Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 20(2008) 1335–1340
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Nitrous oxide emissions in nonflooding period from fallow paddy fields

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Received 18 October 2007; revised 22 November 2007; accepted 12 January 2008

Abstract

The study was conducted to investigate the N_2O emissions and dissolved N_2O in the leachate during the nonflooding period in nongrowing paddy fields. Three kinds of paddy soils were repacked to soil columns and were supersaturated with water initially and dried gradually in a greenhouse to attain the N_2O emissions flux during the incubation. Soils with the texture of silty clay-loam (Q and H) produced cracks during the drying of soil, but soil with the texture of silty loam (X) did not form the cracks. Cracked soils had similar amount of N_2O emissions, and the mean N_2O flux was 1,280.9 and 1,133.3 μg/(m^2·h) from Q and H soil, respectively, during the incubation; whereas the mean N_2O flux from noncracked X soil was 426.3 μg/(m^2·h), i.e., significantly different from cracked soils. From cracked soils, the diurnal N_2O emissions reached two peaks at 14:00 and 2:00, but such emissions peaked only at 2:00 from noncracked soil. The dissolved N_2O concentrations in leachates from noncracked soil columns were greater than those from the cracked soil columns, and it indicated that the preferential flow might not affect the amounts of dissolved N_2O in leachates during soil cracking. Supersaturated dissolved N_2O in the leachate was potential source of N_2O emissions. Fallow paddy fields have big risks of N_2O emissions during nonflooding periods.

Key words: nitrous oxide emission; cracks; soil drying; paddy soil

Introduction

The estimated range of N_2O emissions from agricultural soils varies widely (Junta *et al*., 2003) because of its strong dependency on soil conditions, irrigation methods, plant types, and climate. The N_2O emissions from paddy fields are considered as the important anthropogenic source because of the widespread plant area. Generally, upland soils have much higher N_2O emissions than that of wetlands/paddy fields. The emissions rate of N_2O from flooded paddy field into the atmosphere is very low (De Datta *et al*., 1991). Flooded paddy fields are not a potential source because N_2O was further reduced to N_2. Mosier *et al*. (1989) reported that less than 0.1% of the applied nitrogen is emitted as N_2O from temperate and tropical paddy fields when the soils are flooded for a number of days before the application of fertilizer. Recent studies showed that N_2O was mainly emitted during nonflooding period (Cai *et al*., 2001; Xing *et al*., 2002) indicating that rice field could serve as a source of N_2O into the atmosphere during wetting and drying cycles, which represents about 22% of N_2O emitted from rice-based cropping systems in China (Xing *et al*., 2002). Moreover, Towprayoon *et al*. (2005) indicated that N_2O emission was related to the number of drain days rather than the frequency of drainage.

Water-saving irrigation (WSI) practices have been one of the basic national policies in China (Li, 2001). Water-saving irrigation regimes for rice has been explored since 1980s, which causes the traditional flooded fields to turn into irrigated fields, and paddy fields have different non-flooding periods. The longer nonflooding period produces soil drying. Consequently, the alternation of soil drying and wetting go through the whole rice growth in irrigated paddy fields. The alternating soil drying and wetting often result in changes of field water levels. Moreover, soil would produce cracks during the nonflooding periods, and such drying further results in some important changes in soil physical and chemical properties such as increasing temperature and perturbation of soil chemical reactions (Magid *et al*., 1999). It is obvious that the development of soil cracks can enhance the transport of water, nutrients, and gases in the soil profile that can affect crop growth in the field (Bandyopadhyay *et al*., 2003; Lu *et al*., 2000).

Macropores and cracks enable the rapid movement of water through semiimpermeable soils under both saturated and unsaturated conditions and can account for high rates of transport of surface-applied fertilizers and other solute through the soil profile. Such flows have been referred to as bypass flow or preferential flow. Preferential water flow formed easily when soil surface was cracked. Nutrient solute was leached fast by preferential flow. Previous

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researches reported that large amounts of nitrate were leached and transformed to the groundwater by preferential flow from agricultural fields (Swensen and Bakken, 1998). We were curious about whether dissolved N_2O was leached during soil cracking as well. Before harvesting of rice, irrigation is often stopped two weeks before the crop reaches maturity by WSI. After harvesting of rice, fields often are left fallow and allowed to dry before the next crop.

