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RESEARCH ARTICLE

Soil CO_2 and N_2O Emissions in Maize Growing Season Under Different Fertilizer Regimes in an Upland Red Soil Region of South China

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Abstract

Upland red soils have been identified as major CO_2 and N_2O sources induced by human activities such as fertilization. To monitor characteristics of soil surface CO_2 and N_2O fluxes in cropland ecosystems after continuous fertilizer applications over decades and to separate the respective contributions of root and heterotrophic respiration to the total soil CO_2 and N_2O fluxes, the measurements of soil surface CO_2 and N_2O fluxes throughout the maize growing season in 2009 were carried out based on a fertilization experiment (from 1990) through of the maize (*Zea mays* L.) growing season in red soil in southern China. Five fertilization treatments were chosen from the experiment for study: zero-fertilizer application (CK), nitrogen-phosphorus-potassium (NPK) fertilizer application only, pig manure (M), NPK plus pig manure (NPKM) and NPK with straw (NPKS). Six chambers were installed in each plot. Three of them are in the inter-row soil (NR) and the others are in the soil within the row (R). Each fertilizer treatment received the same amount of N (300 kg ha^{-1} yr^{-1}). Results showed that cumulative soil CO_2 fluxes in NR or R were both following the order: NPKS>M, NPKM>NPK>CK. The contributions of root respiration to soil CO_2 fluxes was 40, 44, 50, 47 and 35% in CK, NPK, NPKM, M and NPKS treatments, respectively, with the mean value of 43%. Cumulative soil N_2O fluxes in NR or R were both following the order: NPKS, NPKM>M>NPK>CK, and soil N_2O fluxes in R were 18, 20 and 30% higher than that in NR in NPKM, M and NPKS treatments, respectively, but with no difference between NR and R in NPK treatment. Furthermore, combine with soil temperature at -5 cm depth and soil moisture (0-20 cm) together could explain 55-70% and 42-59% of soil CO_2 and N_2O emissions with root interference and 62-78% and 44-63% of that without root interference, respectively. In addition, soil CO_2 and N_2O fluxes per unit yield in NPKM (0.55 and 0.10 kg C t^{-1}) and M (0.65 and 0.13 g N t^{-1}) treatments were lower than those in other treatments. Therefore, manure application could be a preferred fertilization strategy in red soils in South China.

Key words: greenhouse gas emissions, carbon dioxide, nitrous oxide, manure, mineral fertilizers, straw return, South China

INTRODUCTION

The increasing release of greenhouse gas (GHG) from soil to atmosphere is an important contributor to global climate change (Smith *et al*. 2007). Carbon dioxide (CO_2) and nitrous oxide (N_2O) are the two most important GHG to contribute to global warming

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(Wang *et al*. 2005), and their release from agriculture fields are important contributors to increases in atmospheric CO_2 and N_2O (Ding *et al*. 2007; Rock *et al*. 2007). Annual global soil CO_2 emissions contribute to about 25% of the total C exchange between the atmosphere and terrestrial ecosystems (Schlesinger and Andrews 2000). About 20% of the global atmospheric sources of N_2O emissions are from agriculture soil (Mosier and Kroeze 2000). In general, the soil C and N released to the atmosphere is thought to be controlled by soil temperature and moisture, quantity and quality of soil organic content, vegetation type, microbial biomass and its activity, soil aeration, soil pH, and field management (Curtin *et al*. 2000; Weitz *et al*. 2001; Ding *et al*. 2007; Li *et al*. 2008; Lin *et al*. 2010). Changes of soil C and N and their releases to the atmosphere are particularly sensitive to management practices such as fertilization. Recently, manure applications have been identified as an essential practice that can benefit both soil fertility and agricultural production (Zhang *et al*. 2009). Therefore, it is important that we focus on the effects of manure and straw applications on cycling of soil C and N particularly their release *via* gas phases in the agriculture ecosystem.

Previous results differ on how fertilizer strategies impact on soil CO_2 and N_2O emissions. The majority of results indicated that manure applications significantly stimulate soil CO_2 and stimulate N_2O production compared with inorganic fertilizers applications (Anderson and Levine 1986; Ding *et al*. 2007). However, Meng *et al*. (2005) indicated that there was no significant difference between the effect of manure and inorganic fertilizer on N_2O emission in a sandy loam soil. Thus, appropriate applications of manure could mitigate the soil CO_2 and N_2O emissions (Bertora *et al*. 2008; Cayuela *et al*. 2010). Especially, the organic materials with high C/N ratio did not increase soil N_2O emission, such as applications of wheat straw (Cai *et al*. 2001). By contrast, application of pig manure with relative low C/N ratios to a clay loam soil significantly increased soil N_2O emission resulting from the favorable conditions provided by the manure for denitrification (Yang *et al*. 2003). Though some studies have quantified the effect of organic and inorganic fertilizers on soil CO_2 and N_2O emissions from various soil types, fertilization experiments over decades are particularly rare so that it hampers our capability to assess continuous fertilization impacts on soil CO_2 and N_2O emissions. Thus, long-term experiments are an important approach to obtain reliable information on soil C and N turnover and soil CO_2 and N_2O emissions (Johnston 1997; Zhai *et al*. 2011).

