JEB™
Website : www.jeb.co.in
E-mail : editor@jeb.co.in

Journal of Environmental Biology

ISSN: 0254-8704 (Print)
ISSN: 2394-0379 (Online)
CODEN: JEBIDP

Study on CH_4 and N_2O emissions from water-saving irrigation in Phaeozem paddy fields in cold areas

F. Q. Wang[1,2,*], W. Guo[1], S. J. Zhu[3] and X. L. Gong[4]
[1]Department of Water Conservancy Engineering, North China University of Water Resources and Electric Power, Zhengzhou-450045, P. R. China
[2]Collaborative Innovation Center of Water Resources Efficient Utilization and Protection Engineering, Henan Province, Zhengzhou 450045
[3]College of Hydraulic and Environmental Engineering, China Three Gorges University, Yichang-443002, P. R. China
[4]Key Laboratory of Water-saving Agriculture, Heilongjiang Education Department, Harbin-150030, P. R. China
*Corresponding Author E-mail: **fortunewang@163.com**

Abstract

Increasing greenhouse gas emissions and water shortage are two main problems associated with cultivation of rice. Soil moisture control is not only a core technology in water-saving irrigation, but also a decisive factor of greenhouse gas emissions. The CH_4 and N_2O emission fluxes from intermittent irrigation and flooding irrigation in Phaeozem paddy fields in cold area were measured *in-situ* to provide a theoretical basis for studying the regulation of CH_4 and N_2O emissions and comprehensive assessing the effect of intermittent irrigation on the environment and control of greenhouse gas emissions. During the rice growing period, CH_4 emissions peaked at the tillering stage, whilst N_2O emissions peaked twice at the tillering and milky ripening stages. The accumulated emission of CH_4 from the implementation of flooding irrigation in paddy fields was 6.46 gm^{-2}, whilst that from intermittent irrigation was 5.47 gm^{-2}. The accumulated emission of N_2O from the implementation of flooding irrigation in paddy fields was 36.88 mgm^{-2}, whilst that from intermittent irrigation was 68.47 mgm^{-2}. The global warming potential of CH_4 and N_2O was 1362.71$kgCO_2ha^{-1}$ from intermittent irrigation in paddy fields, a value 108.12 $kgCO_2ha^{-1}$ lower than that from flooding irrigation. Intermittent irrigation can thus be used to effectively decrease and control the combined greenhouse effect of CH_4 and N_2O emissions from rice paddy fields.

Publication Info
Paper received:
22 October 2015

Revised received:
27 April 2016

Re-revised received:
5 May 2016

Accepted:
23 June 2016

Key words

Emission flux, Greenhouse effect, Greenhouse gas, Intermittent irrigation, Phaeozem in cold area, Water-saving irrigation

Introduction

The area covered by paddy fields in China accounts up to 20% of the world total, and about one-third of the total crop field area in China. However, water shortage problems are experienced in both northern and southern regions of the country. Hence, the study on water-saving irrigation techniques in paddy fields is of great practical significance.

Paddy fields are important sources of CH_4 and N_2O emissions. CH_4 emissions from the cultivation of rice account for 20% of the total global CH_4 emissions (Yuan *et al.,* 2009), and the N_2O emissions from rice cultivation are also high. The greenhouse effects of CH_4 and N_2O are twenty one times and three hundred ten times more than that of CO_2, respectively. The annual increase in atmospheric CH_4 and N_2O levels are 4.99 ppb and 0.8±0.2 ppb per year (Yue *et al.,* 2003).

Related research results have shown that soil moisture could be a dominant factor affecting greenhouse gas emissions from paddy fields. Therefore, if water-saving irrigation techniques is to be implemented in paddy fields, the problem of water shortage and emission of greenhouse gases can be resolved effectively. In Heilongjiang, Northeast China, where rice paddy fields cover an area of up to 3 330 000 hm^2, there is an urgent need to solve these two problems.

However, until now, studies on CH_4 and N_2O emissions from paddy fields have mainly focused on fluvoaquic soil, red soil and paddy soil in the south of China (Yue *et al.,* 2003; Yuan *et al.,* 2008). Few studies have been carried out on Phaeozem paddy fields in cold areas, or on greenhouse gases emissions from paddy fields utilizing water-saving irrigation techniques.

