1}$, with added straw, on February 16, 2014), and 31 kg N ha$^{-1}$ (Figure 3e, 60 kg N ha$^{-1}$, with added glucose, on February 12, 2014). The soil NH$_4^+$-N concentration at 0–15-cm soil depth was < 2 kg N ha$^{-1}$ in all treatment plots for the full period of the experiment (Figures 3b, 2d and 2f).
3.3 Dynamics of CO₂ and N₂O emissions

The measured CO₂ emissions include both plant and soil respiration because the gas measurement chamber was opaque. The highest CO₂ emissions were from permanent grassland (Figure 4a,c,e). No obvious difference was found between the addition of 0, 30, and 60 kg N ha⁻¹ for all kinds of added C (Figure 4a,c,e). The emission of CO₂ increased in the plots with 60 kg N ha⁻¹ fertilizer, and the response to fertilization was highest in the plots with added glucose (Figure 4a,c,e) and remained high for about 1 week. The CO₂ emissions were slightly higher in the plots with added straw than in the plots with no added C in the later periods of the experiment (Figure 4a,c).

The N₂O emissions increased slightly after the addition of C and N, but the peaks were very low in the permanent grassland for all kinds of added C (Figure 4b,d,f). N₂O emissions increased dramatically to 8.8 and 27.7 mg d⁻¹ m⁻² on February 16, 2014, with the addition of glucose and 30 and 60 kg N fertilizer, respectively (Figure 4f). The N₂O emissions from the permanent grassland and many of the other treatments were clearly negative on February 16, 2014 (Figure 4b,d,f).

3.4 Cumulative CO₂ and N₂O emissions

The cumulative CO₂ emissions were higher from the grassland than from all other treatments (p < .05) (Figure 5a). N fertilizer levels did not increase the cumulative CO₂ emissions from the plots with all kinds of added C. The addition of straw and glucose resulted in higher cumulative CO₂ emissions than without C addition, but these were not statistically significant.

N fertilization did not increase the cumulative N₂O emissions from the plots without the addition of C nor from the plots with added straw (Figure 5b). However, the cumulative N₂O emissions increased to 75 and 165 mg N m⁻² in the plots with added glucose and 30 and 60 kg N ha⁻¹ fertilizer, respectively (Figure 5b). The cumulative N₂O emissions from the plots without the addition of C were −4, −8, and 0 mg N m⁻² from the unfertilized, 30 and 60 kg N ha⁻¹ fertilized plots, respectively. With the addition of straw, the mean cumulative N₂O emissions from the unfertilized plots were −3 mg N m⁻², but were 11 and 5 mg N m⁻² from the plots with the addition of 30 and 60 kg N ha⁻¹, respectively. There was a tendency toward negative N₂O emissions from the plots without the addition of C, but N fertilization stimulated N₂O emissions when straw was applied to the soil, although the value was low and not significant. The combination of N fertilizer and glucose greatly increased the cumulative N₂O emissions (p < .05).

4 DISCUSSION

4.1 Effect of C source on mineral N

The soil NO₃⁻-N content is decreased by denitrification, leaching, immobilization, and the uptake of N by plants (Mengel, 1999). In our study, the soil NO₃⁻-N content was...
increased by N fertilization and the decrease in the NO$_3^-$-N content of soils was more rapid in the soils treated with glucose than in the soils without the addition of C or with the addition of straw. These differences in the rate of removal of NO$_3^-$-N were probably caused by different rates of denitrification, as a result of the different types of C added. The addition of glucose under laboratory conditions increased denitrification (Gao et al., 2016; Warneke, Schipper, Matiashek, et al., 2011), and denitrification was always limited by the availability of C rather than by the availability of NO$_3^-$-N. The rate of removal of NO$_3^-$-N and the denitrification rate increased linearly with the availability of C (Warneke, Schipper, Bruesewitz, McDonald, & Cameron, 2011). Our study shows that the availability of C was also a limiting factor in denitrification under cold field conditions (<10°C, not frozen). However, the addition of straw did not stimulate high denitrification, indicating that low temperature limits the rate of decomposition of straw (Melillo et al., 1989). Devêvre and Horwáth (2000) showed that the rate of mineralization of wheat straw was halved when the temperature was decreased from 25 to 5°C. The mineralization of straw provides an additional source of N to the soil.

