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Nitrous oxide emissions as influenced by amendment of plant residues with different C:N ratios

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Abstract

To investigate the influence of plant residues decomposition on N₂O emission, laboratory incubations were carried out for a period of 21 days using urea and five plant residues with a wide range of C:N ratios from 8 to 118. Incorporation of plant residues enhanced N₂O and CO₂ emissions. The two gas fluxes were significantly correlated ($R^2 = 0.775$, $p < 0.001$). Cumulative emissions of N₂O and CO₂ were negatively correlated with the C:N ratio in plant residues ($R^2 = 0.783$ and 0.986 for N₂O, and 0.854 for CO₂, respectively). A negative relationship between the N₂O–N/NO₃[–]–N ratio and the C:N ratio was observed ($R^2 = 0.867$) when residue plus urea was added. We calculated the changes in dissolved organic C (DOC) and the relevant changes in N₂O emission. The incorporation of residues increased DOC when compared with the control, while the incorporation of residue plus urea decreased DOC. Cumulative emissions of N₂O and CO₂ were positively correlated with DOC concentration measured at the end of the incubation. In addition, the N₂O emission fraction, defined as N₂O–N emissions per unit N input, was not found to be a constant for either residue-N or urea-N amendment but dependent on C:N ratio when plant residue was incorporated.

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1. Introduction

Nitrous oxide (N₂O), produced naturally in soils through the microbial processes of nitrification and denitrification, causes global warming and stratospheric ozone depletion. Model calculations suggest that atmospheric N₂O may approach a value ranging from 354 to 460 ppb by 2100, compared with the present concentration of 316 ppb (IPCC, 2001). Annual anthropogenic emissions to the atmosphere are estimated to be 3–8 Tg N and recent estimates suggest that agricultural systems impart a large portion of anthropogenic emissions (Mosier and Kroeze, 1998). To meet the food demand for the growing population worldwide, application of synthetic fertilizer has increased rapidly. The consumption of synthetic

fertilizer N in Asia, for example, is estimated to increase approximately 50% by 2030 (Zheng et al., 2002), which will most likely be accompanied by a proportional increase in N₂O emissions.

Several parameters have been identified that affect the rate of N₂O emission from agricultural system, including N supply (Bouwman, 1996; Brown et al., 2000; Maggionto et al., 2000), temperature (Goodroad and Keeney, 1984; Castaldi, 2000), pH (Daum and Schenk, 1998; Mogge et al., 1999) and soil moisture (Dobbie et al., 1999; Zheng et al., 2000). As a practical manner to improve soil fertility, amendment of local organic residues has been gaining worldwide support. Incorporation of crop residues provides a source of readily available C and N in the soil, and subsequently influences the CO₂ and N₂O emissions (Flessa and Beese, 1995; Cochran et al., 1997; Lemke et al., 1999). The residue type was thought to be an important factor affecting N₂O emission (Aulakh et al., 1991; McKenney et al., 1993; Shelp et al., 2000). Although the amount of N that recycles into agricultural fields through residues may add 25–100 Tg N yr^{–1} into agricultural soils

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(mainly from crop residues) the amount converted to N_2O is unknown (Mosier and Kroeze, 1998), because the quality of residues (usually low) used by farmers is largely undocumented. This has been analyzed implicitly by comparing studies where different residues have been used (e.g. McKenney et al., 1993).

Mineralization of plant residues and thus the N_2O emission was found to be dependent on C:N ratio of the residues (Eichner, 1990; Aulakh et al., 1991; Németh et al., 1996). An earlier study conducted by Patten et al. (1980) demonstrated that the rate of denitrification was dependent on the quantity of organic C readily utilized by denitrifying microorganisms, while the organic C in various pools is not completely available to microorganisms. As a specific fraction of soil organic C, the dissolved organic carbon (DOC) represents easily degradable and available to microorganisms (Boyer and Groffman, 1996; Yano et al., 1998). The influence of crop residue type and related quality (C, N, or lignin content, and C:N and lignin:N ratios) on residue decomposition has been well documented (e.g. Heal et al., 1997). However, few studies have been dedicated to associating N_2O emission with soil DOC in relation to residue decomposition. Furthermore, quantification of the N_2O derived from synthetic N and/or from organic N is still far from being understood when synthetic N is applied into the soil accompanied by various plant residues.

Laboratory incubations were carried out by incorporating various plant residues and urea into soil samples. The objectives of this study were to investigate the impact of decomposition of residues with different C:N ratios on N_2O emission, and hence to better understand the contribution of crop residue incorporation to N_2O emissions. We also attempt to address the significance of residue C:N ratio in N_2O emission associated with soil DOC.