In the present study, CH_4 and N_2O emission fluxes from intermittent irrigation and flooding irrigation Phaeozem paddy fields in cold areas were measured *in situ*, and the results were analyzed. These provided a theoretical basis for comprehensive assessment of the effects of different water-saving irrigation processes on CH_4 and N_2O emissions and a mean for optimizing the most appropriate irrigation technique.

Materials and Methods

Experimental site : The geographical coordinates of the Heilongjiang Rice Irrigation Central Station are 45° 63' N, 125° 44' E. This site is in cold area, with Phaeozem soil, a field capacity of 39.60%, dry bulk density of 1.10 g cm^{-3}, organic matter content of 4.96%, total nitrogen content of 0.188%, total phosphorus content of 0.083%, total potassium content of 1.89% and pH 6.05. The site has an annual mean temperature of 2-3°C, annual effective accumulated temperature (greater than or equal to 10°C) between 2500°C and 2800 ºC, solar radiation amounting to 4000-4300 MJ $m^{-2}a^{-1}$, annual mean rainfall of 500-600 mm and annual mean evaporation of 700-800 mm. The crop growth period was between 156 and 171 days, (mean: 164 days), with annual frost-free period of 128 days. It is a cool-temperate zone having windy and dry in spring, hot and rainy in summer, cool and moderate in autumn and cold and dry in winter.

Experimental treatments : The rice variety No.2 BFLZ was grown under similar conditions (in terms of seedlings, transplanting, density, fertilization and pesticide use) in all of the experimental treatments. Intermittent irrigation was used as water-saving irrigation technique and flooding irrigation was carried out for comparison. There were a total of six experimental plots: 2 treatments each with 3 replicates. Each plot area was 10m×10m, around which were planted some rice as protection lines. To decrease lateral penetration, impervious materials were installed between the plots. The materials employed were plastic boards and cement ridges, which were buried 40 cm below the field surface. A square stainless steel base was placed 10 cm below the field surface in the center of each plot of dimension 50cm×50cm×15cm. The base was used for the collection of greenhouse gas samples and estimation of gas emission fluxes.

The transplant date was 7 June (2012), the plant density was 30cm×10cm, (3 plants per point), harvesting was done on 22 September(2012), (total growth days: 108). All of the treatments received same fertilizer application, details of which are listed in Table 1. The water management standards for different irrigation modes are listed in Table 2.

Sampling : The CH_4 and N_2O emission fluxes were measured using a static chamber *in-situ*. The static chamber was made of Plexiglas, and comprised of a top box, a middle box, and a stainless steel base. There was a seal groove at the top of bottom stainless steel (width: 2 cm, depth: 5 cm). A hole (diameter: 2 cm) was present on the sidewalls of stainless steel base, buried below the surface. The dimensions of the middle box was 50cm×50cm×50cm, with a seal groove having dimensions identical to those of the top of the base. The dimensions of the top box were 50cm×50cm×50cm. The boxes were covered with insulated material.

The gas sample collection time was selected between 10:00 hrs and 11:30 hrs (Kanno *et al.,* 1997; Xu *et al.,* 1999; Li *et al.,* 1998; Buendia *et al.,* 1998; Hou *et al.,* 2000). First, the mini fan was operated for 2-3 min to ensure adequate mixing of the gases in the static chamber, and then, the gas samples were collected. Time and temperature readings were recorded simultaneously. A total of four gas samples were collected at 0, 10, 20, and 30 min after the collection process began.

Laboratory analysis : The gas samples collected were taken to the laboratory for prompt analysis. The analysis equipment was a gas chromatograph (SHIMADZU GC-14B). A hydrogen flame ionization detector (FID) was used to detect CH_4 (Li *et al.,* 2007). A thermal conductivity detector (TCD) or electron capture detector (ECD) was used to detect N_2O. The other configuration conditions are listed in Table 3. According to the peak area of standard gas and its concentration, a standard calibration curve was produced.

Using this standard curve, gas concentrations was calculated from the corresponding gas peak area.

The gas was injected by using a micro-injector. Before injection, the gas concentration was predicted according to experience and the last gas concentration. Then, a suitable concentration of standard gas was selected to fit the standard curve, for which the correlation coefficient was more than 0.999. The standard CH_4 and N_2O gases were provided by MAX LTD.

