Nitrous oxide emissions after incorporation of winter oilseed rape (*Brassica napus* L.) residues under two different tillage treatments

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Abstract

The aim of this study was to investigate the effect of crop residues from winter oilseed rape on N_2O emissions from a loamy soil, and to determine the effect of different tillage practices on N_2O fluxes. We therefore conducted a field experiment where crop residues of winter oil seed rape (*Brassica napus* L., OSR) were replaced with ^{15}N labelled OSR residues. Nitrous oxide (N_2O) emissions and ^{15}N abundance in the N_2O were determined for a period of 11 months after harvest of OSR and in the succeeding crop winter wheat (*Triticum aestivum* L.) cultivated on a Haplic Luvisol in South Germany. Measurements were carried out with the closed chamber method in a treatment with conventional tillage (CT) and in a treatment with reduced soil tillage (RT). In both tillage treatments we also determined N_2O fluxes in control plots where we completely removed the crop residues.

High N_2O fluxes occurred in a short period just after OSR residue replacement in fall and after N-fertilization to winter wheat in the following spring. Although N_2O emissions differed for distinct treatments and sub-periods, cumulative N_2O emissions over the whole investigation period (299 days) ranged between 1.7 kg and 2.4 kg N_2O-N ha^{-1} with no significant treatment effects. More than half of the cumulative emissions occurred during the first eight weeks after OSR replacement highlighting the importance of this post-harvest period for annual N_2O budgets of OSR.

The contribution of residue N to the N_2O emission was low and explained by the high C/N-ratio fostering immobilization of mineral N. In total only 0.03 % of the N_2O-N emitted in the conventional tillage treatment and 0.06 % in the reduced tillage treatment stemmed directly from the crop residues. The ^{15}N recovery in the treatments with crop residues was 62.8 % (CT) and 75.1 % (RT) with more than 97 % of the recovered ^{15}N in the top soil.

Despite our measurements did not cover an entire year, the low contribution of the OSR residues to the direct N_2O emissions shows, that the current IPCC tier 1 approach, which assumes an EF

of 1.00 %, strongly overestimated direct emissions from OSR crop residues. Furthermore, we could not observe any relationship between tillage and crop residues on N_2O emission, only during the winter period were N_2O emissions from reduced tillage significantly higher compared to conventional tillage. Annual N_2O emission from RT and CT did not differ.

1 Introduction

In 2014 the acreage of winter oilseed rape (OSR) in the European Union (EU) was 6.7 x 10^6 ha with an average yield of 3.6 Mg ha^{-1} (*FAOSTAT*, 2017). The production of OSR in the EU increased between 1993 and 2014 by 43.1 % (*FAOSTAT*, 2017). This development was mainly a result of the higher demand for biodiesel due to the Renewable Energy Directive (*RED*, 2009), implying that a share of 10 % of transport energy need is made by biofuels. Rapeseed oil is the most common feedstock for biodiesel, which is the major biofuel in Europe (*Hamelinck* et al., 2012). Cultivation of oilseed rape (including production of fertilizers and agro-chemicals, transportation of the feedstock to a biofuels production plant and the use of fertilizers) as feedstock for biodiesel production in Europe contributes between 75 and 86 % of total GHG emissions (66.7-119.5 g CO_2 MJ_{fuel}^{-1}) (*Hoefnagels* et al., 2010).

N_2O is a climate-relevant trace gas and it is also involved in stratospheric ozone depletion (*Granli & Bøckman*, 1994; *Crutzen*, 1981; *Saggar* et al., 2004). N_2O has a 298 times higher specific heat adsorption potential when compared to the same mass of carbon dioxide (CO_2) (*Mhyre* et al., 2013). In 2015, the atmospheric N_2O concentration was 328 ppb and about 21 % higher than in the pre-industrial era (*WMO*, 2016). More than 50 % of the anthropogenic N_2O is emitted from agricultural soils (*Clais* et al., 2013). The main source for N_2O from agricultural soils is microbial denitrification in soil compartments with low oxygen availability. Nitrification, the microbial oxidation of ammonia to nitrate is a further N_2O source with a probably lower contribution to N_2O emissions from agricultural soils when compared to denitrification (*Flessa* et al., 1996). Apart from these two processes, the share of further N transformation processes in soils is currently under discussion (i.e. *Shaw* et al., 2006; *Butterbach-Bahl* et al., 2013). Since all these processes rely on mineral N as substrate, N-input (N fertilization or N in crop residues) generally increases N_2O emission from soils (*Stehfest & Bouwman*, 2006). Several studies indicated a strong correlation between the mineral N contents of the top soil or the N surpluses with the N_2O emissions from arable fields (*Kaiser & Ruser*, 2000; *Van Groenigen* et al., 2010).

Oilseed rape is known for its high N demand during early growth stages and a low N removal with the seeds resulting in high N surplus which are susceptible to gaseous or leaching losses into the environment (*Rathke* et al., 2006). N uptake by OSR plants ends early (*Malagoli* et al., 2005) whereas mineralization of organic soil N proceeds. As a result, mineral N under OSR is generally high in the harvest period (*Christen & Fried*, 2011).

Leaving crop residues in the field has many positive environmental effects such as nutrient transfer over winter, carbon sequestration, and reduction of soil erosion (*Chen* et al., 2013). On the other hand, adverse effects as i.e. increased N_2O emissions after incorporation of crop residues were reported (*Baggs* et al., 2000; *Chen* et al., 2013). *Moiser* et al. (1998) estimated a global production of 0.4 million tons of N_2O-N yr^{-1} from crop residues.

Winter N_2O emissions can account for 50 % of the annual N_2O emissions if distinct frost/thaw cycles occur during this period (*Kaiser & Ruser*, 2000; *Jungkunst* et al., 2006). *Kaiser* et al. (1998) showed that N_2O emissions during the winter season decreased with increasing C/N-ratio of crop residues.

