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Effect of Rice Residues on Carbon Dioxide and Nitrous Oxide Emissions from a Paddy Soil of Subtropical China

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Abstract A pot incubation experiment with rice residues (straw and root) was conducted under aerobic condition (60% of WHC, water holding capacity) for a period of 55 days in a greenhouse. The emissions of carbon dioxide (CO_2) and nitrous oxide (N_2O) were determined by the closed chamber method in a paddy soil. The soil was derived from quaternary red clay, and collected from the Ecological Station of Red Soil, the Chinese Academy of Sciences, located in Jiangxi Province, a subtropical region of China. The emissions of CO_2 and N_2O were increased by the amendment of rice residues. Significantly positive correlation was found between N_2O and CO_2 fluxes (R = 0.650*−0.870*, $P \leq 0.05$). The cumulative emissions during the early stage of the incubation (<25 days after residue addition) accounted for about 67%–86% and 67%–80% of the total amount of CO_2 and N_2O emissions, respectively. Cumulative emissions and emission factors of the two gases were higher in the soils amended with rice straw than those with rice root. The two gas fluxes were positively correlated with microbial biomass C and N, as well as soluble organic C. N_2O flux was positively correlated with NH_4^+–N content at the early stage (<25 days), and negatively with NO_3^-–N content at the later stage of this incubation (25–55 days), implying that both nitrification and denitrification may have contributed to N_2O production.

Keywords carbon dioxide · C sequestration · nitrous oxide · paddy soil · rice residues

1 Introduction

Carbon dioxide (CO_2) and nitrous oxide (N_2O) are two important greenhouse gases in the atmosphere contributing about 50% and 5% to the global warming, respectively (Lal & Kimble, 1995). The atmospheric CO_2 and N_2O concentrations are currently estimated as about 370 ppm and 316 ppb, and further increasing at a rate of 0.5% and 0.25% yr^{-1}, respectively (IPCC, 2001). Soils are regarded as the important sources for the production of the two gases. Global emissions of CO_2 and N_2O from soils account for 68–75 Pg CO_2–C yr^{-1} and 6.2 Tg N_2O–N yr^{-1}, respectively (Mosier, 1998; Raich & Potter, 1995; Kroeze, Mosier, & Bouwman, 1999).

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CO_2 in soils is produced through various processes such as biological oxidation of soil organic matter, decomposition of crop residues and root respiration. N_2O is produced mainly by microbial nitrification and denitrification processes (Mosier, 1998). The emissions of CO_2 and N_2O from soils depended on many factors including soil temperature, moisture, pH, organic matter content, fertilization and irrigation (Curtin, Selles, Wang, Campbell, & Biederbeck, 1998; Mosier, 1998; Maag & Vinther, 1999; Inubushi et al., 2000; Lou, Li, & Zhang, 2003). As a practical measure for improving soil fertility, incorporation of crop residues to soils has been widely used in agricultural production around the world. The amendment of crop residues generally increases readily available C and N in soils, and thus affects CO_2 and N_2O production and emissions from soils (Flessa & Beese, 1995; Curtin et al., 1998; Lu, Watanabe, & Kimura, 2003; Millar & Baggs, 2004). Furthermore, the magnitude of CO_2 and N_2O emissions varies with the types, quality or chemical composition of the residues added to soils (Curtin et al., 1998; Baggs, Reese, Smith, & Vinten, 2000; Shelp, Beauchamp, & Thurell, 2000). Usually, greater CO_2 and N_2O emissions were obtained in the soils incorporated with the residues containing high N content and low lignin content (Kaiser et al., 1998; Millar & Baggs, 2004).

The influences of plant shoot residues and related qualities (e.g., lignin content, C:N or lignin:N ratios, etc) on residue decomposition and mineralization together with CO_2 and N_2O emissions have been extensively studied (Curtin et al., 1998; Huang, Zheng, Wang, & Xu, 2004; Millar & Baggs, 2004). Nevertheless, very few studies have addressed the role of plant root residues in the trace gas emissions. Some researchers demonstrated that the decomposition of root residues was slower than the shoot residues of the same plant due to the differences in their chemical compositions such as cellulose and lignin contents (Puget & Drinkwater, 2001; Lu et al., 2003). Thus, the amount of CO_2 and N_2O emitted from the soils incorporated with root residues should be lower than the incorporation of their shoot residues. However, this hypothesis has not yet been confirmed. In paddy soils, rice straw and root residues are the main inputs of crop residues to soils, which not only plays important roles in nutrient supply and crop yields, but also promotes C sequestrations when organic C inputs from rice residues exceed CO_2 emissions from the soils (Witt et al., 2000; Lu et al., 2003). However, very little information is available regarding the relative contributions of rice straw and root residues to C sequestrations and CO_2 effluxes in rice paddy soils, because rice root biomass retained in paddy soils is largely undocumented. The objectives of this study were to evaluate the CO_2 and N_2O emissions in a rice soil as influenced by the incorporations of rice straw and rice root.

2 Materials and Methods

The paddy soil used in this study was collected from the Ecological Station of Red Soil, the Chinese Academy of Sciences, located in Yingtan, Jiangxi Province, China (28°15′30″N, 116°55′30″E). The region has a typical subtropical monsoon climate with an annual precipitation of 1,795 mm, annual evaporation of 1,318 mm and a mean annual temperature of 17.6°C. Doube rice (i.e., early and late rice)-fallow rotation is a popular system distributed in the paddy soils of this region. After the late rice was harvested, paddy fields were usually fallowed without floodwater layer from November to April (i.e., winter to spring).