Gas flux equation : Greenhouse gas emission fluxes were calculated under the assumption that the gases were exhausted or absorbed at a certain speed (Huang, 2003).

In a closed system, the initial gas concentration was C_0; after a certain period t, it became C. Then, the gas concentration equation was $C=kt+C_0$. The slope of the equation was k=dC/dt, which represented the change in gas concentration per unit time. The area of cross-section of sampling gas was A, the effective height in the box was H, and the volume of gas in the box was AH. The gas emission flux per unit area was :

$$F=\frac{dm}{dt\cdot A}=\frac{\rho\cdot AH\cdot dC}{dt\cdot A} \qquad (1)$$

According to the ideal gas equation of state (Clapeyron equation):

$$PV=\frac{m}{\mu}R(T+273.15) \qquad (2)$$

The gas density equation was obtained from:

$$\rho=\frac{m}{V}=\frac{P\mu}{R(T+273.15)} \qquad (3)$$

Equation (3) can be substituted into equation (1) and equation (4) is obtained:

$$F=\frac{P\mu}{R(T+273.15)}\cdot H\cdot\frac{dC}{dt} \qquad (4)$$

Equation (4) shows gas emission flux equation, indicating change in mass of gas per unit time and unit area.

where, F is the gas emission flux $mg{\cdot}m^{-2}{\cdot}h^{-1}$; P is the average gas pressure in the sampling box, which is assumed to be the standard atmospheric pressure 1.012×155Pa; μ is the gas mass per mol ($g{\cdot}mol^{-1}$); R is the universal gas constant (8.314J mol^{-1} K^{-1}); T is the average gas temperature in the sampling box (ºC); H is the effective height (m) in the box, which refers to the height from the water surface to the top of the box when water was present in the field, and the height of the box itself when there is no water.

The molar mass of CH_4 was 16.043 (g mol^{-1}) and the molar mass of N_2O is 44.013(g mol^{-1}). Hence, the equations below can be derived accordingly. The equation for CH_4 emission flux is given below :

$$F=\frac{16.0425\times1.01235\times10^{5}}{8.31441(T+273.15)}\cdot H\cdot\left(\frac{dC}{dt}\times60\times10^{-6}\right)=\frac{11.71986}{T+273.15}\cdot H\cdot\frac{dC}{dt} \qquad (5)$$

The equation for N_2O emission flux given below:

$$F=\frac{44.013\times1.01235\times10^{5}}{8.31441(T+273.15)}\cdot H\cdot\left(\frac{dC}{dt}\times60\times10^{-6}\right)=\frac{32.15359}{T+273.15}\cdot H\cdot\frac{dC}{dt} \qquad (6)$$

Results and Discussion

CH_4 emissions : Fig. 1 indicates CH_4 emission for different irrigation modes in rice fields for every stage during growth period. It not only showed CH_4 emission fluxes, but also the regularities of emission, and difference for the irrigation modes. Water management in rice fields had an important effect on CH_4 emission during every stage of the growth period. Fig. 1 clearly shows that the CH_4 emission flux associated with flooding irrigation in paddy fields peaks once (at the tillering stage). At the turning green stage, the CH_4 emission flux was very little. At tillering stage, the CH_4 emission flux rose abruptly to a peak ($5.142mg{\cdot}m^{-2}{\cdot}h^{-1}$), which lasted for about 28 days. Then, at the jointing-booting and heading-flowering stages, the CH_4 emission flux began to decrease, but was still at elevated level of 3.279 mg m^{-2} hr^{-1} and 3.824 mg m^{-2} hr^{-1}, respectively. This period lasted for 22 days. At milky and yellow ripening stages, the CH_4 emission flux decreased further to 1.550 mg m^{-2} h^{-1} and 0.952 mg m^{-2} h^{-1}, respectively.