On the one hand, high C/N-ratios (well above 30) can lead to a short-term immobilization of mineral N and thus reduce the substrate availability for N_2O production. On the other hand, crop residues release easily available C. The turn-over of this C and the associated oxygen (O_2) consumption can lead to anaerobic conditions favoring denitrification and thus stimulating N_2O release (*Flessa & Beese*, 1995). As shown by *Ruser* et al. (2017) NO_3 concentrations in the top soil after OSR harvest slightly decreased but they were obviously still sufficient to enhance N_2O emissions in the post-harvest season at five study sites in Germany. Due to the incomplete immobilization of mineral N it can therefore not generally be assumed that OSR crop residues with a high C/N-ratio reduce N_2O emission. In their meta-analysis, *Chen* et al. (2013) reported slightly positive effects for C/N- ratios between 45 and 100 on N_2O emission from agricultural soils. Even the application of *Miscanthus x giganteus* residues with C/N-ratio of 297 induced N_2O emissions which were significantly higher when compared to a control without crop residues. In all these studies, increased N_2O emissions induced by crop residues with a high C/N ratio were explained with the formation of anaerobic microsites as a result of the short-term availability of easily decomposable C during the decomposition of crop residues thus favoring denitrification and N_2O release (*Li* et al., 2013).

The IPCC's (2006) methodology assumes that 1 % of the residue-N is emitted into the atmosphere as direct N_2O emission within the first year after application. Several investigations reported emission factors (EFs) for crop residues between 0.62 and 2.8 % (*Kaiser* et al., 1998; *Harrison* et al., 2002; *Millar* et al., 2004; *Vinther* et al., 2004; *Novoa & Tejeda*, 2006). The high variability of EFs reported for crop residues was the reason why *Delgado* et al. (2010) suggested adjusting the EF according to the C/N ratio.

Reduced tillage (RT) is defined as abstaining from ploughing, i.e. tillage practise without soil inversion (*Townsend* et al., 2016). Reduced soil disturbances in combination with crop residue retention in the field was shown to be efficient in increasing organic C and N stocks in the uppermost soil layer (*Al-Sheikh* et al., 2005; *Ghimire* et al., 2012), soil erosion control and water conservation (*Krauss* et al., 2017). Results of studies on the effect of tillage on N_2O emissions are contradictory. When compared to conventional tillage, RT reduced N_2O emissions (i.e. *Koga*, 2013; *Wang & Dalal*, 2015), resulted in similar N_2O emissions (i.e. *Abdalla* et al., 2013; *Negassa* et al., 2015) or, which was the majority of experiments, increased emission (i.e. *Baggs* et al., 2000; *Venterea* et al., 2005). *Lognoul* et al. (2017) reported 10 times higher emissions under a seven-year-old reduced tillage system than under conventional tillage. This result was attributed to higher total N and SOC contents, and a larger microbial biomass in the uppermost soil layer, caused by limited digging and mixing of crop residues under RT. Conditions such as increased soil moisture and availability of organic C compounds as energy supplier favour denitrification and they are therefore crucial for N_2O production and release from soils under RT. Similarly, the reason for less aeration inside RT soil could be the presence of higher water-filled porosity thus lowering O_2 diffusion into the soil (*Linn & Doran*, 1984).

The most common tillage method for OSR in Germany is ploughing followed by harrowing but direct drilling is also applied (*Rathke* et al., 2006). Particularly in dry summers, the latter practice has the advantage of conserving soil moisture and therefore it is becoming more popular (*Rathke* et al., 2006). OSR yield seems not to be affected by RT (*Bonari* et al., 1995; *Christen* et al., 2003).

The effect of OSR crops residues on N_2O emissions during the post-harvest period have hardly been investigated, therefore the main hypotheses of this study were: (1) as a result of incomplete immobilization of mineral N after harvest, N_2O emissions are stimulated through OSR crop residues which provide easily available C, which thus favor anaerobic conditions, (2) nevertheless, due to the high C/N-ratio of OSR residues, the emission factor derived from ^{15}N labelling technique of crop residues is lower than the IPCC default of 1 %, and (3) N_2O fluxes from reduced tillage system are higher than from the conventional system after OSR crop residue application.

2 Material & Methods

2.1 Study site

The field site was located on the research station Ihinger Hof (University of Hohenheim), South Germany (48°44'40.7"N, 8°55'26.4"E). The station is located 478 m above sea level, the mean annual temperature is 8.3 °C and the long-term annual precipitation is 738 mm. The soil of the study site was classified as Luvisol (Table 1) with a high silt content. The experiment was conducted from the end of July 2014 to June 2015. Before the trial, the site was used as arable land with OSR (var. Visby) as preceding crop, fertilized with 180 kg N ha^{-1}. In October 2014, winter wheat (*Triticum aestivum* L., var. Julius) was sown as a succeeding crop and fertilized with calcium ammonium nitrate in 3 doses (30, 80, and 55 kg N ha^{-1} at BBCH stages 24, 32, and 61 resp. inflorescence emergence, *Meier*, 2001) in spring to summer 2015.

((Table 1))

2.2 Preparation of ^{15}N labeled crop residues

To label OSR residues with ^{15}N, young plants (BBCH 3) were transplanted from field to pots (volume: 80 l, surface area 0.4 m^2) filled with a mixture of clayey loam and sand (6:4 w:w) and equipped with a closed water circulation system to avoid leaching losses. We chose the same planting density as under field conditions (35 plants m^{-2}, corresponding to 14 plants per pot). ^{15}N enriched potassium nitrate (KNO_3) with 60 atom % ^{15}N was used for fertilization. The N amount used for labeling (180 kg N ha^{-1}, corresponding to 6.8 g N per pot based on the pot surface) also followed field conditions. In order to avoid sulphur (S) deficiency, 90 kg S ha^{-1} (corresponding to 3.4 g S per pot based on the pot surface) was applied as Kieserite ($MgSO_4 \cdot H_2O$). Plants were harvested 15 weeks after transplanting (BBCH 85). The plants were bulked and separated into pod, litter, stem, grain and (washed) roots before oven drying at 60°C. After drying, the different plant parts were roughly cut into 2-6 cm pieces. Separately, aliquots of each part were ground finely to determine the C- and N-concentration, and the ^{15}N abundance with an isotope ratio mass spectrometer (IRMS, Delta C; Finnigan MAT, Germany) coupled with an elemental analyzer (EA 1108; Fisons Instrument, Italy). The final average ^{15}N abundance of the crop residues was 14.4 atom% with a C/N-ratio of 51.7. The share of each plant part and the ^{15}N abundance in each part as well as in the mixture applied to the field is shown in Table 2.