Red soil, developed from Quaternary red clay and classified as Ferralic Cambisol (FAO 1988), covers 1.13 million km^2 of China, and accounting for 11% of the nation's total land (Lu and Shi 2000). It is the dominant soil in southern China with subtropical monsoon climate. Under such a climate with high rainfall and temperature, the region may emit vast amounts of greenhouse gases. Relatively few reports have assessed soil CO_2 and N_2O emission in the region. Double cropping systems rotated with summer corn (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) dominate this agriculture region's agriculture today. Because soil CO_2 and N_2O emissions during maize growing season occupy higher emission potential than those in wheat growing season (Meng *et al*. 2005; Ding *et al*. 2007; Zhai *et al*. 2011), we choose to monitor soil CO_2 and N_2O emissions from corn in response to five continuous-applied fertilizer and organic amendments. The aims of this study, based on a 19-yr continuous fertilization experiment are: (1) to investigate how soil temperature and moisture control monthly variations of soil CO_2 and N_2O emission in different fertilization treatments; (2) to characterize effects of organic and inorganic fertilizer applications on soil CO_2 and N_2O emissions throughout the maize growing season, and (3) to quantity the contributions of root effects to total soil CO_2 and N_2O fluxes under different fertilizations.

RESULTS

Soil properties and crop yields

From November 1990 to July 2009, the soil organic carbon (SOC) contents of zero-fertilizer application control (CK), inorganic nitrogen, phosphorus and potassium combination (NPK) and inorganic NPK fertilizer with straw return (NPKS) treatments were not significant different from the original value, while the SOC contents in the 0-20 cm depth of soil of the inorganic NPK fertilizer and pig manure combined (NPKM), pig manure alone (M) treatments increased by 64 and 78% compared to the original value (Table 1). The total N content in soil treatments with manure increased 38 and 56% compared to the original value, and 57 and 63% to the control. Also, soil P and K (total P and K, Olsen-P and available K) contents in the treatments with manure were higher than in the other three treatments. During the past 19 yr, soil pH in the manure treatments (NPKM and M) increased to about 6.5 and in the NPK and NPKS treatments decreased to nearly 4.0.

Maize grain and straw yields of the NPKM and M treatments were higher than those of the other three treatments (Table 1). The application of manure clearly increased crop yield. In contrast, the yield of zero-fertilizer control (CK) decreased. The results suggested that 19 yr continuous application of manure applied enough available nutrients into the soil for acceptable crop growth, thus applications of manure or NPK combined with manure are important strategies to maintain or increase crop yield.

Table 1 Soil characteristics in the topsoil (0-20 cm) and crop yield (kg ha^{-1}) at Qiyang experimental site in the initial year (1990) and after 19 years (2009)

Year	Treatment	Bulk density (g cm^{-3})	pH$^{1)}$	SOC (g kg^{-1})	Total (g kg^{-1})			Extractable (mg kg^{-1})			C/N	Maize yield (kg ha^{-1})		
					N	P	K	N	P	K		Grain	Straw	G/S$^{2)}$
1990		1.19	5.7	8.58	1.07	0.45	13.28	79	10.8	122	8.02	609	837	0.7
2009	CK	1.31	5.9	7.36	0.94	0.45	15.63	68	3.0	60	7.83	185	612	0.7
	NPK	1.19	4.5	9.94	1.18	1.06	14.11	92	36.0	181	8.42	1351	2002	0.3
	NPKM	1.26	6.3	14.11	1.48	1.65	14.70	117	209.3	278	9.53	6303	5089	1.2
	M	1.34	6.8	15.33	1.54	1.78	14.88	140	184.2	330	9.95	5853	4835	1.2
	NPKS	1.21	4.2	8.58	1.07	1.00	12.93	87	31.2	188	8.02	2461	2490	1.0

1) 1:1 w/v water.

2) G/S means grain yield divided by straw yield.

Soil CO_2 and N_2O emission rates and fluxes

The soil CO_2 fluxes in each treatment with or without root interference were the lowest at the beginning of the growing season in late March, and soon afterwards increased gradually and reached a maximum in July with substantial fluctuations among treatments especially in June and July (Fig. 1). The trends of CO_2 fluxes with or without root interference were similar with that the maximum soil CO_2 fluxes from NPKM (855 mg m^{-2} h^{-1}), M (1 056 mg m^{-2} h^{-1}) and NPKS (1 382 mg m^{-2} h^{-1}) treatments were significantly higher than those from NPK and CK. Soil CO_2 fluxes from the NPK and CK treatments were consistently low throughout the growing season (Fig. 1).