The tested soil was classified as a Haplic Stangnic Anthrosol, and derived from quaternary red clay (Soil Taxonomic Classification Research Group of China, 1993). After collection, the wet soil was air-dried to adjust soil moisture content to approximately 45% of WHC (water holding capacity), and then passed through a 4 mm sieve to remove the small stones and visible plant debris. The soil contained total organic C of 5.1 g kg^{-1}, total N of 0.52 g kg^{-1}, NH_4^+–N of 45.0 mg kg^{-1}, NO_3^-–N of 15 mg kg^{-1}, pH of 5.1 (1:1, soil/water ratio), clay content of 35% (<1 μm). Total carbon was determined using dichromate oxidation, and total N with Kjeldahl method. Mineral–N (NH_4^+–N and NO_3^-–N) was extracted in 0.5 M K_2SO_4 solution, and determined using the methods described by Keeney and Nelson (1982). Soil pH (1:1 soil–water paste) was measured with electrometry (pH electrode), and clay content with pipette method (Page, Miller, & Keeney, 1982).

The rice residues examined were rice straw and rice root, which were immediately sampled after rice harvest. After sampling, the residues were oven-dried for four days at 70°C, milled and passed through a 3 mm sieve. The non-passed residues (>3 mm) were

used in the experiment. Total organic C in the residues was determined by dichromate oxidation, and total organic N by Kjeldahl procedure (Page et al., 1982). Cellulose and lignin were measured by the acid detergent fibre method (Van Soest & Wine, 1968). The above measurements were replicated three times. The selected properties of the residues were presented in Table I.

Sub-samples of the moisture-adjusted soil weighing 1.0 kg were incorporated with 1.0 g of the rice straw or rice root (>3 mm), and then put into cylindric ceramic pots ($D \times H = 10 \times 12$ cm). All pots were weighed and irrigated with distilled water daily to keep the soil moisture content at 60% of WHC, and arranged in a randomized complete block design with three replicates. The above aerobic incubation was conducted under greenhouse conditions, with daily soil temperature gradually increasing from 10°C at the start to 25°C at the end of the incubation. This change of temperature was designed to simulate the subtropical conditions during the fallow seasons as mentioned above. Soil temperature was monitored throughout the experiment by soil thermometer inserted to a depth of 5 cm in the pot (data not shown).

N_2O and CO_2 emission rates were measured using a closed chamber method. Gas samplings were carried out at 5-day intervals for the early stage of the incubation (<25 days) and thereafter at 15-day intervals (25–55 days), because plant residues were generally decomposed at a rapid rate within 20 days after incorporation (Flessa, Potthoff, & Loftfield, 2002; Millar & Baggs, 2004). All measurements were conducted in the morning (09:00–11:00 A.M.). We have previously found that soil CO_2 fluxes in the morning generally well represented the mean daily fluxes (Lou et al., 2003). The chamber for gas collection was 25 cm in height and 15 cm in diameter, with a rubber septum fixed in the top of the chamber. During gas sampling, the pots were moved and placed in a plastic trough filled with 3-cm depth water, and then the chambers were put over the pots. The bottoms of the chambers were sealed with the water in the trough. Ten ml of gas samples were collected using an air-tight syringe through the rubber septum at 0, 15, 25 and 35 min after the enclosure of the chambers. Then, the gas samples were immediately injected into evacuated 10-ml glass vials. The total N_2O and CO_2 concentrations in the gas samples were determined with GC (Shimadzu 14B, Japan) equipped with ECD and TCD, respectively. N_2O and CO_2 emission rates were calculated from the linear equation of the temporal increase in the concentrations of N_2O and CO_2 in the chambers.

Soil samples were destructively taken from three additional replicates of each treatment at each sampling occasion throughout the experiment, and temporarily stored at 5 °C in the dark for measuring soluble organic C and N (SOC and SON), microbial biomass C and N (MBC and MBN) as well as mineral N (NH_4^+ and NO_3^-) within 48 h. MBC and MBN were determined using the fumigation-extraction method (Vance, Brookes, & Jenkinson, 1987; Brookes et al., 1985). Briefly, one portion of fresh soils (20 g oven-dried equivalent) was extracted with 50 ml of 0.5 M K_2SO_4 by shaking for 30 min, filtered through Whatman No. 42 paper, and frozen at −20°C until analysis. Simultaneously, another portion of soil samples was fumigated with ethanol-free chloroform for 24 h at 25°C and then extracted as above. MBC and MBN were calculated as the difference between the total organic carbon and nitrogen in the fumigated and non-fumigated extracts using $K_{EC} = 0.38$ and $K_{EN} = 0.45$, respectively. Soluble organic carbon and nitrogen were extracted with 0.5 M K_2SO_4 from the non-fumigated soils and measured by dichromate oxidation and Kjeldahl digestion procedure, respectively (Alef & Nannipieri, 1995). Mineral-N was extracted in 0.5 M K_2SO_4 solution, and NH_4^+ and NO_3^- in the extract determined using the methods described by Keeney and Nelson (1982).

Statistical analysis was performed using SPSS software (SPSS Inc., 2000). All data were expressed

Table I Chemical properties of the residues used in this study

Material	Total C (g kg^{-1})	Total N (g kg^{-1})	Lignin (g kg^{-1})	Cellulose (g kg^{-1})	C/N	Mineral N[a] (mg kg^{-1})
Rice straw	434.5 ± 7.6 a	10.56 ± 0.3 a	107.0 ± 6.4 b	283.0 ± 6.9 a	41.4 ± 0.5 a	–
Rice root	311.4 ± 6.5 b	8.68 ± 0.20 b	174.0 ± 5.8 a	268.0 ± 4.3 b	35.9 ± 0.1 b	–

[a] Mineral N = $NH_4^+ + NO_3^-$, which was not detected in the water extracts of the rice residues. Values in a column followed by the same letter were not significantly different ($P \leq 0.05$) by IST (Independent Samples T Test) method.