2. Materials and methods

2.1. Materials

Fresh soil samples with an initial water content of 13% (w/w) were collected from approximately 0–20 cm depths of wheat-cultivated field in March 2002. Five plant residues including rapeseed (*Brassia chinensis*) cake, potato (*Dioscorea esculenta*) stalk, maize leaf (*Zea mays*), wheat (*Triticum aestivum*) straw and sugarcane (*Saccharum officinarum*) stalk were selected as organic N source. Physico-chemical properties of the soil and the contents of C and N for the plant residues were determined according to the Chinese Soil Society guidelines (Lu, 2000). The soil consisted of 4% sand, 45% silt and 51% clay with an initial pH of 6.1. Total organic C and N was 20.5 and 1.6 g kg⁻¹, respectively. Table 1 shows the C:N ratios in the plant residues.

Table 1
C and N content of incorporated plant residues

Residue	C (g kg ⁻¹)	N (g kg ⁻¹)	C:N
Rapeseed cake	518	65	8
Potato stalk	404	11	37
Maize leaf	394	7	57
Wheat straw	505	8	63
Sugarcane stalk	472	4	118

2.2. Incubation

The plant residues were oven dried at 70 °C to a constant weight. Both plant residues and fresh soil sample were ground to pass through a 2-mm stainless steel sieve for use. For each treatment, 80 g fresh soil was taken in a glass bottle of 580-ml and the soil was preincubated for 7 days to stabilize the microbial activity so as to avoid an undesired microbial peak. Preincubation and the afterwards incubation of the soil samples were carried out in the dark at 20 °C and water content of 0.25 g g⁻¹. Distilled water was added to achieve the desired moisture content. Two sets of bottles were used for gas sampling: one set was thoroughly incorporated with 160 mg plant residues per bottle, and the other was thoroughly mixed with 160 mg plant residues plus 26 mg urea per bottle. Bottles without residue application for each set were set up as corresponding control. Two replicates were conducted in the experiment. The incubation lasted 21 days.

Gas sampling was taken twice a day for the first 12-day incubation and thereafter once a day by a gas-tight syringe from the headspace of the bottles after closing with rubber septa for 2 h. The bottles were flushed with ambient air for 30 min at a rate of 300 ml min⁻¹ and resealed for the next measurement. The incubation bottles were kept open after sampling and regularly corrected for water loss to keep the desired soil moisture of 0.25 g g⁻¹.

Nitrous oxide and CO₂ concentration were simultaneously analyzed with a modified gas chromatograph (Agilent 4890D) equipped with two detectors of FID and ECD. Nitrous oxide was separated by two stainless steel columns (column-1 with 1 m length and 2.2 mm i.d., column-2 with 3 m length and 2.2 mm i.d.) that were packed with 80–100 mesh porapak Q, and detected by ECD. Carbon dioxide was separated by one stainless steel column (2 m length and 2.2 mm i.d.) that was packed with 50–80 mesh porapak Q, afterwards hydrogen reduced CO₂ to CH₄ in a Nickel catalytic converter at 375 °C, and CH₄ was detected by FID. The oven was operated at 55 °C, the ECD at 330 °C and the FID at 200 °C, respectively.

2.3. Detection of the dissolved organic carbon

Water-soluble organic C (i.e. DOC) in the soil samples was measured before and after incubation. To extract the DOC, a 10-g (on air-dried base) subsample was shaken in

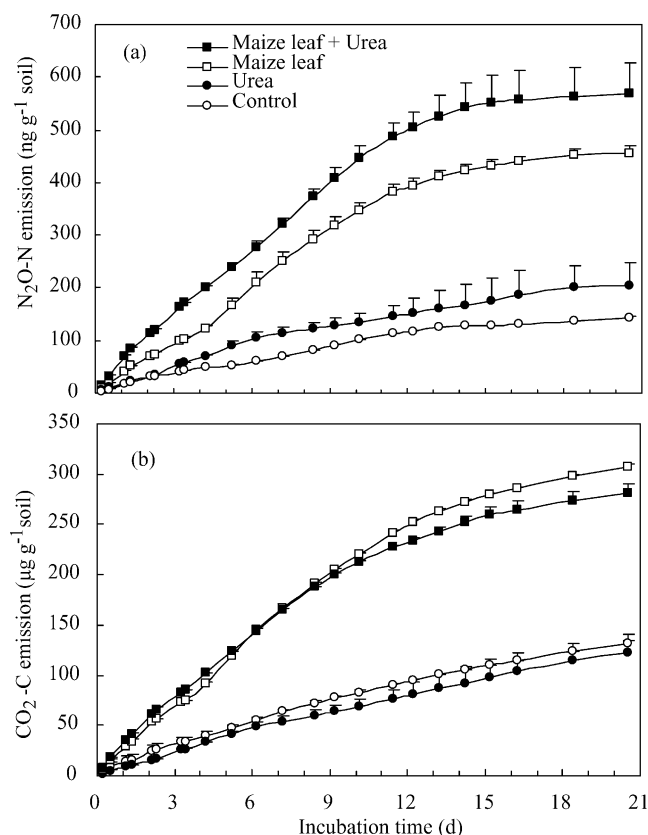


Fig. 1. Cumulative emissions of N_2O (a) and CO_2 (b) for different treatments. The vertical bars represent standard error. CO_2 derived from urea breakdown was deducted from the cumulative emission of CO_2 .