Although the presence and significance of soil cracks has long been inferred from field observation, typically many studies have followed a numerical approach to derive models of water and solute flux. However, the N_2O emissions from fallow paddy soils undergoing soil drying in the nonflooding and the effects of soil cracking on the N_2O emissions have rarely been studied. Moreover, the change of dissolved N_2O in the leachate needs more attention because the transfer of preferential flow may cause big accumulation of potential N_2O emissions.

Accordingly, the goals of the study were conducted to investigate soil cracking and quantify the N_2O emissions from the paddy soils with different cracking intensity during the nonflooding period with no rice growth. Specifically, this study was focused on the transport of dissolved N_2O by preferential water flow to gain the potential N_2O emission after soil surface cracking. In contrast to the traditional flooded irrigation, we tried to find another method, while at the same time not impacting on N_2O emissions, which may be detrimentally affected by practicing WSI.

1 Materials and methods

1.1 Soil samples

Three different paddy soils were collected from fallow paddy fields, two (Q and H) from Shuangqiao Farm, 120°17′E and 30°19′N; and the other (X) from Zhejiang University, 120°15′E and 30°25′N. The basic characteristics of these collected soils are shown in Table 1. The soils Q and H have the same texture, silty clay loam, but have great differences in organic matter content and total nitrogen content. However, the soil X was with silt loam texture and had especially low organic matter.

1.2 Soil column experiments

Soil column experiments, including three kinds of paddy soils, were conducted by soil drying that is generally practiced after rice harvesting in the paddy fields in southeastern China. Soil samples were air dried, pass through a 2-mm sieve, and repacked in a polyvinyl chloride column with 0.30 m in diameter and 1.0 m in depth. This series of pretreatment for soil samples is to simulate the typical tillage of paddy fields. Three replicates were performed for each soil. There was a 10-cm layer of sand at the bottom in each soil column to simulate the *in situ* fields. The soil surface was leveled at 10 cm below the top of the columns. After the soil columns were flooded continuously for approximately two weeks, they were drained completely. Soils in columns were reirrigated to oversaturation with 2 cm standing water layer above the soil surface without commercial nitrogen fertilizer application, and then they were dried gradually by evaporation in the greenhouse.

1.3 Measurements

Nitrous oxide gas was collected every day at 8:00–9:00 A.M., and N_2O emissions were determined using static chambers as described by Hutchinson and Mosier (1981) by covering a surface area of 0.09 m^2 with a volume of 0.027 m^3. Gas samples from the chambers were collected using a two-way needle through a vacuum vial with a volume of 18.5 ml. The gas samples were collected at 0, 10, 20, and 30 min after placing the chambers on the soil surface. The analysis of the collected gas samples was performed using a Gas Chromatograph (14 B, Shimadzu, Japan) with electron capture detector (ECD) from Institute of Soil Science, Chinese Academy of Sciences. Nitrous oxide concentration in the gas sample was also estimated using the ECD. N_2 was used as the carrier gas, and the flow rate was maintained at 30 ml/min, and no ascarite was used. Column, injector, and detector temperatures were set at 65, 120, and 350°C, respectively. The N_2O gas emissions were calculated by linear regression.

In addition, leachates at the outfall at the bottom of soil columns were collected to measure pH and the concentration of dissolved N_2O. The concentration of dissolved N_2O in the leachates was determined by a headspace equilibration technique as described by Liikanen *et al.* (2002) and was calculated according to the Henry's law as described by Terry *et al.* (1981). Volume of each soil crack was calculated using the total length, average width, and depth of the crack as described by Bandyopadhyay *et al.* (2003). At the same time, the topsoil samples were also collected to determine soil water content by oven-dry method in soil columns. Otherwise stated, all results are means of three replicate analysis with standard errors less than 5% of the mean value.

2 Results

2.1 Soil moisture

On day 3, the standing water on the soil surface was still about 1 cm in Q and H soil columns, but not in the X soil columns. Table 2 shows the changes of soil gravimetric

Table 1 Physical and chemical properties of the paddy soils used in the experiment

Soil	Texture	pH (water:soil = 2.5:1)	Organic matter (%)	Total nitrogen (g/kg)	Clay (%)	Silt (%)	Sand (%)
Q	Silty clay loam	6.89	2.71	2.75	32.25	67.59	0.16
H	Silty clay loam	6.30	4.59	3.82	31.76	68.43	0.81
X	Silt loam	5.64	0.60	0.92	10.42	88.10	1.48

Q and H soils are from Shuangqiao Farm; X soil is from Zhejiang University.