Soil N_2O fluxes also showed obvious variations during the growing season (Fig. 2). The peak occurred on late April. The maximum soil N_2O flux from the NPKS treatment (168 μg m^{-2} h^{-1}) were the highest of the five treatments, and the soil N_2O flux was rarely lower than 3.6 μg m^{-2} h^{-1}. Similarly, soil N_2O fluxes from the control were consistently low throughout the

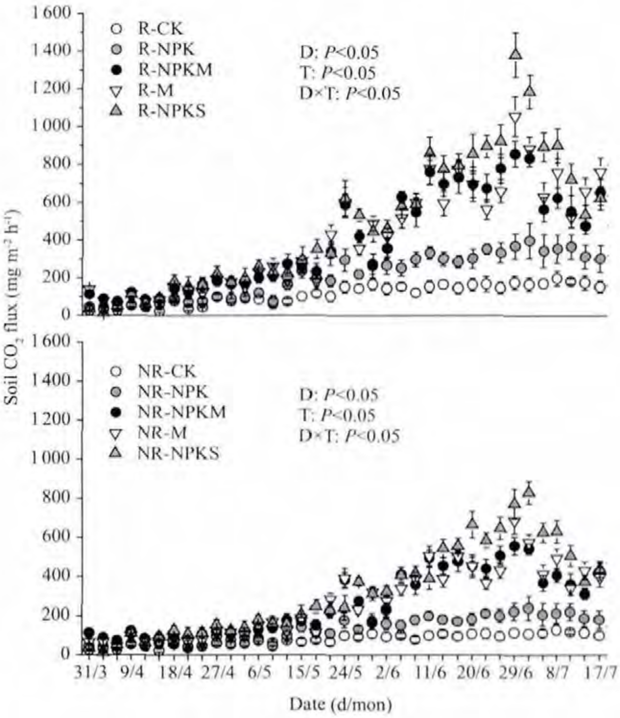

Fig. 1 Soil CO_2 fluxes with (R) or without (NR) root interference in five fertilizer strategies during maize growing season in 2009. D, date; T, treatments. Error bars denote the standard error of three replication of each treatment. The same as below.

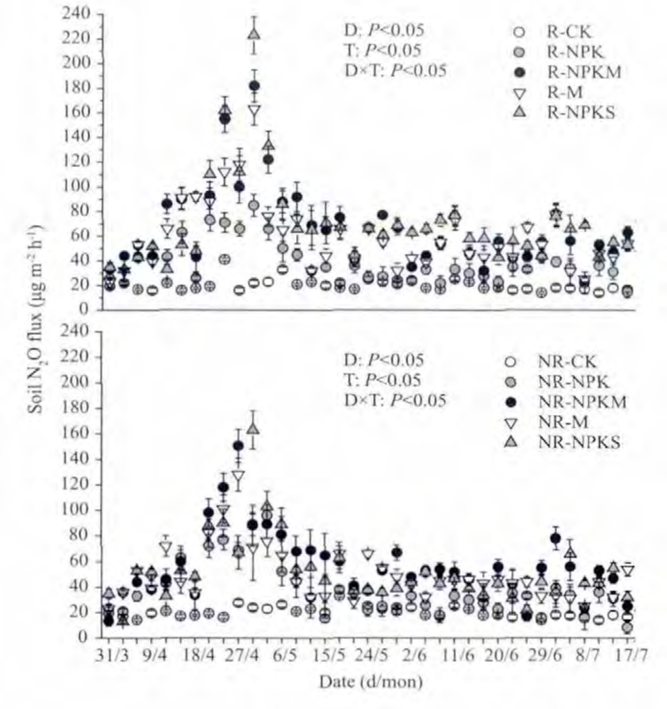

Fig. 2 Soil N_2O fluxes with (R) or without (NR) root interference in five fertilizer strategies during maize growing season in 2009.

growing season.