40 ml deionized distilled water for 2 h, centrifuged for 20 min at 12,500 rpm, and then filtered through Whatman no. 5 paper. Concentrations of total C (TC) and inorganic C (IC) in the prepared soil supernatant liquid were detected through the combustion/non-dispersive infrared gas analysis method by using a Total Organic Carbon Analyzer (MODEL TOC-5000A, SHIMADZU). The DOC was then determined by subtracting the IC from TC concentration.

3. Results

3.1. N_2O and CO_2 emissions as influenced by amendments of plant residues and urea

Cumulative emissions of N_2O and CO_2 for some treatments are given in Fig. 1a and b, respectively. Apparently, amendments of plant residue enhanced both N_2O and CO_2 emissions, which is in accordance with the results from Aulakh et al. (1991) and Flessa and Beese (1995). Assuming that the CO_2 from urea breakdown was completely released over the incubation, amount of the CO_2 -C emission was approximately $65 \mu g g^{-1}$ soil in this study. When the CO_2 -C derived from urea breakdown was deducted, cumulative amounts of CO_2 emission from the urea treatments are similar to that from urea-free treatments (Fig. 1b).

Table 2 shows the cumulative emissions of N_2O and CO_2 within the 21-day incubation. When plant residue was incorporated, cumulative N_2O emission for the amendment of sugarcane stalk and rapeseed cake was 1.7 and 3.0 times higher than that for the control, respectively. Meanwhile, the emission of CO_2 increased by a range from 58% for the sugarcane stalk to 171% for the rapeseed cake, while ANOVA test indicated that there was no significant difference between the treatments of urea free and urea amendments ($p > 0.50$). On the other hand, cumulative emission of N_2O and CO_2 for the amendments of urea plus plant residue, when compared with the emission for the amendment of urea, increased by 12–285% and 47–175%, respectively. It is noteworthy that cumulative N_2O emission for the amendment of sugarcane stalk plus urea was approximately 40% lower than that for the sugarcane stalk amendment (Table 2). Compared with the amount of synthetic N amendment ($169 \mu g-N g^{-1}$), the residue-N input was very small for the sugarcane stalk ($9 \mu g-N g^{-1}$). Vigil and Kissel (1991) integrated N immobilization data from several medium to long-term experiments with residues having a wide range of C:N ratios, and showed that the break-even point

Table 2
Cumulative emissions of N_2O and CO_2 over a 21-day incubation for different amendments

Amendment	Without urea		With urea	
	N_2O-N ($ng g^{-1}$ soil)	CO_2-C ($\mu g g^{-1}$ soil)	N_2O-N ($ng g^{-1}$ soil)	CO_2-C^a ($\mu g g^{-1}$ soil)
Control	141.5 ± 4.4	128.6 ± 1.7	204.0 ± 42.5	122.8 ± 17.4
Rapeseed cake	568.4 ± 74.9	349.0 ± 45.8	786.5 ± 40.2	337.6 ± 4.6
Potato stalk	475.9 ± 8.1	322.4 ± 14.6	674.8 ± 4.7	335.6 ± 7.5
Maize leaf	456.4 ± 13.2	307.9 ± 2.1	569.1 ± 58.9	280.8 ± 10.3
Wheat straw	393.1 ± 20.9	266.8 ± 13.0	479.4 ± 65.7	218.2 ± 33.5
Sugarcane stalk	384.3 ± 88.1	203.1 ± 12.4	229.3 ± 50.5	180.1 ± 51.5

^a CO_2 derived from urea breakdown was deducted from the cumulative emission of CO_2 .