Fig. 1 indicates that for intermittent irrigation in rice fields, CH_4 emissions peaked twice (at the tillering and heading-flowering stages). At tillering stage, the emission flux increased to highest level across all the growth stages (4.329 mg m^{-2} hr^{-1}). At the jointing-booting stage, the emission flux decreased gradually. At heading-flowering stage, the emission flux increased again, but to a smaller peak (2.772 mg m^{-2} hr^{-1}). Across all the growth stages, CH_4 emission associated with the intermittent irrigation of rice fields was higher at the tillering, jointing-booting, and heading-flowering stages, because of efficient water management. The characteristic of alternating between shallow and deep water level was good for anaerobic environment under the conditions of an existing water layer. This produced large amount of methane, for overflowing of unoxidized methane under the condition of no water layer. Meanwhile, it accelerated the decomposition of organic matter in the soil. Additionally, these were periods of vigorous growth where the rice plants developed to their reproductive stage. During these phases, plants emited significant volumes of CH_4 gas. At milky and yellow stage, due to decreasing water consumption and final growth, CH_4 emission decreased gradually.

From the above analysis, it was observed that for every growth stage, the total CH_4 emission flux associated with the use of flooding irrigation in rice field was higher than that from intermittent irrigation. For both flooding irrigation and intermittent irrigation, CH_4 emission peaks appeared at the tillering stage. At turning green stage, CH_4 emission from both flooding irrigation and intermittent irrigation was smaller: which was probably related to the transplanted rice plants turning green and initial establishment of water layer.

N_2O emissions : Fig. 2 presents N_2O emission fluxes from both intermittent and flooding irrigation of rice fields for every stage during growth season. There were two N_2O emission peaks out of six growth stages of rice, during tillering and milky ripening stages. The regularities of N_2O emissions from two irrigation modes were different. The irrigation mode was seen to have a significant effect on N_2O emissions during rice growth period. N_2O emission associated with flooding irrigation in paddy fields is lower than that of intermittent irrigation for every growth stage. Under flooding irrigation condition, a deep water layer existed over a long period to form a strict anaerobic environment. This enabled completion of denitrification process and for much of the N_2O produced in the process to be decomposed as N_2. N_2O emissions from flooding irrigation showed a single peak characteristic. At turning green stage, emission flux was low (5.67 g m^{-2} hr^{-1}). At tillering stage, the flux increased sharply to the highest point (39.3 g m^{-2} hr^{-1}); subsequently, at jointing-booting stage, the flux decreased sharply (5.91 g m^{-2} hr^{-1}). At heading-flowering and milky ripening stages, the emission flux decreased to its lowest points of 2.91 g m^{-2} hr^{-1} and 2.88 g m^{-2} hr^{-1}, and at yellow ripening stage, it increased slightly (7.44 g m^{-2} hr^{-1}). The regularity of N_2O emissions from flooding irrigation in rice field was related to water management associated with flooding irrigation and other field management measures. Before rice turns green, the paddy was fertilized with a certain amount of basic fertilizer. At tillering stage, the second fertilizer was applied. The two fertilizer applications provided sufficient. Paddy field drainage at late tillering stage changed the aeration status of soil in paddy field and supplemented the oxygen required for nitrification process. So, at tillering stage, the first N_2O emission peak occured. After tillering stage, there was a layer of water in the rice field again, and an anaerobic environment was formed in the root soil. Hence, at the following jointing-booting, heading-flowering and milky ripening stages, all the N_2O emissions were low. At yellow ripening stage, the rice paddy field became dry naturally and the water layer disappeared, because of which the anaerobic environment no longer existed. And then, there was a second N_2O emission peak which was produced as intermediates in the nitrification and denitrification processes occurring in paddy fields.

Fig. 2 shows that N_2O emissions from intermittent irrigation in paddy fields had two peaks: one at tillering stage and other at yellow ripening stage. Compared to flooding irrigation, the N_2O emissions from intermittent irrigation in paddy fields were significantly higher. Under the conditions of intermittent irrigation, the first N_2O emission peak appeared at the tillering stage. After that, the N_2O emissions decreased sharply. At the jointing-booting, heading-flowering and milky stages they again increased slowly until yellow ripening stage, when the second emission peak appeared. Regulation of alternate shallow and deeper water layers associated with intermittent irrigation constantly changed the anaerobic and aerobic conditions of soil environment in rice fields which promoted N_2O production and emission. Therefore, there was an increasing trend of N_2O emission at jointing-booting and heading-flowering

Table 1 : Fertilizer application data

	Nitrogen	Phosphate	Potash
Base fertilizer	72 kghm^{-2}	72 kghm^{-2}	104 kghm^{-2}
Tillering fertilizer	54 kghm^{-2}	0	0
Panicle fertilizer	36 kghm^{-2}	18 kghm^{-2}	26 kghm^{-2}
Grain fertilizer	18 kghm^{-2}	0	0