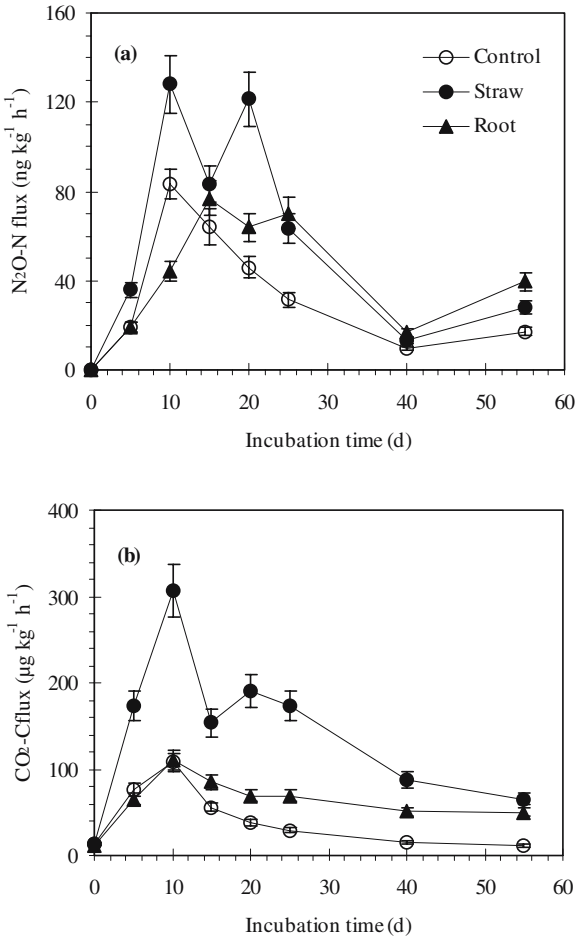

Figure 1 Changes of N_2O–N and CO_2–C fluxes from a paddy soil amended with rice straw and root under aerobic incubation. Values are the mean of triplicates. *Vertical bars* indicate the standard error of the averages.

as means ± standard errors and tested by Duncan's test method at the 5% or 1% probability level. Simple regression procedure was carried out to describe N_2O and CO_2 fluxes in relation to MBC, MBN, SOC, DON and mineral-N.

3 Results

3.1 N_2O and CO_2 fluxes as affected by amendments of rice residues

In comparison with the control, the amendment of rice residues obviously stimulated N_2O emission from the rice paddy soil. Generally, N_2O fluxes were increased from the start of the incubation to 25 days after the incorporation of rice residues, and then decreased until the end of this study. Furthermore, N_2O fluxes were affected by the type of rice residues amended in the soil, especially at the early stage of the incubation (<25 days), following the order of rice straw > rice root (Figure 1a).

Similarly, CO_2 fluxes were also enhanced by the amendment of rice residues (Figure 1b). CO_2 fluxes were clearly increased within 10 days after the incorporation, followed by a gradual decrease to their lower values. Moreover, CO_2 flux was higher in the soil amended with rice straw than rice root (Figure 1b). As described above, N_2O flux and CO_2 flux showed similar fluctuations over the entire incubation. Statistical analyses further indicated that N_2O flux was significantly positively correlated with CO_2 flux (Figure 2).

3.2 N_2O and CO_2 cumulative emissions and their emission fractions

Cumulative emissions of CO_2 and N_2O are presented in Table II. Obviously, compared with the control, both CO_2 and N_2O emissions were increased in the soils amended with rice residues, which is in accordance with other reports (Huang et al., 2004; Millar & Baggs, 2004). During the incubation, the two gases were mostly emitted at the early stage (<25 days). The cumulative emissions during the early stage accounted

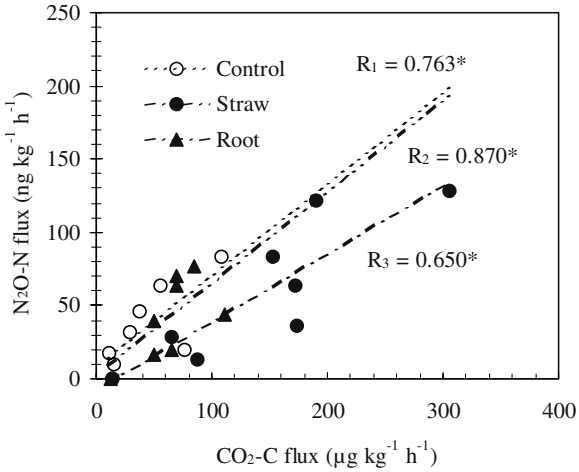

Figure 2 Correlation of N_2O–N flux to CO_2–C flux in a paddy soil amended with rice straw and root under aerobic incubation. In this Figures, R_1, R_2 and R_3 represent the correlation coefficients for the treatments without residue addition (control), amended with rice straw and rice root, respectively. * = significant at $P \leq 0.05$.