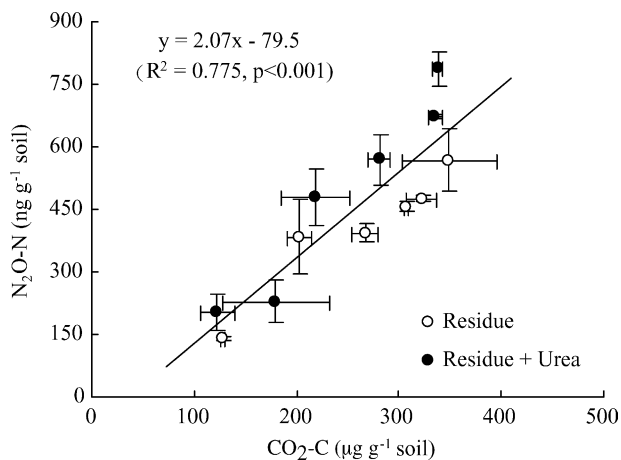


Fig. 2. Correlation of cumulative N_2O emission against cumulative CO_2 emission. The vertical and horizontal bars represent standard error. CO_2 derived from urea breakdown was deducted from the cumulative emission of CO_2 .

between net N immobilization and mineralization of residues was at a C:N ratio of 41. The sugarcane stalk with higher C:N ratio presumably stimulated NH_4^+ immobilization and N_2O consumption through its reduction to N_2 (Van Cleemput et al., 1994; Ellis et al., 1996), and hence reduced N_2O production.

Most soil microorganisms get their energy and substance from organic materials. Nitrogen mineralization and the following transformation, i.e. nitrification and denitrification whereby N_2O is produced as an immediate product, are intimately linked to the organic C decomposition. When N_2O emissions were plotted against CO_2 emissions, an indicator of organic C decomposition, a positive relationship between these two parameters is significant (Fig. 2). In field observations, N_2O emissions were also found to strongly correlate with CO_2 emissions (Barton and Schipper, 2001; Zou et al., 2004).

3.2. N_2O and CO_2 emissions associated with C:N ratio in plant residues

Our results indicated that the C:N ratio is a good predictor of N_2O and CO_2 emissions. Both N_2O and CO_2 emissions were negatively correlated with the residue C:N ratio (Figs. 3 and 4), yielding the correlation coefficient R^2 ranging from 0.783 ($p < 0.05$) to 0.986 ($p < 0.001$). Results of Fig. 3 also corroborate our previous finding that seasonal N_2O emission from wheat-cultivated soil was negatively correlated with soil C:N ratio when 18 paddy soils were involved in an outdoor pot experiment (Huang et al., 2002).

Bremner and Blackmer (1981) reported that $\text{N}_2\text{O}/\text{NO}_3^-$ ratio and N_2O emission rate all increased with decreasing C:N ratio in organic amendments to a well-aerated soil. Their soil samples were incubated at 50% of the field capacity and 30°C for 13 days. The C:N ratio in their

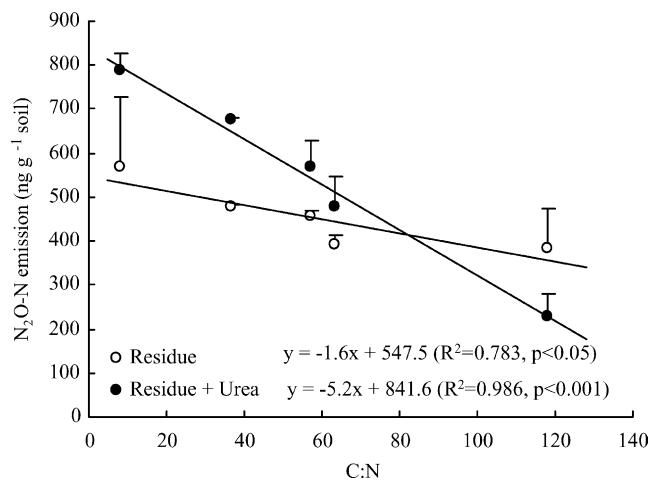


Fig. 3. Correlation of cumulative N_2O emission against C:N ratio in added plant residues. The vertical bars represent standard error.

organic amendments ranged from 5.7 to 35.0. Correlation of the $\text{N}_2\text{O}/\text{NO}_3^-$ ratio with the C:N ratio in residues, when urea was incorporated, gave a similar result (Fig. 5) as by Bremner and Blackmer (1981). However, we did not find a relationship between these two parameters under urea-free condition.

3.3. Relationships among N_2O emissions, DOC in soil samples and C:N ratio in plant residues

Compared with the initial value of $8.4 \pm 0.4 \mu\text{g g}^{-1}$ measured before incubation, the DOC concentrations measured at the end of incubation increased for the soil samples with amendment of rapeseed cake and potato stalk, decreased for the soil sample with amendment of sugarcane stalk, and did not change significantly for the soil samples with amendment of maize leaf and wheat straw (Table 3). When the soil samples were amended with residue plus urea, however, the DOC concentrations after the 21-day incubation decreased for all soil samples as compared with