4.2 | CO$_2$ emissions

Our field study in winter showed that the addition of glucose increased CO$_2$ emissions during the first week after application, in agreement with other incubation studies (Blagodatskaya
et al., 2007; Li, Hu, Mao, Zhao, & Zeng, 2015; Nottingham, Griffiths, Chamberlain, Stott, & Tanner, 2009), which indicates higher microbial activity. However, our results also showed that there was no relationship between the emission of CO₂ and the levels of N addition, or a tendency for a decrease in the emission of CO₂ in the soils without added C and/or with the addition of glucose. The cumulative emissions of CO₂ from soils with the addition of 60 kg N ha⁻¹ fertilizer were reduced by 20 and 10% with respect to unfertilized soils without the addition of C and with the addition of glucose, respectively (Figure 4a). Li et al. (2015) reported similar results and showed that excessive N fertilization can be mineralized via the respiration of C or can induce N mineralization (Sterner & Elser, 2002). Although the addition of glucose stimulated denitrification, which also releases CO₂, the emission of CO₂ from soils with the addition of 60 kg N ha⁻¹ was lower than that from unfertilized soils, which indicates that the CO₂ from denitrification was only a small part of the total CO₂ emissions. Considering the decreased emission of CO₂ with an increase in N fertilization, the increased CO₂ emissions from soils with the addition of straw (Figure 4a) were probably caused by the mineralization of the straw. The addition of N decreased the C:N ratio of the soil and a lower C:N ratio stimulated the mineralization of straw (Knorr, Frey, & Curtis, 2005; Li et al., 2015).

4.3 | N₂O emissions

Large seasonal variations have been observed in the N₂O fluxes measured across all ecosystems. It is widely accepted that low soil temperatures limit the emission of N₂O in winter (Saggar et al., 2013) by limiting the activity of microorganisms involved in nitrification and denitrification (Braker, Schwarz, & Conrad, 2010). However, the emission of N₂O from soils in winter varies from very low (Miao, Qiao, Han, Brancher Franco, & Burger, 2014) or even negative (Saleh-Lakha et al., 2009) to very high values of > 40% of the annual emissions of N₂O (Alm, Saarnio, Nykänen, Silvola, & Martikainen, 1999; Maljanen, Hytönen, & Martikainen, 2010; Pfab et al., 2011). Our study represented all three scenarios with the addition of different sources of C.

We found negative N₂O emissions in treatments without the addition of C. It is generally assumed that complete denitrification, which reduces N₂O to N₂, is responsible for the consumption of N₂O (Chapuis-Lardy, Wrage, Metay, Chotte, & Bernoux, 2007) and that microorganisms carrying nitrous oxide reductase (nosZ) are involved in complete denitrification (Bakken & Frostegard, 2017). Nitrifier denitrification also reduces N₂O to N₂ (Wrage-Mönning et al., 2018). Some of our treatments with N fertilizer resulted in negative emissions of N₂O, especially from February 12, to February 17, 2014, when rainfall events occurred. We infer that low temperatures and a higher soil moisture content coupled with a limited source of C drive N₂O consumption. Low temperatures not only reduce microbial activity, but also decrease gas diffusion in soils, which favors complete denitrification and lower N₂O:N₂ ratios (Heincke & Kaufenjohann, 1999). Precipitation increases the water-filled pore space in soils and restricts the availability of O₂, again favoring complete denitrification (Davidson, 1992; de Klein et al., 1996; Rudaz, Wälti, Kyburz, Lehmann, & Fuhrer, 1999). Geng, Chen, Han, Wang, and Zhang (2017) reported that rainfall reduces the stimulatory effect of the addition of N on N₂O emissions.