Table II CO_2 and N_2O cumulative emissions during the periods of 25 and 55 days of the incubation

Treatment	CO_2–C (mg kg^{-1} soil)		Percentage[1] (%)	N_2O–N (μg kg^{-1} soil)		Percentage[2] (%)
	25 days	55 days		25 days	55 days	
Control	37.29 ± 2.49 c	43.28 ± 2.89 c	86.15	29.26 ± 1.46 b	36.63 ± 2.44 c	79.87
Rice straw	119.8 ± 7.98 a	153.9 ± 10.3 a	77.81	51.84 ± 3.46 a	63.59 ± 4.24 a	81.52
Rice root	48.20 ± 3.21 b	72.34 ± 4.82 b	66.63	32.95 ± 2.20 b	49.23 ± 3.28 b	66.93

Percentage[1] and [2] were calculated using the equation = 25 × 100/55 days, representing the amount of CO_2 and N_2O emissions during the early periods (<25 days) accounted for the total amount of the emissions, respectively. Values are the mean ± SE (standard error). Means in a column followed by the same letter were not significantly different ($P \leq 0.05$) by Duncan's test method.

for about 67%–86% and 67%–80% of the total amount of CO_2 and N_2O emissions, respectively (Table II). The cumulative emissions of CO_2 and N_2O depended on the type of rice residues added to the soils. Regardless of CO_2 and N_2O, higher cumulative emissions were found in the soils incorporated with rice straw than rice root (Table II).

Furthermore, emission factor was calculated to further evaluate N_2O and CO_2 emissions in relation to rice residues with different total organic C and N contents, which is defined as N_2O–N or CO_2–C emission related to the total N or C added (IPCC, 2000; Huang et al., 2004). In this study, emission factor was estimated as below:

CO_2 emission factor (%) = $(\sum CO_2\text{–}C_R - \sum CO_2\text{–}C_{CON}) \times 100/C_A$, where $\sum CO_2\text{–}C_R$ = cumulative CO_2–C evolved from soils amended with residues (straw or root) during the given period (25 or 55 days), $\sum CO_2\text{–}C_{CON}$ = cumulative CO_2–C evolved from control soils without residues during the given period, and C_A = C added from residues.

N_2O emission factor (%) = $(\sum N_2O\text{–}N_R - \sum N_2O\text{–}N_{CON}) \times 100/N_A$, where $\sum N_2O\text{–}N_R$ = cumulative N_2O–N evolved from soils amended with residues during the given period, $\sum N_2O\text{–}N_{CON}$ = cumulative N_2O–N evolved from control soils without residues during the given period, and N_A = N added from residues.

Emission factors of N_2O and CO_2 changed with incubation time and rice residues (Table III). Emission factors were significantly higher in the treatment with straw than root, which is consistent with the tendencies of N_2O and CO_2 cumulative emissions (Table II). About 9.33% and 25.5% of C added from root and shoot were respired within 55 days of incubation. The total N_2O–N emissions from amendment of residues were equivalent to 0.15% and 0.26% of the N derived from root and shoot (Table III).

3.3 Changes of microbial biomass C and N

The variations of microbial biomass C and N (MBC and MBN) were presented in Figure 3. Compared with the control, MBC was rapidly increased from 0 to 10 days after the amendment of rice residues and reached the peak values, and then gradually reduced to the lower values near to the control. The amount of MBC also varied with the type of rice residues added to the soil, usually with the order of straw > root (Figure 3a).

The changes of MBN were similar to MBC (Figure 3b). In general, higher values of MBN content were found at the early stage of this study (10 days after the addition of residues). Also, during the early period of this incubation, significant differences in MBN was observed between different treatments with

Table III CO_2 and N_2O emission factors during the periods of 25 and 55 days of the incubation

Treatment	CO_2 Emission Factor (%)[1]		N_2O Emission Factor (%)	
	25 days	55 days	25 days	55 days
Straw	18.9 ± 1.27 a	25.5 ± 1.70 a	0.21 ± 0.02 a	0.26 ± 0.02 a
Root	3.51 ± 0.24 b	9.33 ± 0.63 b	0.04 ± 0.01 b	0.15 ± 0.01 b

[1] Emission factor is defined as N_2O–N or CO_2–C emission per unit N or C input (IPCC, 2000; Huang et al., 2004). Values are the mean ± SE (standard error). Means in a column followed by the same letter were not significantly different ($P \leq 0.05$) by Independent Samples *T* Test at $P \leq 0.05$.