Our data also indicate that the highest cumulative soil CO_2 and N_2O fluxes resulted from the NPKS treatment and the lowest were from the CK with or without root interference (Table 2). The highest total CO_2 flux, up to 4 280 kg C ha^{-1} was from the NPKS treatment and was about 2.3 and 4.3 times higher than those from the NPK and CK treatments, respectively. The cumulative CO_2 flux differed among treatments, from the highest to the lowest in the following sequence: NPKS (4 280 kg C ha^{-1})>M (3 793 kg C ha^{-1})>NPKM (3 481 kg C ha^{-1})>NPK (1 489 kg C ha^{-1})>CK (995 kg C ha^{-1}). Furthermore, the contribution of root respiration to soil CO_2 fluxes was 40, 44, 50, 47 and 35% in CK, NPK, NPKM, M and NPKS treatment, respectively, with the mean value of 43%. During the experimental period the highest total soil N_2O flux from the NPKS treatment, up to 836 g N ha^{-1} was nearly 1.4 and 4.0 times higher than those from the NPK and CK treatments, respectively, but was not significantly different from the value measured from the M treatment. Thus, the following order of total soil N_2O fluxes among treatments was found: NPKS, M>NPKM>NPK>CK. In addition, soil N_2O fluxes with root interference were 18, 20 and 30% higher than that without root interference in NPKM, M and NPKS treatment, respectively, but with no difference in NPK treatment (Table 2). In addition, soil CO_2 and N_2O fluxes per unit yield in NPKM (0.55 and 0.10) and M (0.65 and 0.13) treatments were lower than those in other treatments, which indicated that long-term application of manure is a prior strategy to benefit for economic yield with the relative less greenhouse gas emissions (Table 2).

Table 2 Cumulative soil CO_2 (kg C ha^{-1}) and N_2O (g N ha^{-1}) fluxes with (R) or without (NR) root interference and CO_2 and N_2O fluxes per unit yield during maize growing season (2009) in the five fertilization treatments

Treatment	Total CO_2	CO_2/Yield	Total N_2O	N_2O/Yield
R-CK	995 e	5.38	213.2 d	1.15
R-NPK	1 849 d	1.37	481.5 cd	0.43
R-NPKM	3 481 b	0.55	749.3 ab	0.12
R-M	3 793 ab	0.65	631.1 b	0.11
R-NPKS	4 280 a	1.74	836.8 a	0.34
NR-CK	567 f	3.07	185.8 d	1.10
NR-NPK	1 109 e	0.82	442.6 cd	0.33
NR-NPKM	2 262 cd	0.36	581.4 b	0.10
NR-M	2 579 c	0.44	504.8 cd	0.10
NR-NPKS	2 996 c	1.22	585.2 b	0.24

The different lowercase letters denote significant treatment effect ($P<0.05$) during each growing stage for soil CO_2 and N_2O, respectively (n=3).

Correlations of soil temperature and moisture with gas emissions in different fertilizations

No significant difference was observed in soil temperature at soil surface ($T_{0\ cm}$) and -5 cm depth ($T_{5\ cm}$) or for soil moisture among the five treatments, thus, the average soil temperature and moisture were shown in Fig. 3. Soil $T_{0\ cm}$ and $T_{5\ cm}$ ranged from 11.4 to 32.3°C and 11.8 to 31.0°C, respectively, and the highest soil temperature of each treatment appeared at 10 July (Fig. 3). Soil moisture varied greatly from 14.5 to 40.5% during maize growing season (Fig. 3).

Our results showed that there was a good relationship between soil CO_2 flux and $T_{0\ cm}$ and $T_{5\ cm}$ throughout the experimental period (Table 3). Soil CO_2 emission was more strongly dependent on $T_{5\ cm}$ (55-78%) than $T_{0\ cm}$ (40-66%). While there is a significantly negative correlation between soil CO_2 emission and moisture (R^2 range from -0.43 to -0.53, n=74) in this dry season. Furthermore, combine soil temperature at -5 cm depth with soil moisture (0-20 cm) could explain 55-70% of soil CO_2 emissions

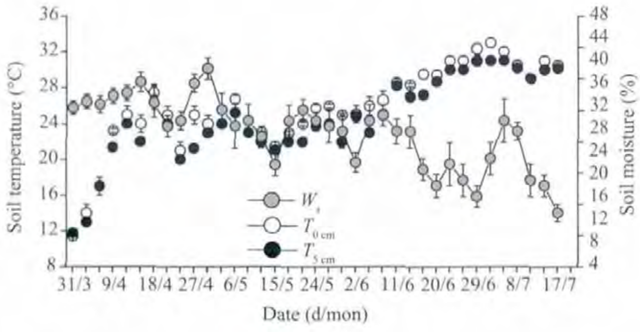

Fig. 3 Dynamics of soil surface temperature ($T_{0\ cm}$, °C), soil 5 cm depth temperature($T_{5\ cm}$, °C) and soil moisture, (W_s, %) during maize growing season in 2009. Each value was averaged across five fertilization treatments and three replicats in each treatment and Error bars denote the standard error of the averages (n=15).