The addition of both straw and N fertilizer increased the emission of N₂O (Köbke et al., 2018; Wu et al., 2018). We observed small increases in N₂O emissions in the fertilized soils. Using direct N₂ measurement techniques, Wu et al. (2018) found that the addition of straw decreased the N₂O:N₂ ratio, but increased N₂O emissions, probably due to the mineralization of straw enhancing the depletion of oxygen (Pothoff et al., 2005) and the substitution of N source. The increased CO₂ emissions and higher soil NO₃⁻ content in our study (straw + 60 kg N) were additional evidence of straw mineralization and higher microbial activity. The limited accessibility to C, lower N₂O:N₂ ratio, and low temperatures limited N₂O emissions on a small scale. Köbke et al. (2018) also found that the addition of crop residues had only a minor effect on N₂O emissions.

We found a large increase in N₂O emissions after the addition of both glucose and KNO₃. Readily available C serves as a source of energy for denitrification by creating anaerobic conditions for microbial respiration (Beauchamp, Trevors, & Paul, 1989; Bhandral, Bolan, Saggar, & Hedley, 2007; Cayuela, Oenema, Kuikman, Bakker, & Groenigen, 2010). The rapid decrease in soil NO₃⁻ and the occurrence of pulses of CO₂ and N₂O after the addition of glucose were also evidence of higher microbial activity and denitrification. These results also imply an exponential increase in N₂O emissions with N fertilization (Song et al., 2018) and show that the readily available C was not a limiting factor.

4.4 | Implications for environmental protection

Many studies have suggested that high N₂O emissions in winter are a result of freeze-thaw cycles (Lu et al., 2015; Sharma, Szele, Schilling, Munch, & Schloter, 2006; Voigt et al., 2017). The N₂O accumulated in soils during freezing may be rapidly released during the spring thaw (Maljanen et al., 2010). Our results suggest that arable soils in temperate regions may be a sink for N₂O, even with the addition of N fertilizer, when temperatures are < 10°C but above freezing. Pulsed emissions of N₂O have been reported during the growing season after the addition of N fertilizer without additional C (Campanha et al., 2019; H. Chen, Zhou, Li, & Xiong, 2019; Gong, Wu,
The results also show that the availability of C is a major constraining factor in denitrification during winter when soil temperatures are low but not freezing. Our results suggest that oilseed straw was not an evident N$_2$O source, when the freeze-thaw cycle was not involved in wintertime. However, there were some limitations to this experiment: (a) The short-term study showed us that slow straw mineralization provided insufficient organic C for soil denitrification in non-frozen winter, but it was not representative for full-year estimation. In our unpublished data, we also found high N$_2$O emissions at the beginning of March, which might be induced by accelerated straw mineralization over winter. (b) The soil in our study was sandy loam, which had a relatively low concentration of organic C, and therefore also limited denitrification. (c) During the study period, there was no heavy rainfall or other extreme weather conditions. Extreme weather may alter the response of soil respiration (Chen et al., 2017). Future studies should include soil with a high content of organic matter over a longer observation period.

5 | CONCLUSIONS

From our field experiment with addition of straw and glucose, and different N fertilizer levels, we found that in non-frozen wintertime, straw mineralization contributes insufficient organic C for denitrification and N$_2$O emissions; however, microorganisms related to denitrification and N$_2$O emissions were significantly stimulated by the addition of glucose. Our results demonstrate that straw does not induce high N$_2$O emissions in winter under conditions where no freeze-thaw cycles or heavy rainfall events are involved, and there is low soil organic carbon concentration. The study provides some useful information about soil denitrification with the presence of oilseed rape straw in wintertime where soil temperature fluctuates between 0 and 10°C. Notwithstanding these caveats, the removal of straw post-harvest or the growing of cover crops after oilseed rape cultivation is still recommended.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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