((Table 2))

2.3 Field preparation

The experiment was conducted by inserting into an existing tillage trial (split-plot design, four blocks). Two tillage treatments were applied: ploughed (CT) and reduced (RT). Ploughing was done using a mouldboard plough to a depth of 30 cm. Reduced tillage was done using a chisel plough to a depth of 15 cm. The tillage experiment was initiated in 2012. After harvest of OSR in 2014, two mini plots were placed in each plot of the tillage experiment: one plot without (-CR) and one plot with (+CR) ^{15}N-labeled OSR residues. The size of each mini plot was 0.6 m x 0.5 m. The mini plot area was cleared and free of stubble, and roots of the OSR were removed and replaced against ^{15}N labelled roots. Proper isolation of the residue treated mini plots was maintained by the use of metallic plates. Base-rings of closed chambers were inserted approx. 10 cm deep in the center of each mini plot. Finally, the residual ^{15}N-labelled crop residues (stem, pod, litter, seeds) were mulched and evenly distributed on the surface of the mini plots (total crop residues 455 g plot^{-1} corresponding to 135 kg N ha^{-1}). Simultaneously with the remaining field, tillage measures were carried out at the end of September. To avoid mechanical carriage of the ^{15}N labeled material by tillage machinery, tillage in the mini plots was simulated manually.

2.4 Determination of trace gas fluxes

The N_2O flux measurements were conducted using the closed chamber method (*Hutchinson & Mosier*, 1981). Fluxes were determined weekly in the morning with additional event driven samplings after N-fertilization, strong rainfall and during thawing of frozen soil. As shown by *Flessa* et al. (2002), this sampling strategy significantly reduces the error of a weekly sampling scheme with an error of approximately 10 % when compared to high resolution measurements. The circular, dark vented chambers had an inner diameter of 30 cm and were described in detail by *Flessa* et al. (1995). During the closure period of 45 minutes, we periodically took four gas samples out of the chambers' atmosphere using a syringe and transferred the gas sample into evacuated glass vials (22.5 ml). In order to determine the ^{15}N-N_2O abundance, we took two further samples, after 0 (tn) and 45 minutes (tn+1).

N_2O and CO_2 concentrations in the gas samples were measured with a greenhouse gas analyzer equipped with a ^{63}Ni electron capture detector (ECD) (Scion 450-GC, Bruker) connected to an autosampler (GX-281, Gilson). The software package Compass CDS (Bruker, 2012) was used to calculate trace gas concentrations. For a consortium of gas analyzing laboratories including our lab, *Ruser* et al. (2017) calculated a flux detection limit lower than 22 µg N_2O-N m^{-2} h^{-1} for 90 % of the flux measurements.

^{15}N-N_2O was determined with an Isotope Ratio Mass Spectrometer (IRMS) delta plus (Finnigan MAT, Bremen, Germany) coupled with a fully automated PreCon-Interface for preparing the N_2O from the air sample (*Brand*, 1995).

As described by *Leiber-Sauheitl* et al. (2013) in more detail, N_2O fluxes were calculated with the HMR package (*Pedersen*, 2012) adjusted by a script, created by *R. Fuß*. The script selects automatically the most suitable model for each flux being either a robust linear or a non-linear (HMR) model.

Cumulative emissions of N_2O were integrated per chamber with:

Equation 1:

$$\text{Cumulative } N_2O\text{-N} = \sum_{i}^{n} \frac{(t_{i+1}-t_i)\times(f_i+f_{i+1})}{2}$$

with cumulative N_2O-N in kg ha^{-1}, t = sampling time [h] and f = gas flux [kg ha^{-1} h^{-1}].

The δ values were calculated with following equation recommended by *Tilsner* et al. (2003):

Equation 2:

$$\delta x_{emitted} = \frac{\delta x_{tn+1} \times c\,(N_2O)_{tn+1} - \delta x_{tn} \times c\,(N_2O)_{tn}}{c\,(N_2O)_{tn+1} - c\,(N_2O)_{tn}}$$

with δx = is the value of the heavy isotope x (‰) and c = concentration of N_2O (ppm).

N input related emission factor (NEF) were calculated as

Equation 3:

$$\text{NEF} = \frac{N_2O_{treatment}}{N_{input}} \times 100$$

with NEF in % and cumulative N_2O-N emissions and N-inputs (crop residue and fertilizer N) in kg ha^{-1}.

Crop residue related emission factors (EF_{CR}) were calculated as

Equation 4:

$$EF_{CR} = \frac{N_2O_{CR}}{N_{input}} \times 100$$

with EF_{CR} in % and cumulative N_2O-N emissions emitted by crop residues and N-inputs (crop residue and fertilizer N) in kg ha^{-1}.

2.5 Soil sampling, laboratory analyses and weather conditions

Soil samples were taken four times during the experimental period to determine the mineral nitrogen content (N_{min}). Due to the small area of the mini plots, a more frequent sampling design was not possible. In the CT plots samples were taken from 0-30 cm depth, in the RT plots we sampled soil from 0-15 cm and from 15-30 cm. For N_{min} analysis, 20 g of fresh soil was extracted with 80 ml of 0.0125 *M* $CaCl_2$ solution. The concentrations of NH_4^+-N and NO_3^--N were quantified using a fully automated flow injection analyzer (FIAstar 5000, FOSS, Denmark).

Soil moisture was determined gravimetrically by drying an aliquot of fresh soil at 105°C for 24 h. The calculation of the water-filled pore space (WFPS) was explained in detail by *Ruser* et al. (1998). In addition, the volumetric water content of the soil was measured in the field simultaneously to the gas measurement in every plot using a mobile soil water monitoring probe (EasyTest FOM/mts, Lublin, Poland). These measurements were carried out as long as the soil was not too dry or frozen thus impeding the use of the probe.

^{15}N abundance in the NH_4^+ and NO_3^- pool was determined using a diffusion procedure according to *Brooks* et al. (1989). For the diffusion method, the $CaCl_2$ extract from N_{min} analysis was used. Isotope Ratio Mass Spectrometer (delta plus, Finnigan MAT, Bremen) coupled with a CN elementar analyzer (Euro EA, Eurovector, Milano, Italy) was used to determine ^{15}N abundance in N_{min} fractions.