Table 2 Soil gravimetric content in three kinds of topsoil

Incubation time (d)	Soil gravimetric content (%)		
	Soil Q	Soil H	Soil X
4	47.4 ± 0.5	52.9 ± 0.5	34.1 ± 0.4
5	43.8 ± 0.4	44.8 ± 0.5	31.2 ± 0.3
6	37.8 ± 0.4	41.0 ± 0.5	28.8 ± 0.3
7	33.5 ± 0.4	37.0 ± 0.4	25.8 ± 0.3
8	29.8 ± 0.3	34.0 ± 0.4	23.4 ± 0.2
9	29.0 ± 0.3	29.5 ± 0.4	22.9 ± 0.2
10	27.4 ± 0.3	27.8 ± 0.3	22.2 ± 0.2
11	26.1 ± 0.3	28.4 ± 0.3	21.1 ± 0.2
12	25.1 ± 0.3	28.8 ± 0.3	21.1 ± 0.2

Data are expressed as mean ± SD.

water content from three kinds of top-soils during the later incubation. The mean soil gravimetric water content was 47.4%, 52.9%, and 34.15% in Q, H, and X soil columns, respectively, during the incubation. In general, the changes in soil moisture decrease as the incubation time increase. Soil moisture decreased sharply from day 4 to day 8 in Q soil columns; there was no significant changes after day 8. Soil moisture decreased rapidly from the day 4 to day 9 in H soil columns, and no obvious changes occurred after the 9th day during the incubation as well. For X soil, the soil gravimetric water content was lower than Q and H soil at the same incubation time, its daily change was not stronger than Q and H soil.

2.2 Generation of cracks and its development

The soil cracks occurred on day 4 for Q soil columns and on day 5 for H, but the surface of the X soil columns did not crack during the whole incubation period. The cracks of the Q and H soil columns attained the maximum levels for the following 4 days as typical progression of the cracks from their generation to maximum plateau can be seen in Fig.1. As shown in Table 3, the variations of the volumes of cracks in Q and H soils were similar. The mean volume of the cracks in the Q and H soils increased linearly from their generation to maximum attainment, and their length, width, and depth did not change when the development of cracks were stable (the volume of the crack was calculated based on the length, width, and depth).

2.3 Nitrous oxide emissions from paddy soils

The mean N_2O emissions from Q, H, and X soils were 1,280.9, 1,133.3, and 426.3 μg/(m^2·h), respectively, during the incubation. The N_2O emissions patterns were significantly different among cracked Q and H soils and

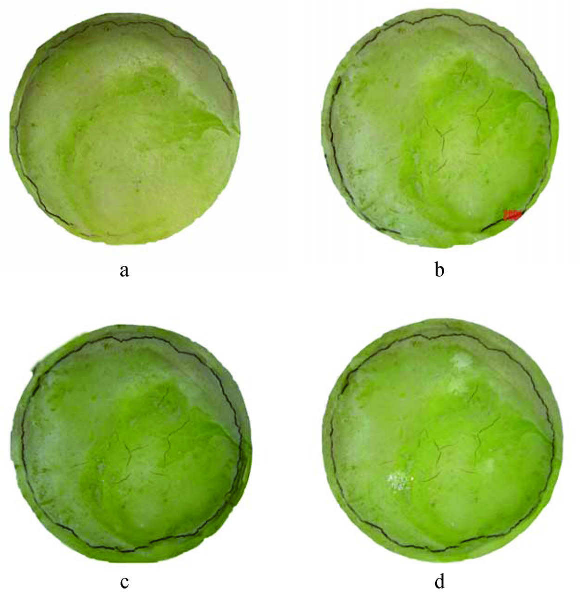

Fig. 1 Changes in cracks from generation to stabilization. (a) day 1; (b) day 2; (c) day 3; (d) day 4.

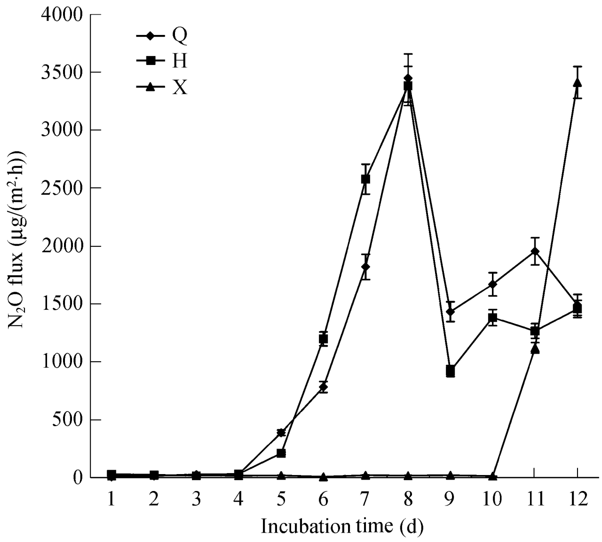

Fig. 2 N_2O emissions flux from three kinds of paddy soils during the incubation (bars indicated mean ± SD, n = 3).