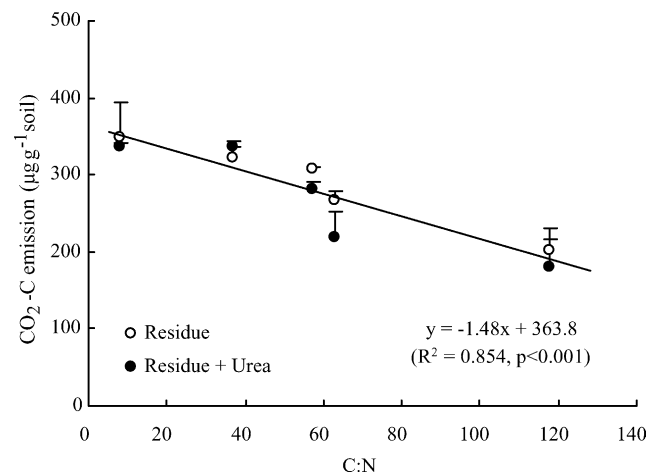


Fig. 4. Correlation of cumulative CO_2 emission against C:N ratio in added plant residues. The vertical bars represent standard error. CO_2 derived from urea breakdown was deducted from the cumulative emission of CO_2 .

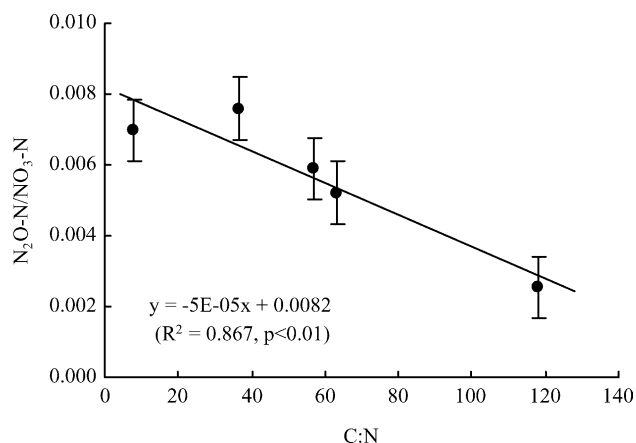


Fig. 5. Relationship between $\text{N}_2\text{O-N}/\text{NO}_3\text{-N}$ from soil samples with amendment of residue plus urea and C:N ratio in added plant residues. The $\text{NO}_3\text{-N}$ concentration was measured at the end of incubation. The vertical bars represent standard error.

the initial value (Table 3). The reduction ranged from $0.6 \mu\text{g g}^{-1}$ (rapeseed cake) to $1.8 \mu\text{g g}^{-1}$ (sugarcane stalk).

After the 21-day incubation, amendment of different residues resulted in a wide variation in the soil DOC concentration, ranging from 7.2 to $12.7 \mu\text{g g}^{-1}$, while the variation was relatively narrow when residue plus urea was amended, ranging from 6.6 to $7.8 \mu\text{g g}^{-1}$ (Table 3). The DOC concentration after the 21-day incubation was negatively correlated to the residue C:N (Fig. 6).

When residue was amended but urea free, cumulative emissions of CO_2 and N_2O from different residues treatment were significantly correlated to the DOC concentration measured at the end of incubation. The higher DOC concentration tends to the higher CO_2 and N_2O emissions (Fig. 7). Though variation in the DOC was relatively narrow when residue plus urea was amended, higher emissions of CO_2 and N_2O were also associated with higher DOC concentration (Fig. 8).

To further evaluate the effect of the DOC associated with organic C decomposition on N_2O emission, changes in the DOC were calculated between soil samples with and without residue amendment. Taking synthetic N application into account, changes in the DOC were calculated between soil samples with and without urea amendment. Similar to

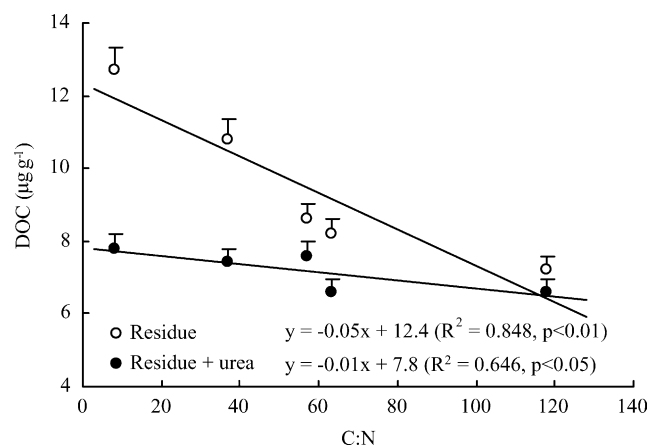


Fig. 6. Correlation of DOC in soil samples against C:N ratio in added plant residues. The vertical bars represent standard error.

the calculation for changes in the DOC, changes in the cumulative N_2O emission were computed.