Table 2 : Water depth (in cm) in paddy field for different irrigation modes

	Turning green	Early tillering	Tillering	Late tillering	Jointing-booting	Flowering	Milky	Ripening
Intermittent irrigation	0-30	0-40	0-40	Drainage	0-30	0-40	0-40	drying
Flooding irrigation	0-30	0_80	0-80	Drainage	0-80	0-80	0-80	drying

Table 3 : Configuration of gas chromatograph

Target compound	CH_4	N_2O	N_2O
Column	GDX-502	Porapak Q	Porapak Q
Carrier gas and its flow (ml min^{-1})	N_2,18	N_2, 18	N_2,18
Oven temperature (°C)	100	80	60
Detector and its temperature (°C)	FID, 200	TCD, 100	ECD, 300
Retention time (min)	1	0.5	0.5

stage, and at yellow ripening stage the second N_2O emission peak appeared.

Accumulated emission of CH_4 and N_2O and their greenhouse effects : Fig. 3 shows accumulated CH_4 emission and Fig. 4 shows accumulated N_2O emission for the whole growth period. Over the whole rice growth period, for flooding irrigation in paddy fields, the accumulated CH_4 emission was 6.46 gm^{-2} and accumulated N_2O emission was 36.88 mgm^{-2}. For intermittent irrigation, the accumulated CH_4 emission was 5.47 gm^{-2} and the accumulated N_2O emission was 68.47 mgm^{-2}. Fig. 3 shows that the accumulated CH_4 emission from intermittent irrigation in rice paddy fields was 15.3% lower than that of flooding irrigation. Fig. 4 shows that accumulated N_2O emission from intermittent irrigation in paddy field was 86.5% higher than that of flooding irrigation.

For the whole growth period, the average CH_4 emission flux from flooding irrigation in paddy field was 2.49 mg m^{-2} hr^{-1} whilst that from intermittent irrigation was 2.11 mg m^{-2} hr^{-1}. The average N_2O emission flux from flooding irrigation in paddy field was 14.23 µg m^{-2} hr^{-1} and that from intermittent irrigation was 26.53 µg m^{-2} hr^{-1}.The CH_4 and N_2O emission from paddy fields are important effects on climate change. The results above showed that water-saving irrigation could sharply decrease CH_4 emission from paddy fields, but this technique also increased N_2O emission. GWPs are often used to represent relative radiation effects of different greenhouse gases of same mass. Hence, different GWPs are directly related to the greenhouse effects of certain gases. Some studies have shown that on centennial-scale climate change, the GWPs of CH_4 and N_2O were not same. Three sets of data highlighting these differences were as follows: 32 and 200 (IPPC, 1995), 23 and 296 (Cai, 1999), 21and 310 (Bhatia *et al.,* 2005).

In the study, 21 and 310 were used to calculate the greenhouse effects of CH_4 and N_2O emission for different irrigation techniques used in paddy fields. The results are listed in Table 4. Which shows that the greenhouse effect of CH_4 from intermittent irrigation in rice field is 1149.52 $kgCO_2ha^{-1}$. Which was 206.99 $kgCO_2ha^{-1}$ lower than flooding intermittent irrigation. The greenhouse effect of N_2O from intermittent irrigation in paddy field was 213.19 $kgCO_2ha^{-1}$, which was 98.87 $kgCO_2ha^{-1}$ higher than flooding irrigation. The total greenhouse effect of CH_4 and N_2O emissions from intermittent irrigation was 108.12 $kgCO_2ha^{-1}$ lower than flooding irrigation.

Influence of irrigation mode on CH_4 emission : The above analysis showed that the water status in fields for different irrigation modes had a clear effect on CH_4 emission (Ghosh *et al.,* 2003). Compared with flooding irrigation, intermittent irrigation substantially decreased CH_4 emission.