Table 3 Correlation coefficients between CO_2 and N_2O emission fluxes and soil moisture (W_s) in 0-20 cm, temperature at soil surface and 5 cm depth ($T_{0\ cm}$ and $T_{5\ cm}$) in the five fertilization treatments during maize growing season (n=39)

Treatment	$T_{0\ cm}$	$T_{5\ cm}$	WFPS	$T_{5\ cm}+W_s$
CO_2				
NR-CK	0.66^{**}	0.71^{**}	-0.46^{**}	0.78^{**}
NR-NPK	0.63^{**}	0.72^{**}	-0.43^{*}	0.74^{**}
NR-NPKM	0.43^{**}	0.59^{**}	-0.45^{**}	0.66^{**}
NR-M	0.40^{*}	0.55^{**}	-0.53^{**}	0.62^{**}
NR-NPKS	0.65^{**}	0.70^{**}	-0.46^{**}	0.77^{**}
R-CK	0.51^{**}	0.66^{**}	-0.39^{*}	0.71^{**}
R-NPK	0.52^{**}	0.63^{**}	-0.42^{*}	0.72^{**}
R-NPKM	0.33^{*}	0.44^{**}	-0.40^{*}	0.59^{**}
R-M	0.40^{*}	0.48^{**}	-0.51^{**}	0.55^{**}
R-NPKS	0.55^{**}	0.59^{**}	-0.49^{**}	0.70^{**}
N_2O				
NR-CK	0.03	0.03	0.51^{**}	0.59^{**}
NR-NPK	0.09	0.09	0.61^{**}	0.63^{**}
NR-NPKM	0.21	0.03	0.29^{*}	0.47^{**}
NR-M	0.18	0.03	0.30^{*}	0.44^{**}
NR-NPKS	0.07	0.02	0.47^{**}	0.58^{**}
R-CK	0.08	0.11	0.44^{**}	0.52^{**}
R-NPK	0.13	0.23	0.48^{**}	0.55^{**}
R-NPKM	0.28	0.06	0.43^{*}	0.46^{**}
R-M	0.06	0.02	0.38^{*}	0.42^{**}
R-NPKS	0.11	0.17	0.41^{**}	0.59^{**}

* and ** indicate $P<0.05$ and $P<0.01$, respectively.

with root interference and 62-78% of that without root interference, respectively.

Soil N_2O emission was strongly related to soil moisture (R^2 range from 0.29 to 0.61, n=74), but little to soil temperature. However, combined soil temperature at -5 cm depth with soil moisture (0-20 cm) could explain 42-59% of soil N_2O emission variations with root interference and 44-63% of that without root interference, respectively (Table 3). The correlation coefficients between soil N_2O emission and moisture were lower in application of manure treatments (M) than those in the other treatments.

DISCUSSION

Control of soil temperature and moisture on soil CO_2 and N_2O emissions

Our results show that soil temperature explained 40-66% ($T_{0\ cm}$) and 55-72% ($T_{5\ cm}$) of soil CO_2 flux changes from all treatments (Table 3). Previous research indicates that soil temperature is related to soil CO_2 flux when soil moisture is above wilting point (Dilustro *et al.* 2005). By contrast, other researchers have reported no significant correlations between soil CO_2 flux and soil temperature greater than 18°C during the maize growing season (Piao *et al.* 2000), since the response of soil CO_2 flux to increased temperature is likely constrained by soil moisture (Maestre and Cortina 2003). In addition, other studies have indicated the relationship between W_s and soil CO_2 flux (Kowalenko *et al.* 1978; Davidson *et al.* 1998; Xu and Qi 2001; Lipiec *et al.* 2003; Yuste *et al.* 2003). For example, Ding *et al.* (2007) reported that this correlation was significant when moisture was <70%, and then declined sharply when moisture was >70%.

Our data also show that soil N_2O fluxes were closely related to moisture, but not to soil temperature (Table 3). Soil moisture explained 29-61% of soil N_2O flux changes during the maize growing season. The result is similar to other reports which indicate that soil N_2O emission was significantly affected by soil moisture when soil temperature was close to the optimum value or higher than 20°C (Granli and Bøckman 1994). The principal pathway of gaseous N loss is aerobic nitrification when moisture is below 60-70% in the soil, as oxygen availability for microorganisms is less limiting (Linn and Doran 1984; Weier and MacRae 1993; Bollmann and Conrad 1998). Although small pockets of anaerobic conditions may stimulate denitrification in soil micro-aggregates during wet periods, it is speculated that nitrification was the principal loss mechanism at our experimental site.

Clearly, soil CO_2 or N_2O flux result from interactive effects of T_s and W_s. For example, the soil CO_2 or N_2O flux may significantly depended on T_s when soil water content is in an appropriate range, and controlled by W_s when soil temperature is at 10°C (Dobbie and Smith 2003; Li *et al.* 2008). Thus, a bivariate model was employed to quantitatively analyze the combined effect of T_s and W_s on CO_2 or N_2O flux for each fertilization treatment. Soil temperature at -5 cm depth and soil moisture (0-20 cm) combined together explained 55-70% and 42-59% of soil CO_2 and N_2O emissions with root interference and 62-78% and 44-63% of that without root interference, respectively. Li *et al*. (2008) found that two-variable equations predicted the CO_2 flux well for whole seasonal measurements. The other similar results also supported this conclusion (Xu and Qi 2001; Yuste *et al*. 2003). Hence, two-variable models were better to estimate the regional or global CO_2 or N_2O budget under different climate conditions even extreme climates (e.g., drought, frozen period).