noncracked X soil (Fig.2). Nitrous oxide emissions flux was much lower before the occurrence of cracks in all the experiments. Daily N_2O emission flux increased with exponential functions after incubation to attain maximum as the cracks were developing closely to maximum (from

Table 3 Characteristics of cracks developed in Q and H soil during the incubation

Time (d)	Total length (cm)		Width (mm)		Depth (cm)		Volume (cm^3)	
	Soil Q	Soil H	Soil Q	Soil H	Soil Q	Soil H	Soil Q	Soil H
4	47.3	0	5	0	2.3	0	54.39	0
5	56.75	87.3	5.5	4	4.5	3.6	140.46	125.71
6	65.45	98.7	6	4.5	5.4	4.2	212.06	186.54
7	65.6	99.4	6.9	6	5.9	4.8	267.06	286.27
8	69.1	86.5	6.5	6	8.3	5.2	372.79	269.88
9	69.2	87	6.5	6	8.3	5.2	373.33	271.44
10	69.2	87	6.5	6	8.3	5.2	373.33	271.44
11	69.2	87	6.5	6	8.3	5.2	373.33	271.44
12	69.2	87	6.5	6	8.3	5.2	373.33	271.44

day 1 to day 8). Different exponential functions for Q and H soils are as follows:

$$F_Q = 1.6973e^{0.762t} \quad R^2 = 0.964 \quad (p < 0.01;\ 1 \leqslant t \leqslant 8) \quad (1)$$

$$F_H = 3.8439e^{0.848t} \quad R^2 = 0.857 \quad (p < 0.05;\ 1 \leqslant t \leqslant 8) \quad (2)$$

where, F_Q and F_H is mean daily N_2O flux from Q and H soil column respectively; and t (d) is time of incubation. The emissions of N_2O in cracked soils peaked on day 8, and the highest emissions from Q and H soil were 3,449.1 and 3,381.2 μg/(m^2·h), respectively. The N_2O emissions decreased after day 9, and the values fluctuated at around 1,500 μg/(m^2·h) from day 9 to the day 12 in the cracked Q and H soils (Fig.2). However, from noncracked X soil, N_2O emissions were about 10–20 μg/(m^2·h) until day 10 of the incubation, but the emissions increased quickly on day 11 and peaked at 3,411.8 μg/(m^2·h).

2.4 Diurnal N_2O emission flux

Diurnal N_2O emissions were measured every 4 h in Q, H, and X soil columns from the day 10 to day 12 in which cracks had developed steadily for cracked Q and H soils. Fig.3 indicates that N_2O emissions reached peaks at 14:00 (in afternoon) and 2:00 (at midnight) from cracked Q and H soils. But N_2O emissions from noncracked X soil had only one peak period that appeared at 2:00 at midnight.

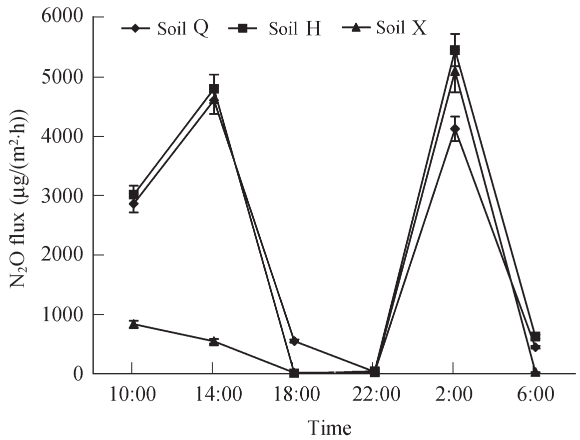

Fig. 3 Diurnal N_2O emissions from three kinds of paddy soils (bars indicated mean ± SD, n = 3).