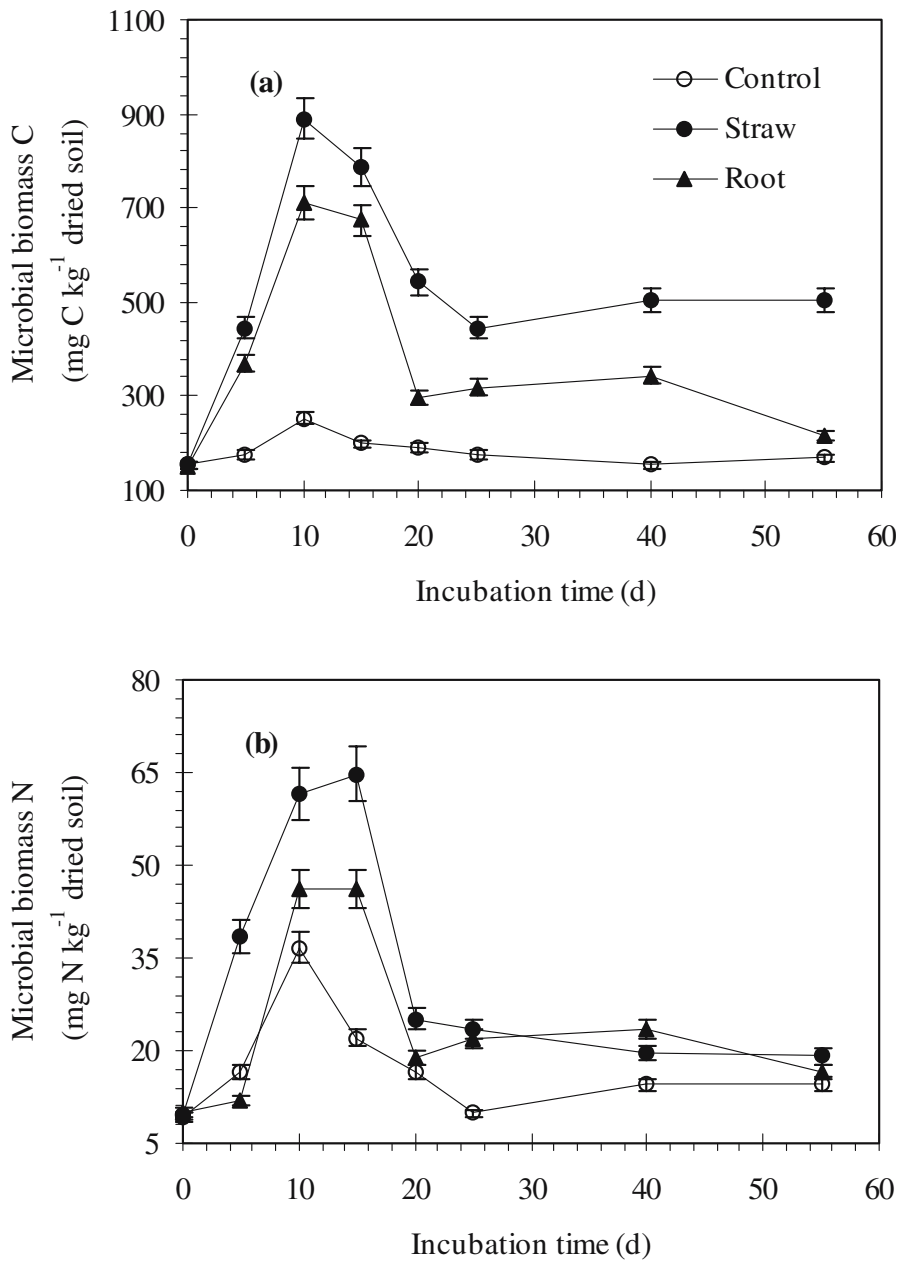

Figure 3 Changes of microbial biomass C and N in a paddy soil amended with rice straw and root under aerobic incubation. Values are the mean of triplicates. *Vertical bars* indicate the standard error of the averages.

rice straw or rice root, following the sequence of straw > root, but no obvious differences at the later period of this incubation (>40 days).

3.4 Changes of soluble organic C and N

The content of soluble organic C (SOC) in soil was obviously elevated by the incorporation of residues at the initial stage of this incubation (<5 days), and then decreased until the end of this study. Moreover, during the initial period, rice straw amendment had more effect on SOC content than rice root (Figure 4a). Similarly, clear increase in the content of soluble organic N (SON) was also found at the earliest stage as SOC described above (Figure 4b). However, after the initial increases, both SOC and SON were lowered, and no evident differences were observed between the treatments amended with rice straw or rice root.