Long-term fertilizations impact on soil CO_2 emissions

The total soil CO_2 fluxes varied from 995 kg C ha^{-1} in zero-fertilizer control (CK) to 4 280 kg C ha^{-1} in the treatment with straw return (NPKS). Soil CO_2 fluxes in the manure and straw treatments (NPKS, NPKM and M) were significantly higher than those in the non-manure treatments (CK and NPK) which was in accordance with previous studies (Ding *et al*. 2007; Mancinelli *et al*. 2010).

In general, higher CO_2 fluxes to a higher organic C input and soil organic C content. Straw and manure application also increased the contents of soil organic matter and nutrients (e.g. soil TN, SOC and P) since the start of the long-term experiments, which was no doubt accompanied by a stimulated effect on microbial activity and thus maintain higher microbial biomass, enzymatic activity, and soil fertility. After 19 yr application of manure, SOC in the NPKM and M treatments were enhanced by 64 and 78%, with only a 15% increase in the NPK treatment and a slightly decrease in the control compared with the initial value. On the other hand, the manure application treatments led to production of more amounts of roots return to the soil and more C respiration (Schüßler *et al*. 2000; Yi *et al*. 2007). Thus, soil CO_2 fluxes from the NPKM and M treatments would be higher than that from the CK and NPK treatments. However, we found that application of inorganic fertilizer plus straw return to the red soil merely maintained soil C, N and P contents, and decreased soil pH to an extremely low level. In addition, the yield of the NPKS treatment was not different from the NPK treatment. Because straw was decomposed and mainly released to the atmosphere that resulted in an insignificant amount of straw carbon sequestered into the soils, which was reflected by the lack of increase in soil C content and Al-toxicity after 19 yr fertilization. In addition, because of the higher soil temperature, more soil organic matter, manure and straw decomposed and the intensively root respiration, and manure and straw application to the red soil obvious increased soil CO_2 fluxes in the late maize growing season (May, June and July).

The results indicated that the contributions of root respiration to soil CO_2 fluxes were 40, 44, 50, 47 and 35% in CK, NPK, NPKM, M and NPKS treatments, respectively, with the mean value of 43%. Our results were lower than the results presented by Ding *et al*. (2007) who demonstrated that the contributions of root respiration to soil CO_2 fluxes were ranged from 56 to 66% in NPK and manure application treatments during the maize growing season in a loam soil. The reason might be due to the higher native soil organic matter and organic C input decomposition rate that caused by temperature and moisture in this red soil region. Hence, the ratios of the contributions of root respiration to soil total CO_2 fluxes were lower.

Long-term fertilization impact on soil N_2O emissions

Total soil N_2O emission varied from 213 g N ha^{-1} in the control to 836 g N ha^{-1} in the NPKS treatment during the maize growing season. These values are higher than the range of 61 to 555 g N ha^{-1} monitored from sandy loam soils (Meng *et al*. 2005), and lower than that from organic farming soils (Maljanen *et al*. 2003). Yang *et al*. (2003) reported that application of pig manure with a low C/N ratio to a clay loam soil significantly increased soil N_2O emission resulting from the favorable conditions provided by the manure for denitrification. Our data also show that organic materials (manure and straw) and inorganic fertilizer contributed to 63-74% $[(N_2O\text{-}N_{treatment}-N_2O\text{-}N_{control})/(N_2O\text{-}N_{treatment})]$ of total soil N_2O emissions (Table 3).

These values are lower than the range of 74-82% monitored from sandy loam soils (Meng *et al.* 2005). The soil pH is also an important factor driving soil N_2O emissions (Simek and Cooper 2002; Cheng *et al.* 2004). In the present study the soil N_2O fluxes from manure application with higher pH were larger than those from NPK and the control with lower soil pH. However, the highest soil N_2O flux from the NPKS treatment with a lower pH is a phenomenon that also occurred in previous research in which some acidic soils showed extremely high N_2O production (Mørkved *et al.* 2007). In addition, fertilizer application and precipitation might lead to higher soil N_2O emission in the early growing season because the priming effect of fertilizer application and the favorable anaerobic conditions.

In addition, the results indicated that inter-row soil N_2O fluxes were 18, 20 and 30% less than that in the soil within the row in NPKM, M and NPKS treatments, respectively, but with no differences in NPK treatment. Sehy *et al.* (2003) conclude that annual N_2O emission in row soil was 28% higher than that in the inter-row soil under N fertilization in maize growing season. In general, the absence of a growing crop could increase summer soil temperatures, which could hypothetically increase ammonia volatilization resulting in less N remaining in the soil for N_2O formation. Furthermore, availability of organic C is an important limitation factor for soil denitrification (Picek *et al.* 2000). High availability of C in the rhizosphere provided by organic C input (manure, straw, plant root and residues, etc.) could provide a high O_2 consumption rate and promote anaerobic micro-sites around the rhizosphere. Hence, soil N_2O in manure and straw application treatments with root inference were higher than that without root inference.