Air temperature and precipitation were provided by the climate station of the research station.

2.6 Plant sampling

At the end of the experiment, aboveground wheat biomass on the mini plots was harvested on May 26th 2015. Plants were dried at 60°C for 48 h. An aliquot was ground and C- and N-contents were determined with a CN elementar analyzer (VarioMax, Elementar Analysensysteme GmbH). A further aliquot was used to measure the ^{15}N enrichment of the wheat.

The percentage of recovery of ^{15}N in soil or plant was calculated according to *Hauck and Bremner* (1976).

Equation 5:

$$^{15}N_{RCE} = 100 \times \frac{p \times (c-b)}{f \times (a-b)}$$

Where p is the total N in soil or plant (kg N ha^{-1}), f the total amount of ^{15}N applied with the crop residues, a the ^{15}N abundance in the crop residues [atom%], b the ^{15}N abundance in the treatments without crop residues (unlabeled) and, c the ^{15}N abundance in soil or plant samples.

2.7 Statistical analyses and further calculations

Cumulative N_2O emissions were divided in three periods: post-harvest period from harvest to tillage (31.07.14 – 01.10.14), winter period (02.10.14 - 02.03.15), and vegetation period (03.03.15 – 29.05.15). For comparison of the cumulative N_2O emissions, an ANOVA was performed using the PROC MIXED procedure by SAS 9.4 (SAS Institute, 2016). For N_2O emissions over time, repeated measures of ANOVA were performed using the PROC MIXED procedure, with an autoregressive AR(1) covariance structure to acknowledge for proximate correlation.

The models for N_2O were as follows:

(1) $\mu_{ij} = \mu + \alpha_i + \beta_{j1} + (\alpha \times \beta)_{ij} + (\gamma_{ij1} \times \beta_j) + \delta_{ij}$

(2) $\mu_{ij} = \mu + \alpha_i + \beta_{j2} + (\alpha \times \beta)_{ij} + (\gamma_{ij2} \times \beta_j) + \delta_{ij}$

with μ= general effect, α= CR (crop residues), β= tillage, γ= WFPS, and δ= CO_2

WFPS and CO_2 were entered as covariants. CO_2 x CR and CO_2 x tillage were not significant and removed from the model.

The model for CO_2 was as follows:

$\mu_{ij} = \mu + \alpha_i + \beta_j + \delta_{ij}$

with μ= general effect, α= CR (crop residues), β= tillage, δ= CO_2

WFPS was entered as covariant. WFPS x tillage were not significant and removed from the model.

Tests for normality and homogeneous variance were performed graphically. Natural log-transformation (*Parkin & Robinson*, 1993) of the N_2O and CO_2 emissions data was carried out prior to the analysis of variance. LSMEANS were calculated and compared with an LSD-test at $\alpha = 5$ %. Ln Daily flux standard deviations were back transformed with the delta method.

3 Results and discussion

3.1 Weather conditions

Several heavy rainfalls (>10 mm d^{-1}) occurred during the first four weeks of our measurements (Figure 1a). The first heavy rainfall within this period occurred with approximately 12 mm d^{-1} two days after surface application of the residues. Highest daily amount of rainfall within the whole investigation period was measured on August 26th (40 mm d^{-1}). With the beginning of the vegetation period in 2015, distinct phases without precipitation (two weeks or longer) were followed by intense rainfall events in March, April and May.

Although mean air temperature dropped on two occasions below 0°C for a longer period in winter, no permanent frost was recorded in 5 cm soil depth (Figure 1a). The first frost period with mean daily air temperature below zero occurred at the end of December 2014 and lasted five days. A second pronounced frost was measured for a period of 10 days at the beginning of February.

The precipitation in the whole experimental period (July 2014 to May 2015) was 776 mm (Figure 1a). It was higher than the long-term mean in this period (620 mm).

((Figure 1))

3.2 Trace gas fluxes

3.2.1 Temporal nitrous oxide flux dynamics

Figure 1b shows mean N_2O fluxes during the study period. Increased N_2O fluxes were measured immediately after crop residue application in conjunction with precipitation (Figures 1a, 1b). Except for two sampling dates at the end of August, the N_2O fluxes increased for more than two months and showed a similar course to the CO_2 fluxes (Figure 1c). In the period between the beginning of the experiment and the end of September 2014 we found a positive correlation between N_2O and CO_2 flux rates ($r = 0.54$, $p < 0.001$, $n = 4$, Pearson correlation).

Such an increase in N_2O release after crop residue application has frequently been observed (*Flessa & Beese*, 1995; *Baggs* et al., 2003; *Millar & Baggs*, 2004). Amendment of crop residues provides easily available labile carbon and nitrogen as substrates which in turn can increase the microbial activity in the soil. Resulting rapid oxygen consumption by microbes during respiration decreases the redox potential and thus favours conditions for denitrification (*Flessa & Beese*, 1995; *Azam* et al., 2002; *Miller* et al. 2008).

In the first two weeks after residue application, CO_2- and N_2O-fluxes from the treatments with crop residues were significantly higher compared to the treatments without crop residues (Figure 1b). By the beginning of September, the higher fluxes were measured in the CT – CR treatment.

This result confirmed observations from a laboratory experiment on the effect of OSR residues with different C/N-ratios on N_2O fluxes from the topsoil of our study site (*Herr*, 2015). After an initial phase where OSR residues stimulated N_2O release, the N_2O emissions decreased below emissions from a treatment without crop residues indicating a microbial immobilization of mineral N as a result of the wide C/N-ratio. Several further studies indicated a net NO_3^- immobilization after application of crop residues with high C/N-ratios (*Chaves* et al., 2007; *Kaewpradit* et al., 2008; *Chen* et al., 2013). Immobilization therefore reduces the availability of mineral N which serves as substrate for microbial N_2O production in soils and thus decreases N_2O emissions (*Huang* et al., 2004).

In the RT + CR treatments we could not observe any mineral N immobilization effect of crop residues on N_2O fluxes (Figure 1b) in September; the fluxes were as low as in the treatment CT+CR and the reason for this phenomenon remained unclear.