CH_4 is the product of methanogenic activity during degradation of the organic matter. Methanogens are anaerobic bacteria, which require a strict anaerobic environment. Under the conditions of flooding irrigation in rice fields, there was a layer of water in the field for a long period which formed anaerobic environment suitable for anaerobic methanogens. Therefore, in paddy field where flooding irrigation is implemented, CH_4 emissions are significantly higher. However, in paddy field with intermittent irrigation, water management involves alternating shallow and deep water levels after tillering stage. This changed soil aeration conditions to destroy the anaerobic environment required by methanogens. In addition, CH_4 produced by methanogens still existing in soil is consumed by methane-oxidizing bacteria as their only energy source and carbon source. From tillering stage onwards, under intermittent irrigation conditions in rice fields, water management is alternate, shallow and wet and soil is in a cycle of shallow and deep water level. If there is a layer of water, anaerobic environment is formed and CH_4 emission is high. When the water layer disappears and soil aeration conditions change, the anaerobic environment is destroyed and this leads to lower emissions of CH_4.

CH_4 production, oxidation and emission refer to chemical and physical action by microorganisms (Bosse *et al.,* 1998). Hence, factors that affect these processes can have effect on final CH_4 emission. These factors can be environmental, such as physical and chemical characteristics of soil, soil moisture, fertilizer application, climate and growth changes in rice plantss (Wang *et al.,* 1997), such as stem and tiller, plant height, dry mass weight, LAI, photosynthetic rate, and respiration rate. Different irrigation modes not only cause different soil environment but also affect plant growth. These, in turn, affect CH_4 emission.

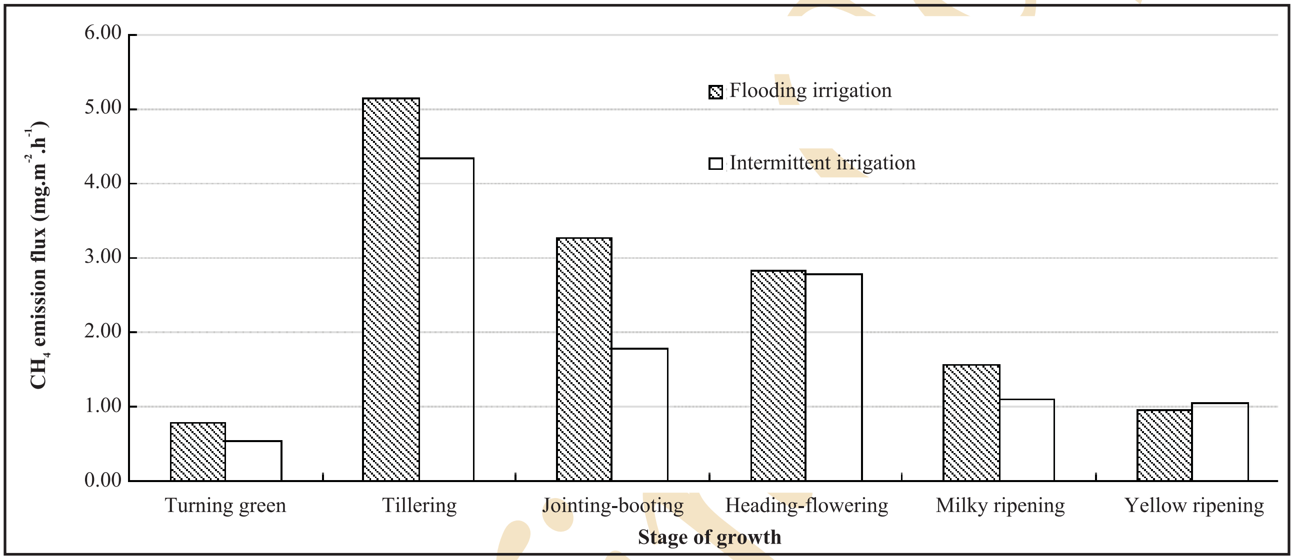

Fig. 1 : Regularity of CH_4 emissions under different irrigation modes during growth periods