Compared with the control, the DOC increased for most soil samples with residue amendment but urea-free treatment. Lower C:N ratio of the residues in general resulted in higher increment in the DOC and N_2O emission (Table 3). The increment of N_2O ($\Delta\text{N}_2\text{O-1}$) was proportionate to that of DOC ($\Delta\text{DOC-1}$). In contrast with the urea-free incubation, however, when urea was added the DOC decreased for all soil samples (Table 3). Lower C:N ratio of the residues resulted in higher reduction in the DOC. Moreover, the changes in N_2O ($\Delta\text{N}_2\text{O-2}$) and DOC ($\Delta\text{DOC-2}$) became disproportionate (Table 3). These results suggested that addition of synthetic N affected the DOC transformation which is dependent on the C:N ratio of the incorporated residues, and the change in N_2O emission is related to the change in DOC.

3.4. Relationship between N_2O emission fraction and C:N ratio in plant residues

Analogous to the calculation of the N_2O emission factor in IPCC (2000), we defined the $\text{N}_2\text{O-N}$ emissions per unit N amendment as emission fraction (EF) and calculated the EFs for the plant residues amendment and the urea

Table 3
Change in DOC and in cumulative N_2O emissions

Amendment	Without urea			With urea		
	DOC ($\mu\text{g g}^{-1}$)	$\Delta\text{DOC-1}^a$ ($\mu\text{g g}^{-1}$)	$\Delta\text{N}_2\text{O-1}^a$ ($\text{ng N g}^{-1}\text{soil}$)	DOC ($\mu\text{g g}^{-1}$)	$\Delta\text{DOC-2}^b$ ($\mu\text{g g}^{-1}$)	$\Delta\text{N}_2\text{O-2}^b$ ($\text{ng N g}^{-1}\text{soil}$)
Control	7.3 ± 0.3			15.0 ± 0.6		
Rapeseed cake	12.7 ± 0.5	5.4	426.9	7.8 ± 0.1	-4.9	218.1
Potato stalk	10.8 ± 0.4	3.5	334.4	7.4 ± 0.2	-3.4	198.9
Maize leaf	8.6 ± 0.2	1.3	314.9	7.6 ± 0.3	-1.0	112.7
Wheat straw	8.2 ± 0.4	0.9	251.6	6.6 ± 0.2	-1.6	86.4
Sugarcane stalk	7.2 ± 0.2	-0.1	242.8	6.6 ± 0.2	-0.6	-155.0

^a Difference between soil samples with and without residue amendment.

^b Difference between soil samples with and without urea amendment.

amendment as follows

$$EF_R = [(\sum N_2O_{N_R} - \sum N_2O_{N_B})/N_R] \times 100\% \quad (1)$$

$$EF_U = [\sum N_2O_{N_{RU}} - \sum N_2O_{N_R}]/N_U \times 100\% \quad (2)$$

where

EF_R = emission fraction for the residue-N amendment (%)

EF_U = emission fraction for the urea-N amendment (%)

$\sum N_2O_{N_B}$ = cumulative N_2O -N emitted from soils without amendments of residue and urea (μg)

$\sum N_2O_{N_R}$ = cumulative N_2O -N emitted from soils with a given residue (μg)

$\sum N_2O_{N_{RU}}$ = cumulative N_2O -N emitted from soils with amendments of residue and urea (μg)

N_R = N added from a given residue (μg)

N_U = N added from urea (μg)

Calculations of the EF_R and the EF_U indicate that the emission fraction is not a constant, but dependent on C:N ratio of the incorporated residue (Fig. 9). Note that emission fraction for the residue amendment (EF_R) is positively related to the C:N ratio, while for the urea amendment (EF_U) is negatively correlated with the C:N ratio. These results strongly suggest that the emission fractions are associated with the amendments of plant residues. Clearly, the synthetic N_2O -N emission is regulated by the residue amendment. Amendments of plant residues with higher C:N ratios could enhance N immobilization and thus reduce the synthetic N loss, which is of great benefit to the reduction of N_2O and improvement of soil fertility.

4. Discussion

4.1. Origins of N_2O emission

There are two main processes of N_2O production: nitrification and denitrification. Since the responsible microorganisms operate under various optimum conditions it is generally assumed that nitrification is the predominant

N_2O producing process under moderately moist (aerobic) and that denitrification is the predominant process under wet (anaerobic) conditions when NH_4^+ and NO_3^- are available in soil (Conrad, 1996; Bouwman, 1998). In our study there were conditions that should have been favorable for nitrification: moderately moist soil samples (water content of 0.25 g g^{-1}) and an aerobic headspace in the bottle. However, the relationships between emissions of N_2O and CO_2 (Fig. 2), as well as between N_2O emissions and DOC (Figs. 7 and 8) implied that denitrification might be a candidate for the active mechanism. Groffman and Crawford (2003) reported that denitrification enzyme activity was highly correlated with soil respiration. Weier et al. (1993) found that denitrification rate was correlated with organic C supply. It is noteworthy that the increment of N_2O (ΔN_2O -2) was accompanied with a reduction of DOC (ΔDOC -2) when both residue and urea was amended (Table 3), suggesting that denitrifiers might consume the DOC and thus denitrification occurred.