After tillage, N_2O fluxes were low until the beginning of December. Low soil moisture contents below 60 % WFPS did not allow for anaerobic conditions necessary for denitrification (*Dobbie* et al., 1999; *Skiba & Ball*, 2002; *Batemann & Baggs*, 2005).

Frost-thaw events occurred between December and March resulting in moderate but steadily elevated N_2O fluxes up to 50 µg N_2O-N m^{-2} h^{-1} which was considerably higher than the background emission in late autumn. These increased background fluxes during winter are in accordance with other studies, whereas we did not measure pronounced flux peaks during thawing of frozen soil (*Flessa* et al., 1995; *Röver* et al., 1998; *Kammann* et a., 1998; *Kaiser &*

Ruser, 2000). The absence of pronounced N_2O pulses during thawing may be explained by the short durations of the frost periods and by the mild temperature conditions. It was shown that N_2O pulses during thawing of frozen soil increase with increasing duration of frost periods and with severity of the soil freezing (*Teepe* et al., 2004; *Risk* et al., 2013; *Xu* et al., 2016).

At the end of winter, in the middle of March, N_2O emissions declined to the background level. N_2O emissions after fertilization were influenced by rainfall events. The highest mean flux in this period was measured with 175 µg N_2O-N m^{-2} h^{-1} in the RT + CR treatment following two precipitation events with 20 and 10 mm d^{-1} at the beginning of May.

High fluxes after N-fertilization and rainfall are usually explained by enhanced denitrification due to the increased availability of nitrate as substrate for N_2O production and anaerobic conditions as a result of increased soil water contents (*Flessa* et al., 1995; *MacKenzie* et al., 1997).

We did not find significant effects of the treatments on median daily flux rate either of the crop residues ($p = 0.78$) or of the tillage treatment ($p = 0.57$) and WFPS ($p = 0.41$).

There was a strong correlation ($p < 0.0001$) between CO_2 fluxes and N_2O fluxes. This indicated heterotrophic microbial denitrification as a main N_2O source during the investigated period. The C availability is an essential factor controlling denitrification (*Knowles* 1982; *Beauchamp* et al., 1989), directly by increasing the energy and electron donator for denitrifiers, and indirectly through enhanced microbial growth thereby stimulating high O_2 consumption (*Beauchamp* et al., 1989; *Garcia-Montiel* et al., 2003, *Gillam* et al., 2008).

3.2.2 Cumulative N_2O emission

Total cumulative N_2O emissions over the whole measuring period varied from 1.7 to 2.4 kg N_2O-N ha^{-1} with no significant differences between the treatments (Figure 2). Although our measurement period covered only 299 days, the order of magnitude of cumulative emissions was similar to annual emissions reported from OSR fields (*Ruser* et al., 2017) as well as from other arable crops (*Jungkunst* et al., 2006).

Between 50-68 % of total N_2O emission was released during the post-harvest period covering only two months, highlighting the importance of that period for N_2O budgets in OSR production. Soil tillage did not affect the emissions in this period.

A high share of post-harvest N_2O emissions to the total annual N_2O loss was also reported from *Ruser* et al. (2017) who measured trace gas fluxes at five study sites representative for German winter oilseed rape production. They explained the high post-harvest emissions with increased nitrate contents combined with O_2 consumption during the turn-over of the OSR residues thus favoring N_2O release from denitrification.

Due to the mild winter conditions this period accounted for only 18-28 % of the total emission. In this period, N_2O emission from the reduced tillage system was significantly higher than from the conventional treatment.

Higher N_2O fluxes under reduced tillage were often observed (e.g. *Johnson* et al., 2005; *Venterea* et al., 2005), particularly in the first years after transition from conventional to reduced tillage (*D'Haene* et al., 2008). The reason for the higher emission was the often reported higher soil moisture in RT systems favouring denitrification (*Aulakh* et al., 1984; *Staley* et al., 1990; *Palma* et al., 1997; *MacKenzie* et al., 1997). Our results confirmed these earlier observations since soil moisture in the RT treatments were predominantly higher when compared to the CT treatments (Figure 1d).

((Figure 2))

The share of the N_2O emission during the vegetation period (of the succeeding winter wheat) to the total emission varied between 14-32 % (Figure 2). Crop residues stimulated N_2O emission during the subsequent cropping season. This effect was significant in the RT treatment (p = 0.03) and appeared in tendency in the CT treatment. CO_2 fluxes in this period showed the same trend but since we used dark chambers and therefore could not differentiate between soil respiration and dark respiration from photosynthesis of the plants within our chambers, we do not present this data, although aboveground wheat biomass was apparently similar in all investigated plots. We assume that this crop residue effect on N_2O emissions during the succeeding cropping season of wheat in the RT+CR treatment was induced by mineralisation of the OSR residues which was indicated by an increase ^{15}N abundance (%) in the nitrate pool between May and June (Table 3). In contrast there was no change of the ^{15}N abundance in the nitrate pool of the CT+CR treatment in the same period. Consequently, this effect did not occur in the CT+CR treatment. The reason for different crop residue response in this period remained unclear; the slightly drier conditions in the CT+CR treatment might have contributed here.

((Table 3))

3.3 Contribution of crop residue N to N_2O emission and ^{15}N recovery

Only 4.2 % in CT+CR and 5.2 % in RT+CT (no significant difference) of the N released as N_2O during the investigated period stemmed directly from the applied OSR crop residues. N_2O production from crop residue N occurred mainly in the first two months before tillage (Figure 3). This corresponds with *Baggs* et al. (2000) who found 65 % of the measured N_2O emissions during two weeks after crop residues incorporation. We interpret this as rapid stimulation of microbial decomposition of the residues (*Shen* et al., 1989) related with anaerobic conditions resulting from microbial respiration which was in connection with the increased C supply as substrate for denitrification favoring higher N_2O emissions.

Table 3 shows the mean soil N_{min} (NH_4^+ and NO_3^-) contents of the treatments, as well as the share of ^{15}N N_{min}, from the + CR treatments. N_{min} values were similar in the + CR treatments. In May the content was highest with approx. 88 kg N ha^{-1} after N-fertilization. The highest share of the crop residue N calculated from $^{15}NH_4^+$ and $^{15}NO_3^-$ was measured in December with 4.8 % in the CT treatment and 6.3 % in the RT treatment. In spring and early summer, the share of crop residues dropped down to approx. 1.0 % in CT+CR and 1.7 % in RT+CR. This low contribution of ^{15}N to the total mineral N explained the low share of ^{15}N-N_2O in the N_2O fluxes.