CONCLUSION

Our results demonstrate that combine soil temperature at -5 cm depth with soil moisture (0-20 cm) could explain 55-70% and 42-59% of soil CO_2 and N_2O emissions in the soil within the row and 62-78% and 44-63% of that in the inter-row soil, respectively. Secondly, soil CO_2 emission increased in the late growing season, but soil N_2O emission increased more rapidly in the early growing season due to the rainfall and fertilization events. And thirdly, soil CO_2 and N_2O emissions in manure application treatments were higher than those in inorganic fertilizer and control treatment, but were significantly lower than those in inorganic fertilizer with straw return treatment. The contribution of root effects to soil CO_2 and N_2O fluxes were 35-50% and 18-30%, respectively. Particularly, soil CO_2 and N_2O fluxes per unit yield in NPKM and M treatments were lower than those in the other treatments. Therefore, manure application can be a preferred fertilization regime to promote crop yield and maintain soil fertility with relative less greenhouse gas (GHG) emissions in the region where red soils dominate in south China.

MATERIALS AND METHODS

Study site and long-term experiment

Long-term field experiments have been conducted since September 1990 at one of the field experimental stations of the Chinese Academy of Agricultural Sciences, located at Qiyang (26°45´N, 111°52´E and 120 m altitude), Hunan Province in South China. Red soil is the dominant soil type. The site has a subtropical monsoon climate with an annual temperature of 18.6°C, annual sunshine of 1 620 h, and annual rainfall of about 1 431 mm. Annual cumulative temperature when the daily temperature is greater than 10°C is *ca.* 5 600 degree-days. Some general soil characteristics regarding the long-term experiments are shown in Table 1.

There were five fertilization treatments in the long-term experiment: zero-fertilizer application control (CK), inorganic nitrogen (N), phosphorus (P) and potassium (K) combination (NPK), inorganic NPK fertilizer and pig manure combined (NPKM), pig manure alone (M) and inorganic NPK fertilizer with straw return (NPKS). There were two replicates per treatment. Each treatment plot had an area of 196 m^2 and is isolated by 10-cm-wide cement baffle plates along the boundaries. N, P and K fertilizers used were urea, calcium superphosphate, and potassium chloride, respectively. The N content in pig manure was determined annually using the method of Kjeldahl that described by Black (1965). The C content of the oven-dried manure was 382 g kg^{-1} and was determined using the vitriol acid-potassium dichromate oxidation method (Walkley and Black 1934). Quantities of fertilizer application for each treatment during the growing seasons are shown in Table 4. All treatments except CK receive the same amount of N (300 kg ha^{-1}). In the fertilizer treatments, fertilizers and manure are applied as basal dressing for summer maize, but

30% as basal dressing and the remainder as top dressing for winter wheat in mid-November, and half the amount of wheat straw was returned to the soil each year in the NPKS treatment.

Table 4 Amount of fertilizers and manure in different cropping seasons and in five fertilization treatments (t ha^{-1}) in 2009

Treatment	CK	NPK	NPKM[1)]	M[1)]	NPKS
Fertilizer N					
Wheat	-	90	27	-	90
Maize	-	210	63	-	210
Fertilizer P					
Wheat	-	16	16	-	16
Maize	-	37	37	-	37
Fertilizer K					
Wheat	-	31	31	-	31
Maize	-	73	73	-	73
Manure applied	-	-	42[2)]	60[2)]	Straw return[3)]

[1)] N deficit was compensated by N in manure.

[2)] Fresh pig manure.

[3)] Half amount of wheat straw was returned.

-, no data.

Maize growth and weather condition

The main cropping system comprises a rotation of winter wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.). In each experimental year, winter wheat was sown in early November and harvested in early May and two rows of maize were intercropped between the wheat strips (50 cm) in early April, and harvested in the middle of July. Fields were left to fallow until the growing season of winter wheat.

Temperature and precipitation data during the experimental period were collected by an automatic meteorological station close to the experimental plots. The dynamics of daily air temperature and precipitation are shown in Fig. 4. The average temperature during maize growing season in 2009 was 23.1°C. The highest temperature was found in July and the lowest in April. The precipitation during the maize growing season in 2009 was 583 mm. About 70-80% of precipitation fell between March and May.