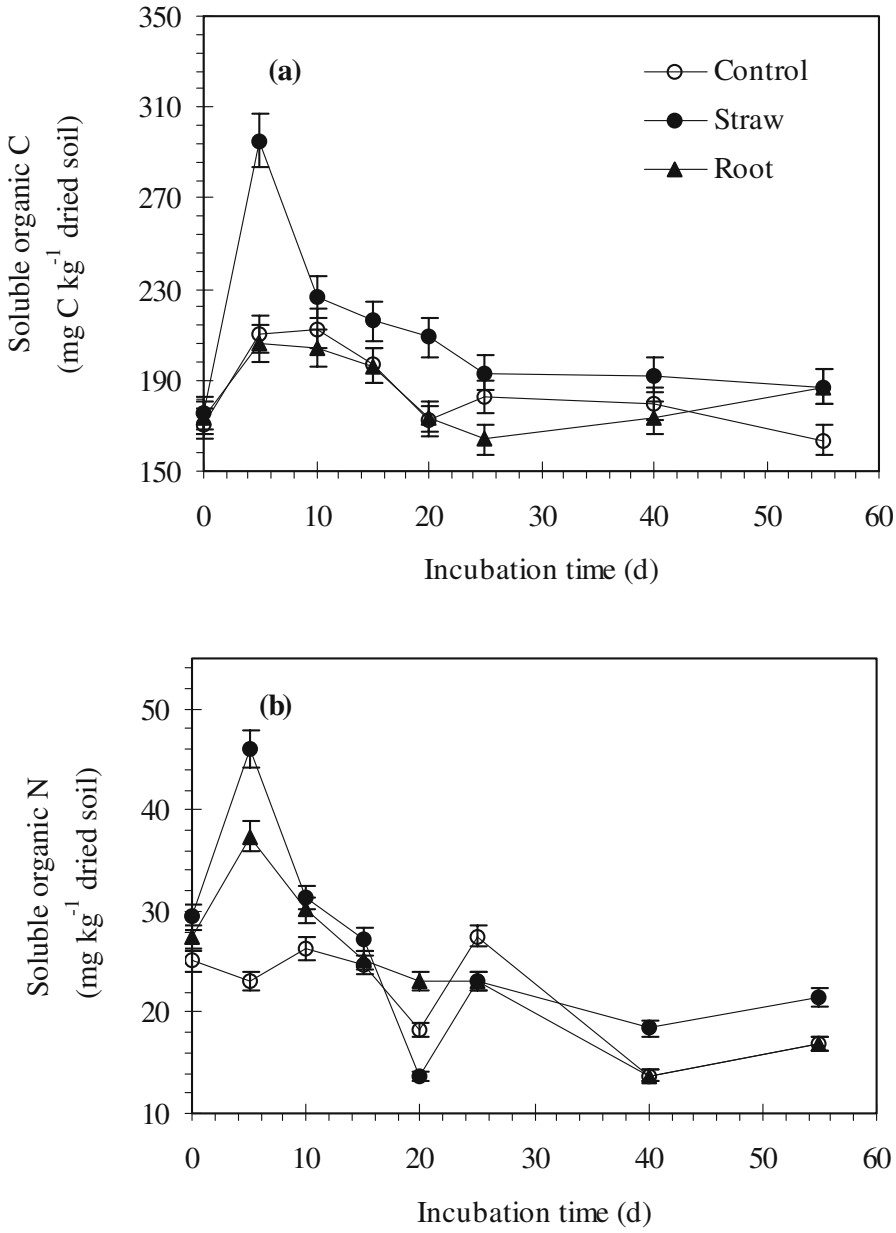

Figure 4 Changes of soluble organic C and N in a paddy soil amended with rice straw and root under aerobic incubation. Values are the mean of triplicates. *Vertical bars* indicate the standard error of the averages.

3.5 Changes of NH_4^+–N and NO_3^-–N contents

Generally, NH_4^+–N content in the soil samples amended with rice straw or rice root was lower than the control. Furthermore, NH_4^+–N content rapidly increased during the initial period (<5 days), and then declined until the end of the incubation (Figure 5a). In contrast, NO_3^-–N content was basically increased during the entire incubation. Lower NO_3^-–N content was found in the soil samples incorporated with rice straw or rice root, compared to the control (Figure 5b).

4 Discussion

4.1 CO_2 flux vs MBC (N), SOC (N), and mineral N

Under non-planted conditions, soil CO_2 emission was mainly caused by microbial respiration, and was an

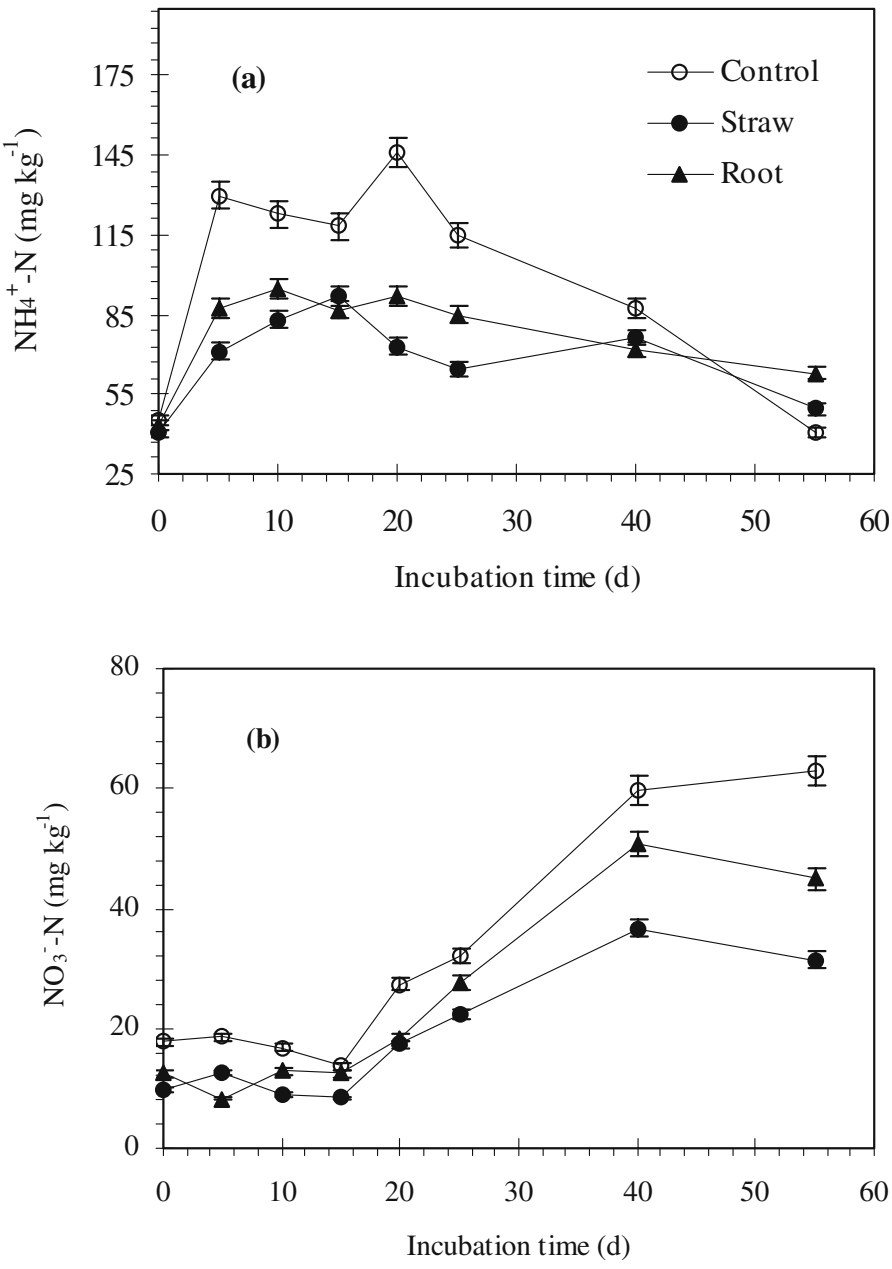

Figure 5 Changes of mineral N in a paddy soil amended with rice straw and root under aerobic incubation. Values are the mean of triplicates. *Vertical bars* indicate the standard error of the averages.