((Figure 3))

The low contribution from crop residues on total N_2O emissions presumably resulted from the wide C/N-ratio of the OSR crop residues. *Pfab* (2011) reported that 38 % of the total N_2O emission stemmed directly from cauliflower residues as a contrasting material (C/N-ratio: 10.4).

The total ^{15}N-recovery rate after the experimental period (Table 4) was 65.0 % (CT) and 75.1 % (RT) respectively. Since N losses from crop residue as N_2O were low (0.06 and 0.09 % of N added, Table 4) main pathways for N losses were presumably over the leaching pathway (NO_3^- or as dissolved organic N) or gaseous as NH_3, NO or elemental N_2. Other field studies found similar recoveries covering ranges between 60 % and 85 % (*Jensen* et al., 1997; *Garza* et al., 2009; *Zhang* et al., 2010). Most of the applied ^{15}N was found in soil (97 %). We assume that the main reason for the high portion of soil-N to the total recovery of the ^{15}N applied was the slow turnover of the high C/N-ratio crop residues as a result of immobilization. In an incubation experiment, *Trinsoutrot* et al. (2000) indicated N immobilization after incorporation of low N OSR crop residue material even 186 days after application of the residues.

((Table 4))

The main proportion of the ^{15}N recovery after termination of the measurements in June was found in the soil fraction (Table 4). This suggests that most of the crop residues were not completely mineralized at that time and that there was still potential for N_2O emission from that source in consecutive years. *Jensen* et al. (1997) found approx. 90 % of the total soil N, resulted from the incorporated ^{15}N rapeseed straw (C/N-ratio 80), after seven months, indicating that there was no loss of straw N during winter, supporting our results.

The total N-input in +CR treatments was 245.3 kg and in –CR treatments 110 kg N ha^{-1}. The N input related emissions factors (NEF) are shown in Table 5. The NEF of 1.84 and 1.57 % respectively from the treatments without crop residues were distinctly higher compared to the NEF of 0.77 and 0.98 % respectively from treatments with crop residues. These results supported the assumption of immobilization effect due to OSR crop residues. The calculated NEF are within the range of 0.3 to 3 % suggested by the IPCC (2006) for N-input related direct N_2O emissions.

Due to the ^{15}N labeling it was possible to calculate a separate emission factor for the crop residues. The EF_{CR} were very low with 0.03 (CT) and 0.05 % (RT) (Table 5). Here the IPCC (2006) is overestimating the share of OSR crop residues.

((Table 5))

4 Conclusions

Despite a stimulating effect of crop residues in the RT+CR treatment over the vegetation period after crop residue incorporation, N_2O emission was not affected over the total experimental period. Therefore, our first hypothesis that crop residues increase N_2O emissions must be declined. In contrast, our second hypothesis of a low emission factor (EF) for OSR crop residues due to a high C/N-ratio was confirmed. The low EF from the crop residues was overcompensated by the obviously high EF from mineral N fertilization of the succeeding wheat crop, thus resulting in EF within the range of the IPCC Tier 1 approach when related to the total N-input.

From the low direct contribution of crop residues to N_2O emission during the post-harvest period we conclude that the increased N_2O fluxes after OSR harvest reported in other studies were predominantly a result of increased N_{min} contents already apparent during the harvest period (1) due to the early ending of N uptake by OSR and (2) due to proceeding soil N mineralization increasing the N_{min} pool.

Furthermore, we found higher N_2O emissions in the RT treatment in the winter period but due to the low contribution of the winter fluxes to the total cumulative N_2O emission this effect was not significant for the entire investigation period. Consequently, we had also to decline our third hypothesis of higher N_2O emissions in the RT system.

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Table 1:

Soil chemical and physical characteristics of the experimental site.

Soil depth	Organic C	Organic N	pH[$]	Sand	Silt	Clay
cm	mg C kg^{-1}	mg N kg^{-1}			%	
0-30	16.8	2.0	6.8	3.2	78.2	18.6
30-60	9.2	1.2	7.0	3.2	77.3	19.5
60-90	5.3	0.7	7.1	7.0	64.3	28.7

[$]pH 0.01 *M* $CaCl_2$

Table 2:

Proportions of the plant parts and their ^{15}N abundance in the mixture of the OSR crop residues applied to field.

Plant part	Amount [g plot $^{-1}$]	Proportions of the mixture [%]	^{15}N abundance [atom% ^{15}N]
Root	50	11.0	9.7
Pod	100	22.0	22.6
Litter	165	36.3	12.3
Stem	130	28.6	12.1
Seed	10	2.1	22.5
Total	455	100	14.4

Table 3:

Mean N_{min} content (± SE) and share of ^{15}N-N_{min} in ^{15}N crop residue amended treatments, conventional tillage (CT) in 0-30 cm and reduced tillage (RT) subdivided into 0-15 and 15-30 cm with (+CR) and without (-CR) crop residue return.

Treatment	Date	depth	N_{min}		^{15}N-N_{min}		
		cm	kg N ha^{-1}	SE	kg N ha^{-1}	SE	%
CT + CR	09.09.2014	0-30	32.0	1.6	1.1	0.4	3.5
	02.12.2014	0-30	31.3	3.3	1.5	0.1	4.8
	12.05.2015	0-30	88.7	25.3	0.8	0.2	0.9
	02.06.2015	0-30	48.3	10.3	0.5	0.1	1.0
RT + CR	09.09.2014	0-30	26.0	0.8	1.4	0.2	5.5
	02.12.2014	0-15	12.7	1.7	1.0	0.1	7.7
		15-30	14.3	1.5	0.7	0.2	4.9
		∑	27.0		1.7		6.3
	12.05.2015	0-15	52.8	5.4	0.6	0.1	1.2
		15-30	34.7	10.7	0.2	0.0	0.6
		∑	87.5		0.8		0.9
	02.06.2015	0-15	23.3	1.7	0.3	0.1	1.1
		15-30	16.1	2.6	0.2	0.1	1.3
		∑	29.4		0.5		1.7
CT – CR	09.09.2014	0-30	28.6	2.3			
	02.06.2015	0-30	105.7	9.4			
RT – CR	09.09.2014	0-30	11.8	0.7			
	02.06.2015	0-30	36.0	9.5			

Table 4:

^{15}N recovery ($^{15}N_{RCE}$) of ^{15}N- crop residues under conventional tillage (CT+CR) and reduced tillage (RT+CR) in N_2O-N, biomass (winter wheat) and soil.