More recent findings suggested that denitrification can occur under aerobic soils. Müller et al. (2003) found that the process of NO_3^- reduction is the predominant N_2O producing mechanism even under aerobic conditions in a temperate grassland soil. Their field observations indicated that soil volumetric water in the main rooting zone (top 10 cm) stayed at approximately $0.3 \text{ cm}^3 \text{ cm}^{-3}$ during the main growth period and O_2 concentrations in the entire soil profile stayed between 15 and 21% throughout most of the observation period. Though conditions in our incubation study might be favorable for nitrification, residue amendment might stimulate microbial growth and activity, and hence promoted oxygen consumption that created temporary anaerobic microsites (Sahrawat and Keeney, 1986; Goek and Ottow, 1988; Cannavo et al., 2003). As a result, autotrophic nitrification might be reduced and N_2O production via denitrification enhanced. McKenney et al. (1993) also observed higher denitrification rates in aerobic than in anaerobic conditions due to organic residues. We simply don't know the contribution of nitrification and denitrification to the overall N_2O emission, because we didn't make any measurements under acetylene inhibition

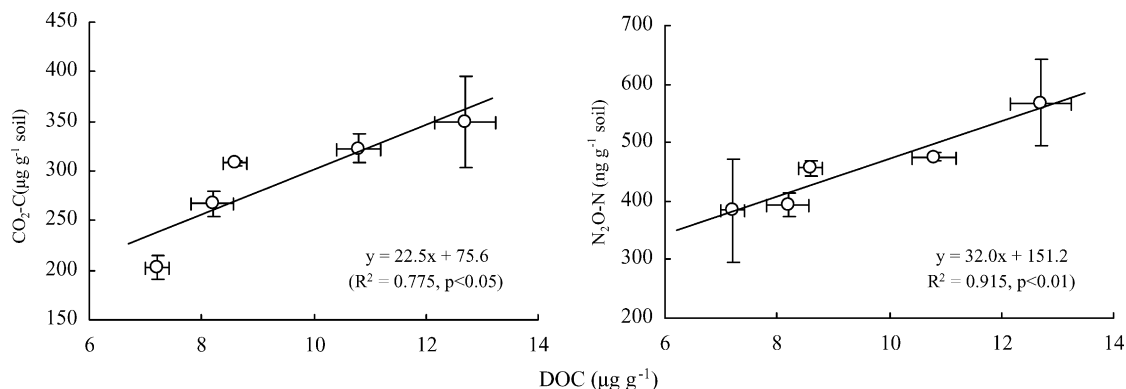


Fig. 7. Correlation of CO_2 and N_2O emissions against DOC with amendment of residue. The vertical and horizontal bars represent standard error.

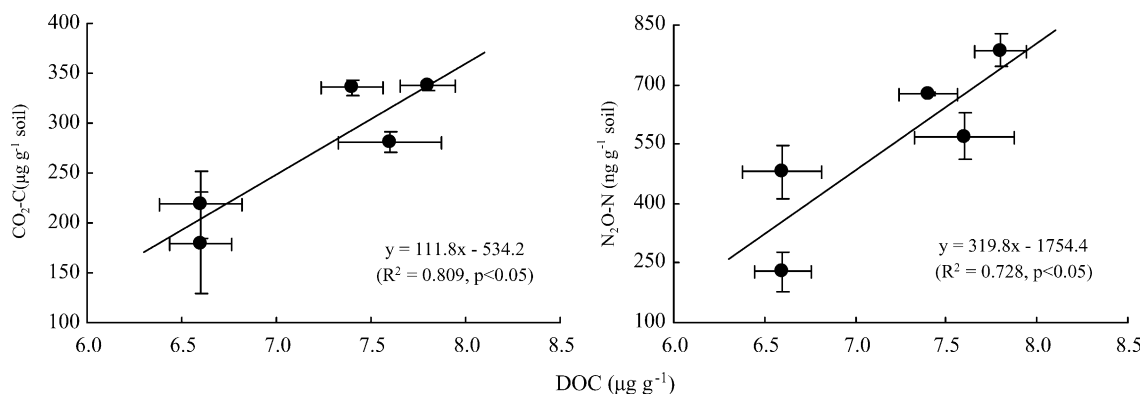


Fig. 8. Correlation of CO_2 and N_2O emissions against DOC with amendment of residue plus urea. The vertical and horizontal bars represent standard error.

which is believed to block the build-up of NO_3^- and the subsequent N_2O production via denitrification (Ambus, 1998). A further investigation is required to identify N_2O production via denitrification under aerobic conditions when organic C is incorporated.