important parameter for evaluating microbial activity in soils. Microbial biomass is representative of size of microbial communities in soil. In this study, similar fluctuations were found in soil CO_2 flux and MBC (N) during the incubation, both with highest values at the early stage and lower at the end of this study (Figures 1b and 3). Statistical analysis showed that soil CO_2 flux was positively correlated with MBC and MBN. For CO_2 flux and MBC, the correlation coefficients were 0.842** to 0.898** and 0.540* to 0.981** during the early (<25 days) and later stages (25–55 days), respectively. For CO_2 flux and MBN, the coefficients were 0.707* to 0.880** and 0.490* to 0.996** for the early (<25 days) and later duration (25–55 days), respectively (Table IV). Soil CO_2 flux and microbial biomass were rapidly increased at the early stage (Figures 1b and 3), indicating that increased C supply and substrate after residue incorporation

Table IV Correlation analysis between CO_2–C flux and biomass C and N, soluble organic C and N, and mineral N (NH_4^+ and NO_3^-) during early (<25 days) and later (25–55 days) stages of this incubation

Treatment	CO_2–C Flux Versus	Correlation Coefficient (R)	
		<25 days (n = 15)	25–55 days (n = 9)
Control	Microbial biomass C	0.842**	0.589*
	Microbial biomass N	0.880**	0.982**
	Soluble organic C	0.928**	0.769*
	Soluble organic N	0.373 *ns*	0.368 *ns*
	NH_4^+–N	0.560*	0.885**
	NO_3^-–N	−0.299 *ns*	−0.996**
Straw	Microbial biomass C	0.855**	0.981**
	Microbial biomass N	0.707*	0.996**
	Soluble organic C	0.935**	0.764*
	Soluble organic N	0.009 *ns*	0.354 *ns*
	NH_4^+–N	0.750*	0.305 *ns*
	NO_3^-–N	−0.059 *ns*	−0.845**
Root	Microbial biomass C	0.898**	0.540*
	Microbial biomass N	0.807*	0.490*
	Soluble organic C	0.676*	0.822**
	Soluble organic N	0.046 *ns*	0.212 *ns*
	NH_4^+–N	0.908**	0.836**
	NO_3^-–N	−0.070 *ns*	−0.969**

* = significant at $P \leq 0.05$, ** = significant at $P \leq 0.01$, and *ns* = not significant.

stimulated microbial activities and simultaneously enlarged the microbial community.

Soluble organic C (SOC) accounted for only a small proportion of the total organic matter in the soil. However, it had a significant influence on soil biological activity. This is consistent with observations made by others (Chantigny, 2003). Similar changes were observed in soil CO_2 flux and SOC, with highest content at the beginning and lower at the end of this incubation (Figures 1b and 4). Significantly positive correlation was obtained between CO_2 flux and SOC, with the correlation coefficients varying from 0.676* to 0.935** and 0.764* to 0.822** during the early (<25 days) and later stages (25–55 days), respectively (Table IV). In contrast, no obvious correlations were found between CO_2 flux and SON although SON might be available to soil microbes (Table IV).

NH_4^+–N content was rapidly increased during the initial period (<5 days), which might be attributed to NH_4^+ desorption and organic N mineralization as a result of air-drying and re-wetting (Figure 5a). NH_4^+–N content followed a similar pattern to that of soil CO_2 flux during the incubation (Figures 1b and 5a). NH_4^+–N content was positively correlated with CO_2 flux, and dependent on treatment (with and without residue additions) and incubation stage (early and later). Correlation coefficients ranged from 0.560** to 0.908** and 0.305 ns to 0.885** during the early (<25 days) and later stages (25–55 days), respectively. Significant correlations between CO_2 flux and NO_3^-–N were only obtained at the later stage (25–55 days), with negative coefficients being 0.845** to 0.996** (Table III). Both contents of NH_4^+–N and NO_3^-–N were generally lower in the treatments amended with residues than those in the control (Figure 5), which implies high C/N rice residues addition increased N immobilization, which was coincided with the changes of microbial biomass C and N (Figure 3).

4.2 N_2O flux vs CO_2 flux, MBC (N), SOC (N), and mineral N

As CO_2 described above, N_2O flux was also increased after amendment of rice residues. Significant positive correlation was found between N_2O flux and CO_2 flux (Figure 2), indicating that enhanced microbial activity after incorporation of rice residues resulted in N_2O production (Azam, Muller, Weiske, Benckiser, & Ottow, 2002). Statistical result showed that soil N_2O flux was significantly positively correlated with MBC and MBN. For N_2O flux and MBC, the correlation coefficients changed from 0.763* to 0.949** and 0.531* to 0.958** during the early (<25 days) and later stages (25–55 days), respectively. For N_2O flux and MBN, the coefficients varied from

0.539* to 0.911** and 0.571* to 0.939** for the early (<25 days) and later duration (25–55 days), respectively (Table IV). Moreover, soluble organic C may also play an important role in N_2O production, with higher correlation coefficients being 0.497* to 0.952** at the early stage (Table V), implying that denitrification might be one of the contributors to N_2O production. Other researchers also observed that the activity of denitrification enzyme was highly correlated to soil respiration (Groffman & Crawford, 2003), and denitrification rate was correlated with C supply (Weier, Doran, Power, & Walters, 1993).