Treatment	N_2O-N	Biomass*	Soil$^{\$}$	$\sum^{15}N_{RCE}$
		%		
CT + CR	0.06	2.2	62.8	65.0
RT + CR	0.09	2.1	72.9	75.1

*aboveground biomass + roots; $^{\$}$plough layer 0-30 cm.

Table 5:

N_2O emission factor for total N-input (NEF) and separately for crop residues (EF_{CR}).

Treatment	NEF	EF_{CR}
	[%]	
CT + CR	0.77	0.03
CT – CR	1.84	-
RT + CR	0.98	0.05
RT – CR	1.57	-

Figure captions

Fig. 1: Daily precipitation, mean daily air and soil temperature (a), mean N_2O flux rates (n=4; ± SE) (b), mean CO_2 flux rates (c), and mean water-filled pore space (WFPS %) (d) as affected by soil tillage and crop residue amendment during the investigation period.

Fig. 2: Mean cumulative N_2O emission (n=4) divided into post-harvest, winter and vegetation periods as affected by soil tillage and crop residue amendment. Different letters indicate statistical significant differences between treatments within one measuring period (Tukey-Test; $p < 0.05$).

Fig. 3: Mean cumulative N_2O emission as affected by tillage (CT and RT) and crop residue (+ CR and – CR) (left Y-axis) and ^{15}N-N_2O emissions from labelled crop residues (n=4, mean ± standard error) (right Y-axis).

Figure 1

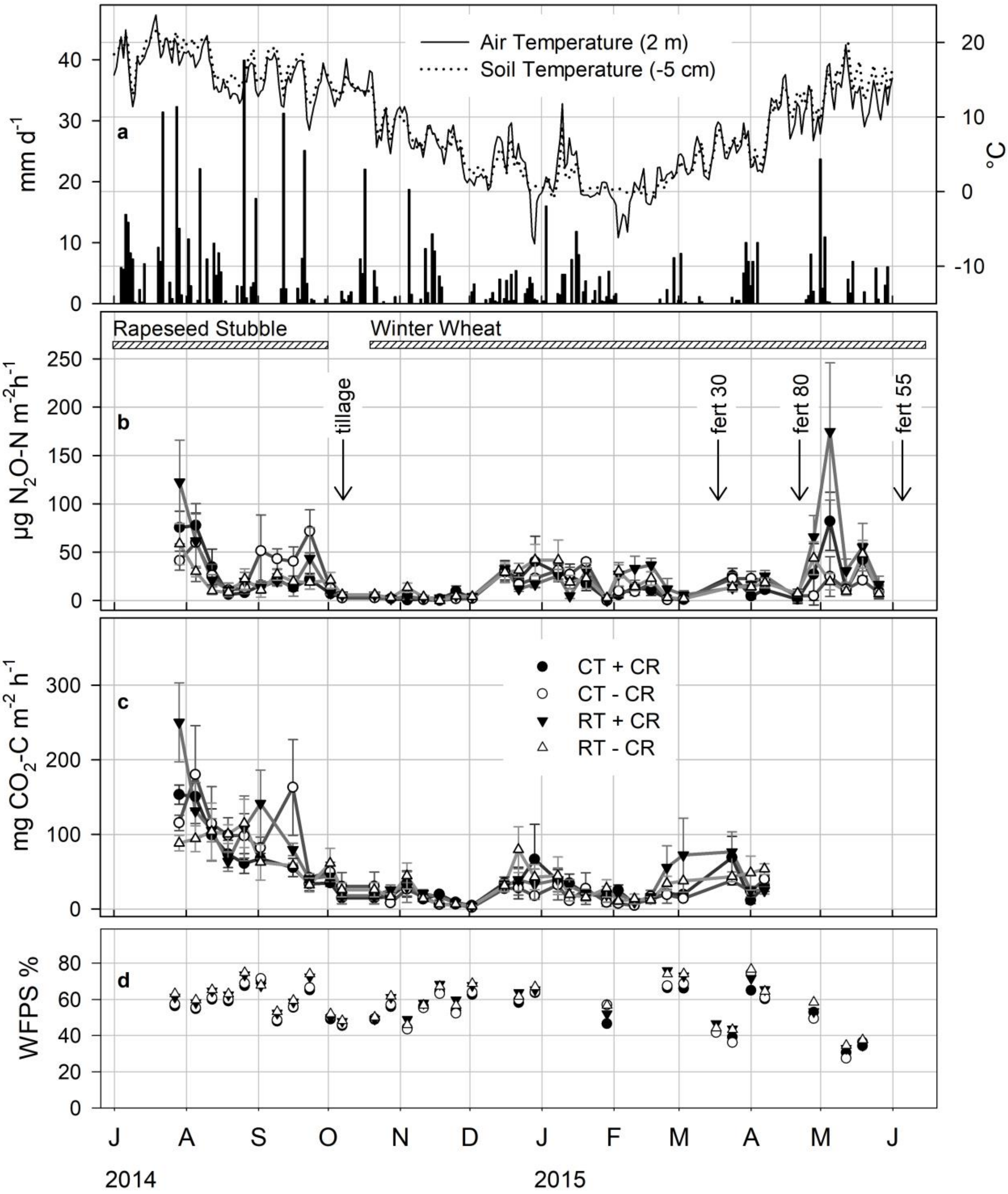

Air Temperature (2 m)
Soil Temperature (-5 cm)
a
mm d^{-1}
°C
Rapeseed Stubble
Winter Wheat
b
µg N$_2$O-N m^{-2}h^{-1}
tillage
fert 30
fert 80
fert 55
c
mg CO$_2$-C m^{-2} h^{-1}
CT + CR
CT - CR
RT + CR
RT - CR
d
WFPS %
J A S O N D J F M A M J
2014
2015