2.5 Dissolved N_2O and pH of leachates

As shown in Fig.4a, the mean dissolved N_2O concentration of leachates were 3.37, 3.88, and 17.69 μg/L from Q, H, and X soil columns, respectively. The value of dissolved N_2O from the leachate ranged between 0.30 and 21.94 μg/L in Q columns, and 0.30 and 16.13 μg/L in H columns, and 0.75 and 40.90 μg/L in Q columns. The dissolved N_2O was below 5 μg/L in Q and H soils from day 2 to day 11 except that from H soil on day 3, which (the dissolved N_2O) was 11.03 μg/L. The highest concentrations of N_2O in leachate were 21.94 and 16.13 μg/L, respectively, from Q and H soil columns.

As shown in Fig.4b, pH from leachate of X soil was lower than that of Q and H soils. pH increased gradually from 5.8 on day 2 to 7.7 on day 11 in X soil. The maximum pH was attained on day 4 in Q and H soils, but the values fluctuated in both soils and were higher than 7 since day 3.

3 Discussion

3.1 Interactions of soil moisture, cracks, and N_2O emissions

Drying of a paddy soil usually results in soil shrinkage and cracking. Cracks are especially prominent if expanding clay minerals are present and can reach depths of 20 ± 65 cm (Cabangon and Tuong, 2000). Crack development is largely a function of moisture conditions, with progressive drying leading to shrinkage and cracking during dry periods. Significant negative linear correlations were obtained between N_2O flux and soil water content in both cracked Q (R^2 = 0.721, $p < 0.05$) and H (R^2 = 0.656, $p < 0.05$) soils. Furthermore, the cracks accelerated the evaporation of topsoil water, which resulted in the reduction of soil moisture and affected the production of N_2O in soils. At the same time, cracks increased the transfer rate of N_2O into the atmosphere. This might explain the high N_2O emission during the soil cracking.

Some differences in volumes of cracks were observed between Q and H soils because of their clay and differences in organic matter contents. In contrast to noncracked soil, the diurnal N_2O emissions showed that cracks stimulated N_2O peak emissions in earlier stage from cracked soils

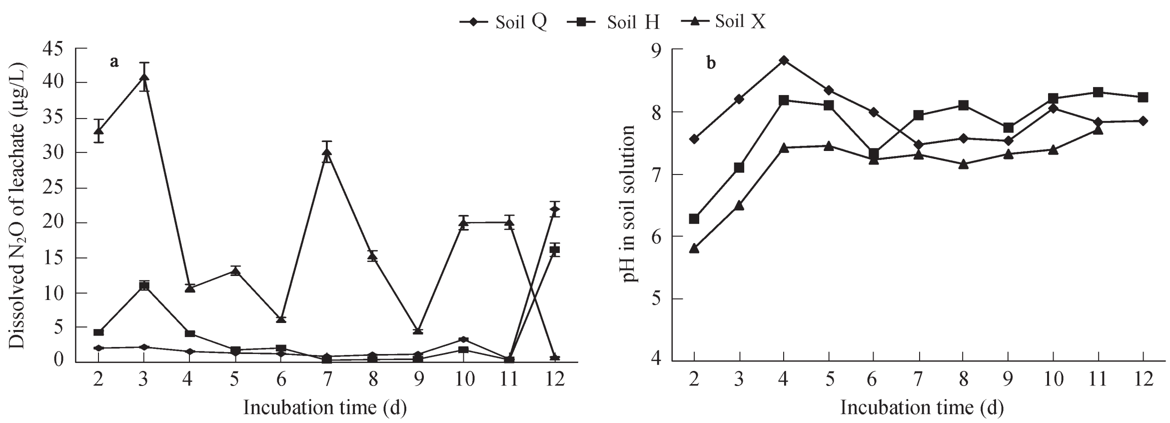

Fig. 4 Dissolved N_2O (a) and pH (b) of leachate (bars indicated mean ± SD, n = 3).

during incubation.

The exchange of O_2 increases in the soil due to crack development and affects the rate of nitrification and denitrification. Oxygen content in cracked soils is much more than in the flooded or noncracked soil. Since nitrification accelerates in cracked soils as well, more NO_3^- is available to be transformed to N_2O by denitrification. In the gradual soil drying, Q and H soils had the same silty-clay loam texture; thus, they had the similar diurnal N_2O emission patterns. The peaks and minima of diurnal N_2O emissions from cracked soils may have been closely related to the respiration and metabolism of microbes since the walls of the crack channels can support a higher microbial biomass, consequently greater microbial processes such as denitrification (Vinther *et al*., 1999). In addition, the appearance of cracks greatly increases the soil porosity, improves the status of aeration, and increases the transfer of N_2O gas from soil into the atmosphere.