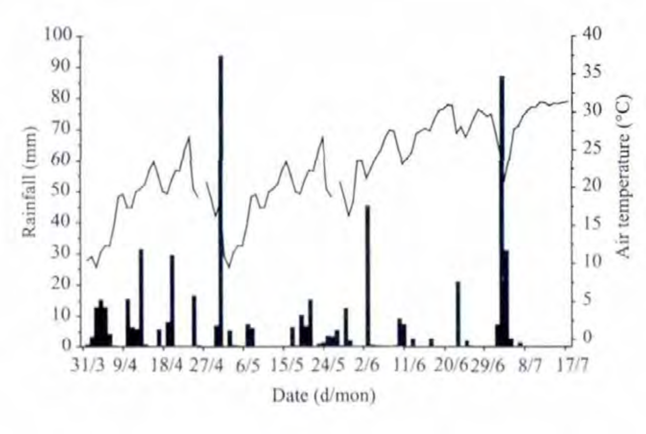

Fig. 4 Daily air temperature and rainfall at Qiyang long-term experimental site during maize growing season in 2009.

Experimental design

During maize cropping in 2009, a closed-opaque-chamber method was used to simultaneously measure CO_2 and N_2O fluxes from the soil surface in three replicate plots of each treatment. The 40 cm length, 30 cm width and 15 cm height PVC chamber (A) was inserted into the soil to a depth of 5 cm within the maize rows (with root) and the 30 cm length, 30 cm width and 40 cm height PVC chamber (B) was inserted into the soil to a depth of 30 cm between the maize rows (without root) at the center of each experimental plot after sowing. A small and silicone-sealed vent was drilled in each chamber to extract gas samples.

Soil sample collection and analysis

Soil samples were collected from the topsoil (0-20 cm) after maize harvested each year. 5-10 cores with 5 cm in diameter were randomly sampled for each plot. Soils from the cores were mixed thoroughly and then four replicates (2 kg soil for each replicate) from the soils were taken. Soil samples were air-dried and then sieved through 2-mm screen before analyzing for pH (1:1 w/v water). Sub-samples of the sieved soils were milled to 0.25 mm for the measurement of SOC and total N content (TN) with the same methods as those for pig manure described in the previous section. Other measurements include soil total P (Murphy and Riley 1962), total K (Knudsen *et al*. 1982), extractable P (Olsen *et al*. 1954) and K (Bao 2000).

Measurement of gas fluxes

Gas sampling started on 31 March and ended on 17 July. The samples were collected between 9:00 a.m. and 12:00 p.m. to minimize the effects of diurnal variation, and sampling events were occurred every 10 or 11 d during maize growing period. On each collection, four samples of chamber air were transferred manually into 50-mL syringes at 0, 10, 20, and 30 min after closure and the gas samples were transferred to pre-evacuated vials fitted with butyl rubber stoppers, and taken to the laboratory for analysis. The air temperature inside the chamber was measured using a mercury thermometer, and soil temperatures at $T_{0\ cm}$ and $T_{5\ cm}$ were measured with a digital thermometer (Model 2455, Yokogawa, Japan). Soil samples at 0-10 cm depth were collected for analysis of soil water content by oven drying at 105-110°C for 24 h, and the results were corrected by soil bulk density and expressed as WFPS (V%) .

CO_2 and N_2O samples were analyzed by gas chromatography (Agilent 6890 equipped with a flame ionization detector) for CO_2 and an electron capture detector for N_2O. The standard CO_2 and N_2O gases were provided by the Institute of National Standard Materials of China. Soil

CO_2 and N_2O fluxes were calculated using a linear increase in CO_2 and N_2O concentrations with time. The mean flux over the maize growing season is the average of all the measurement data weighted by the intervals between adjacent measurement events. The cumulative CO_2 and N_2O emissions are the products of the mean fluxes and the duration of the season.

Statistical analysis

We assumed that the difference between soils CO_2 (or N_2O) fluxes from the soil within the row (R) and the inter-row (NR) were equal to the contribution of plant roots effect on soil CO_2 and N_2O fluxes, then the root contributions to soil CO_2 and N_2O emissions were evaluated according to the following equation:

$$(f)\%=(R-NR)/R\times100$$

In order to assess the combined effect of T_s (soil temperature at -5 cm) and W_s (soil moisture at -5 cm) on R_s, bivariate models were employed to examine the relationship (Li *et al*. 2010):

$$R_s=\alpha e^{\beta T_s} W_s^{\beta_1}$$

Where, α, β and β_1 are fitted parameters.

A two-way ANOVA was applied to test effects of fertilization, date and their interaction on soil CO_2 and N_2O fluxes. The main factors include fertilization and date. The post hoc test employing Tukey-HSD was used to test main effect or interactive effect of fertilization and date. These analyses were performed in R (ver. 2.14.2, R-project, online free statistical software). Linear and exponential analysis was used to quantity the positive and negative correlations between soil CO_2 and N_2O fluxes and other factors. This statistical analysis was performed with SPSS for Windows (ver. 17.0). In these analyses, the statistical significance level was set up at $P<0.05$.

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