Figure 2

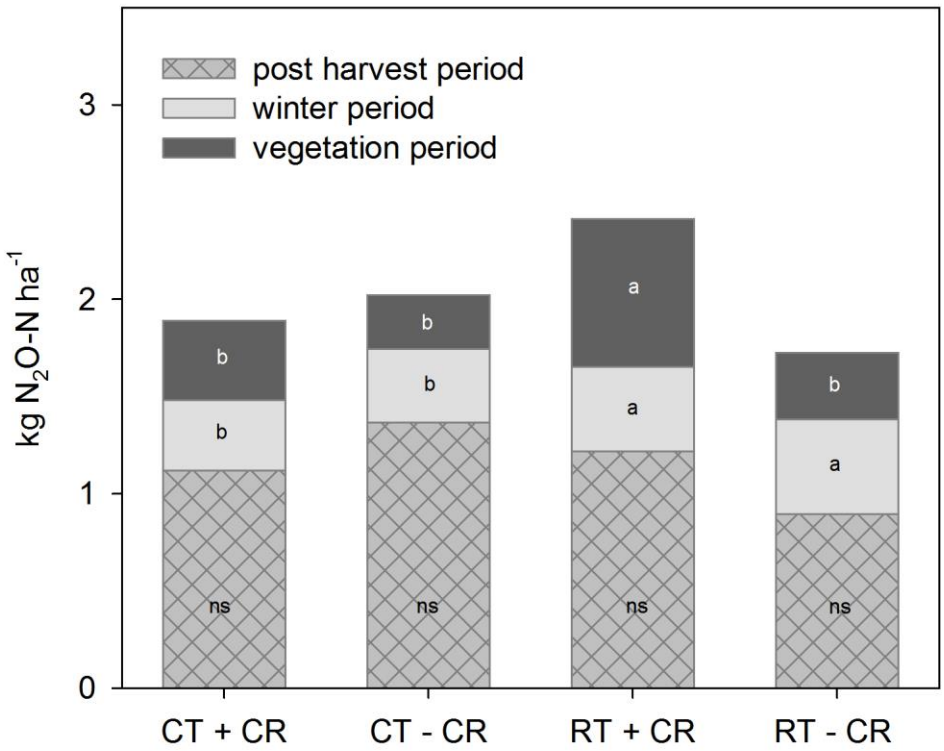
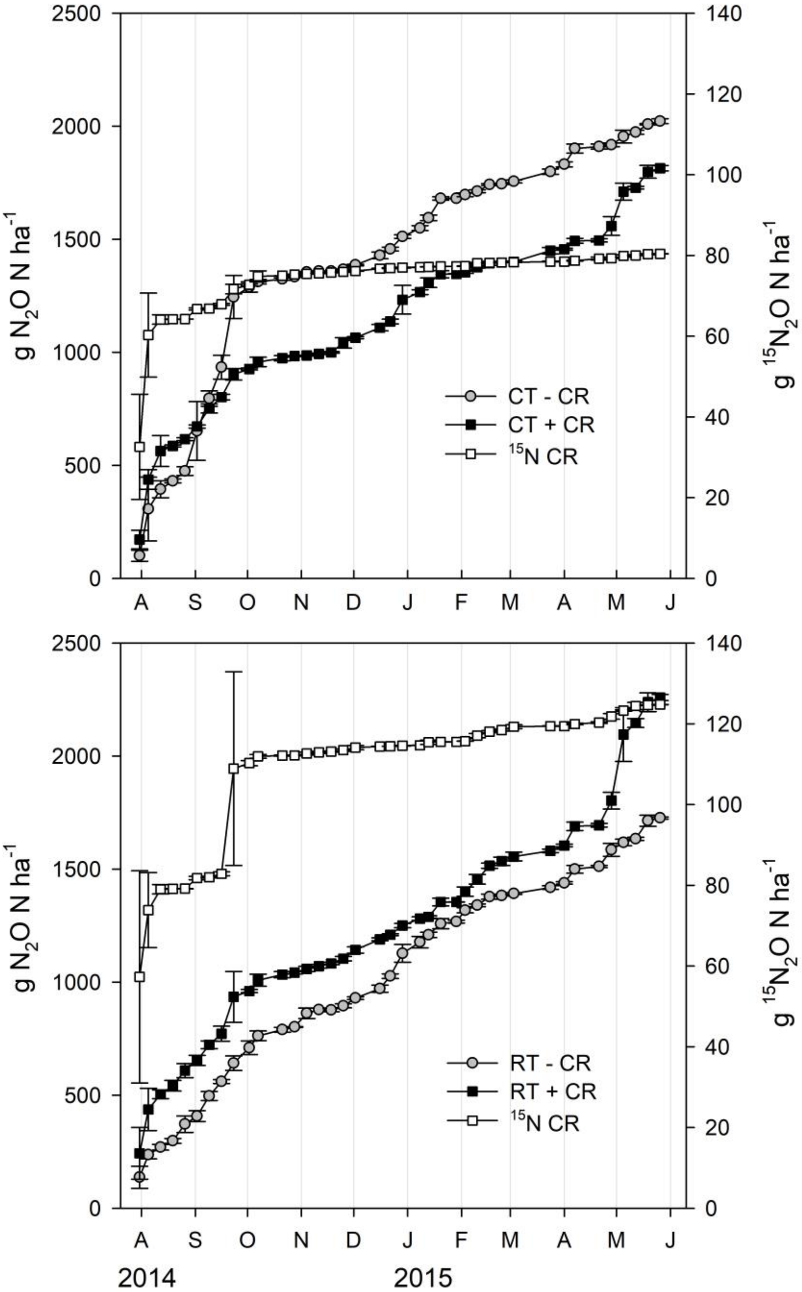

post harvest period
winter period
vegetation period
kg N_2O-N ha^{-1}
0
1
2
3
b
b
ns
b
b
ns
a
a
ns
b
a
ns
CT + CR
CT - CR
RT + CR
RT - CR

Figure 3


g N2O N ha-1
g 15N2O N ha-1
CT - CR
CT + CR
15N CR
RT - CR
RT + CR
15N CR
A
S
O
N
D
J
F
M
A
M
J
2014
2015