N_2O production results from two biological processes, nitrification and denitrification. Generally, nitrification is the dominant contributor to N_2O production under aerobic conditions by oxidizing NH_4^+ to NO_3^-, and denitrification is the predominant under anaerobic conditions through reducing NO_3^- to N_2O (Bouwman, 1998). Thus, the dynamics of mineral N (NH_4^+ and NO_3^-) are closely related to N_2O production and emission in soils. However, observations on the correlations of N_2O flux to mineral N content (NH_4^+ and NO_3^-) are inconclusive. Some researchers reported that N_2O flux was negatively correlated with mineral N (NH_4^+ and NO_3^-) in soils (Millar & Baggs, 2004), others found positive correlation with NO_3^- content (Maljanen, Liikanen, Silvola, & Martikainen, 2003), while still others observed no correlation between the flux and mineral N (McTaggart, Clayton, Parker, Swan, & Smith, 1997). The above contradictory results reflected the complexity of factors controlling N_2O emissions, including not only mineral N (NH_4^+ and NO_3^-), but also N supply level, soil moisture, temperature and residue addition (Inubushi, Naganuma, & Kitahara, 1996; Huang et al., 2004). In this study, N_2O flux was markedly positively correlated with NH_4^+–N content at the early stage (R = 0.597* to 0.905**), and negatively with NO_3^-–N content at the later stage (R = −0.792* to −0.997**) (Table V), suggesting that both nitrification and denitrification may have contributed to N_2O production (Millar & Baggs, 2004, 2005). However, it is difficult to distinguish between the two processes in our study.

4.3 CO_2 and N_2O emissions as influenced by residue quality

In this study, the total cumulative emissions of CO_2 and N_2O were significantly different between the treatments amended with straw and root residue (Table II). The emitted CO_2 might be mainly produced from the decomposition of the rice residues incorporated in the soil, because the tested soil

Table V Correlation analysis between N_2O–N flux and biomass C and N, soluble organic C and N, and mineral N (NH_4^+ and NO_3^-) during early (0–25 days) and later (25–55 days) stages of this incubation

Treatment	N_2O–N Flux Versus	Correlation Coefficient (R)	
		<25 days (n = 15)	25–55 days (n = 9)
Control	Microbial biomass C	0.932**	0.922**
	Microbial biomass N	0.911**	0.939**
	Soluble organic C	0.497*	0.329 *ns*
	Soluble organic N	0.152 *ns*	0.395 *ns*
	NH_4^+–N	0.597*	0.517*
	NO_3^-–N	−0.164 *ns*	−0.901**
Straw	Microbial biomass C	0.949**	0.958**
	Microbial biomass N	0.884**	0.919**
	Soluble organic C	0.893**	0.372 *ns*
	Soluble organic N	0.409 *ns*	0.126 *ns*
	NH_4^+–N	0.905**	0.474 *ns*
	NO_3^-–N	−0.242 *ns*	−0.997**
Root	Microbial biomass C	0.763*	0.531*
	Microbial biomass N	0.539*	0.571*
	Soluble organic C	0.952**	0.058 *ns*
	Soluble organic N	0.414 *ns*	0.401 *ns*
	NH_4^+–N	0.692*	0.083 *ns*
	NO_3^-–N	−0.368 *ns*	−0.792*

* = significant at $P \leq 0.05$,
** = significant at $P \leq 0.01$, and
ns = not significant.

contained low organic C with 5.1 g kg^{-1}. The decomposition of the residues enhanced N_2O emission, since significant correlation was observed between N_2O flux and CO_2 flux (Figure 2). Total CO_2 and N_2O emissions and their emission factors were significantly higher in the treatment with straw than root (Tables II and III), which may be attributed to the chemical composition or quality of the residues. Compared with rice root, rice straw contained more organic C, organic N and cellulose, but less lignin content (Table I). As already well known, cellulose in the residues was readily accessible for soil microbes (Magill & Aber, 2000). Therefore, compared to root, the amendment of straw more enhanced microbial activity and stimulated CO_2 emission due to the decomposability of more cellulose contained in the straw added to the soil. Lignin content was negatively correlated with N_2O emissions in the soils incorporated with agroforestry residues (Millar & Baggs, 2004). In the present experiment, higher amount of lignin in rice root may decrease organic C degradation in the residue, and available C supply was reduced, and hence nitrification and denitrification were depressed, with the result of lower N_2O emission (Tables II and III). These findings indicated that, chemical compositions of rice residues might play an important role in predicting CO_2 and N_2O emissions in the soils incorporated with the residues. Moreover, based on our present research, the ratio of C-to-N may be unsuitable for predicting CO_2 and N_2O emissions in soils amended with residues. Higher ratio of C-to-N was found in rice straw, but the emissions of CO_2 and N_2O in the treatment with rice straw were also higher, compared to rice root with lower ratio of C-to-N (Tables I and II), which is opposite to the report from some researchers, indicating that cumulative emissions of N_2O and CO_2 were negatively correlated with the C-to-N ratio in plant residues (Huang et al., 2004). Certainly, since only two type of rice residues were tested in our experiment, further research is needed to investigate the contribution of different residues to the emissions of CO_2 and N_2O, and to assess the controlling factors in predicting CO_2 and N_2O emissions from paddy soils.

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