4.2. Bioavailability of DOC and residue C:N ratio

N_2O emissions measured from soil samples receiving organic and/or inorganic N were greater than that from control (Table 2), which confirms the results of other authors such as Granli and Bøckman (1994) who reported that the rate of N_2O production is partially controlled by C susceptible to mineralization. Several studies have implied that the amount of DOC is a measure of the readily available resource for microbial growth and biological decomposition, often being considered as a good index of C availability (Paul and Beauchamp, 1989; Liang et al., 1996; Jensen et al., 1997). Similarly, Zack et al. (1990) reported that microbial biomass C was highly correlated with DOC. Results of Figs. 7 and 8 suggest that DOC is bioavailable substrate. Very similar results were reported by several other authors (e.g. Burford and Bremner, 1975; Liang et al., 1996; Martín-Olmedo and Rees, 1999).

Silver and Miya (2001) found that the root decay constant (yr^{-1}) was significantly negatively correlated with root C:N ratio when they analyzed a total of 175 data sets from the literature. Khalil et al. (2002) reported that N_2O production was increased by decreasing the C:N ratio of different organic matter. Kiese and Butterbach-Bahl (2002) found a strongly negative correlation between mean annual N_2O emission rate and C:N ratio of tropical rain forest soils. Relationships between emissions of N_2O and CO_2 (Fig. 2), between the gas fluxes and DOC (Figs. 7 and 8), as well as between DOC and crop residue C:N (Fig. 6) also imply that crop residue C:N might play an important role in CO_2 and N_2O emissions. Residues with lower C:N decomposed more (Fig. 4), might provide a greater opportunity for producing more DOC (Fig. 6), hence resulting in higher N_2O emissions (Fig. 3). This is partly

supported by Hadas et al. (2003) who reported that lower C:N residues have higher water-soluble organic C. Heal et al. (1997) explained that substrates with C:N ratios < 20 decompose rapidly and NH_4 is released through mineralization. Plant material with intermediate C:N ratios of 25–75 can also decompose quickly, but N mineralization activity is often reduced by increased microbial immobilization as well as protein complexation by polyphenols when the cells lyse. Substrates with high C:N ratios (> 75) are often much more difficult to break down and are generally characterized by greater amounts of structural woody materials such as lignin, condensed tannins and terpenes, as well as low available N for decomposer organisms (Heal et al., 1997).

As far as the composition of DOC is concerned, Boyer and Groffmann (1996) found a higher microbial degradation of water-soluble humic acids compared to fulvic acids, while Glatzel et al. (2003) reported that CO_2 efflux was negatively correlated with the portion of humic acids in bulk DOC. To better understand the role of DOC associated with organic C decomposition in N_2O emission, a further investigation should focus on examining the residue

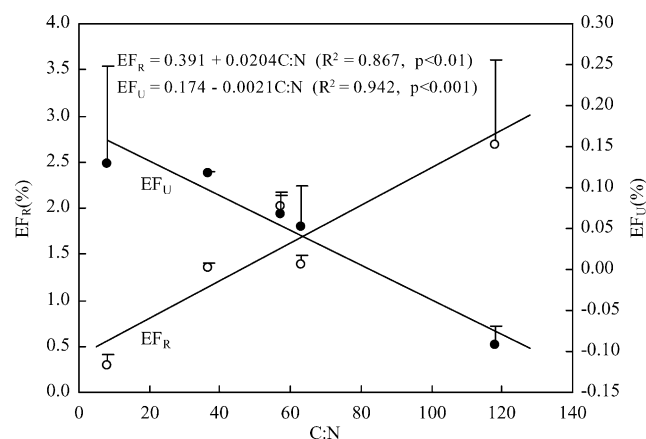


Fig. 9. Dependence of N_2O emission fraction on C:N ratio in added plant residues. See text for details in calculations of EF_R and EF_U . The vertical bars represent standard error.

composition, corresponding DOC properties and their relationship to CO₂ and N₂O emissions.

5. Conclusions

Incorporation of plant residues enhanced N₂O and CO₂ emissions. This enhancement was quantitatively dependent on C:N ratio of the residues, lower C:N ratio of the residues inducing higher concentration of DOC and larger amount of N₂O emission. A further conclusion is that the N₂O–N emission fraction for either residue-N or urea-N amendment is not a constant but dependent on the C:N ratio when plant residue was incorporated.

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