As cracks developed, the power functions correlation were attained between the mean volume and N_2O flux in cracked Q ($R^2 = 0.998$, $p < 0.01$) and H ($R^2 = 0.974$, $p < 0.01$) soils, and so were the mean surface area and mean depth (Huang *et al.*, 2005). However, we also found that crack formation could primarily result from some boundary effects of the soil columns. This could lead to a possibility of overestimation of N_2O emissions in the cracked Q and H soils compared with noncracked X soil at the early stages of the incubation. Usually, cracks become steady after developing 78 d, and that is the reason why we just observed the changes of N_2O emissions.

However, in noncracked soils, the emissions reached a peak on day 11 because of the decrease in soil moisture. As shown in Table 1, the topsoil water tended to remain unchanged after the later stage of the incubation in these experiments; it might be that the topsoil water movement appeared to be balanced. The soil porosity reached the maximum because of the lowest soil moisture on day 11, which resulted in the occurrence of emissions peak. This indicated that each soil would produce a N_2O emissions peak during drying whether soil would crack. The interaction of soil moisture and cracks with N_2O emissions was complex. Thus, we could not determine which factors influenced the N_2O emissions the most, before we understand the mechanism of the cracks formation, and the variance on activity and types of microorganism accompanying the cracks. In this article, it has been shown that obvious difference of N_2O emissions accompanied the formation of soil cracks in the fallow paddy soils. It is crucial to continue investigating the correlation between N_2O emissions and soil cracks and further research on the mechanism of crack formation, types of microorganisms, and their role in N_2O emissions.

3.2 Effects of soil leachate on N_2O emissions

The concentration of dissolved N_2O in the equilibrium with the ambient atmosphere is about 0.3 μg/L; obviously, the leachates were supersaturated with N_2O in the three types of soils. As shown in Fig.4a, it was higher from noncracked X soil than cracked Q and H soils. Any N_2O in excess of the atmospheric equilibrium concentration is assumed to be released into the atmosphere sooner or later, so the dissolved N_2O in the leachate is a potential source of N_2O emissions. Since N_2O is quite soluble in water, much of the N_2O was dissolved at the soil solution, diffused through the liquid-filled pore space, and finally diffused into the leachate by preferential flow. Because preferential flow phenomena are common in many soils (Swensen and Bakken, 1998), these processes lead to increased flow velocities and to a smaller reactive-adsorptive capacity of the soil. Solute may be transported by such flow process (Jardine *et al*., 1989). Therefore, dissolved N_2O may be transported to the subsoil. Here, it seemed that preferential flow did not affect the dissolved N_2O in the leachate because the dissolved N_2O was higher in noncracked X soil than in cracked Q and H soils. As described previously, cracked soils (Q and H) emitted much more N_2O gas than noncracked X soil; that is why the residue N_2O in cracked soils was less than in the X soil, indicating that the more soil emitted N_2O, the less dissolved N_2O in leachate. Although the dissolved N_2O caused more diffusion of N_2O into the atmosphere from cracks, there was no significant correlation between N_2O emissions and the dissolved N_2O in leachate because the preferential water flow changed the solute move in the pore-water. In addition, the thick soil columns with 80-cm depth could lag and block N_2O emissions from the leachate.

Nitrous oxide emissions from paddy field during rice growing period are correlated with soil redox potential (Xing *et al*., 2002), and redox potential affects pH, in turn, N_2O emissions. The optimum pH range for denitrification is 7.0–8.0. The pH levels lower or higher than this range (7.0–8.0) cause inhibition of N_2O reductase and influence the N_2O accumulation. Most of the pH levels in the leachates were in the range of 7.0–8.0. However, there was no significant correlation between pH in leachates and N_2O emissions because the pH of leachates is different from the pH of soils.

4 Conclusions

Nitrous oxide emission peaks were attained during nonflooding period in fallow irrigated paddy soils. There are positive correlation between soil cracking and N_2O emissions. The diurnal N_2O emission dynamic from cracked soils had two peaks that appeared at 14:00 and 2:00, but there was only one peak that appeared at 2:00 from noncracked soil. Dissolved N_2O in the leachate was a big potential to emit N_2O. Since fallow paddy fields are key contribution to N_2O emissions during nonflooding period, it is necessary to control irrigation methods to reduce N_2O emission in fallow paddy fields.

Acknowledgments

This work was supported by the National Basic Research Program (973) of China (No. 2002CB410807).

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