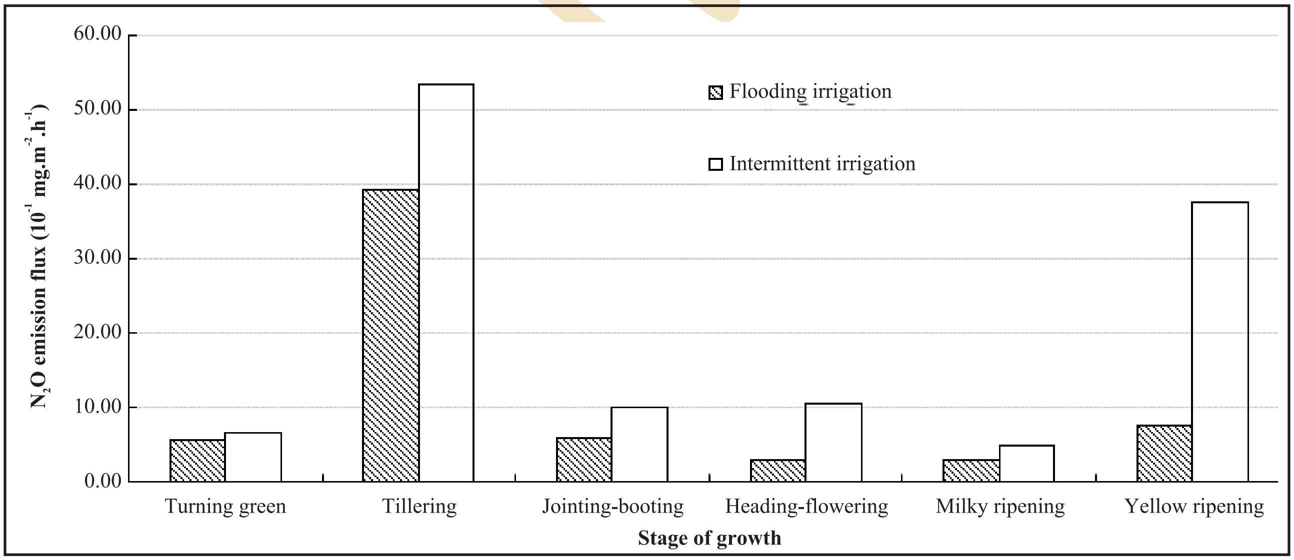

Fig. 2 : Regularity of N_2O emissions under different irrigation modes during growth periods

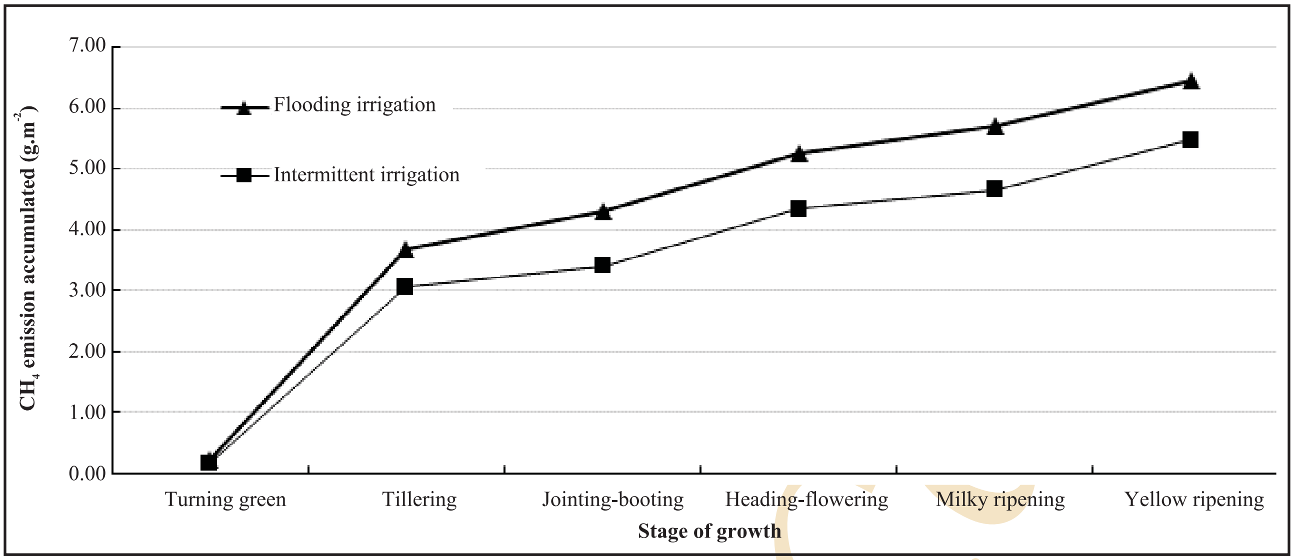

Fig. 3 : Accumulated CH_4 emission for different irrigation modes

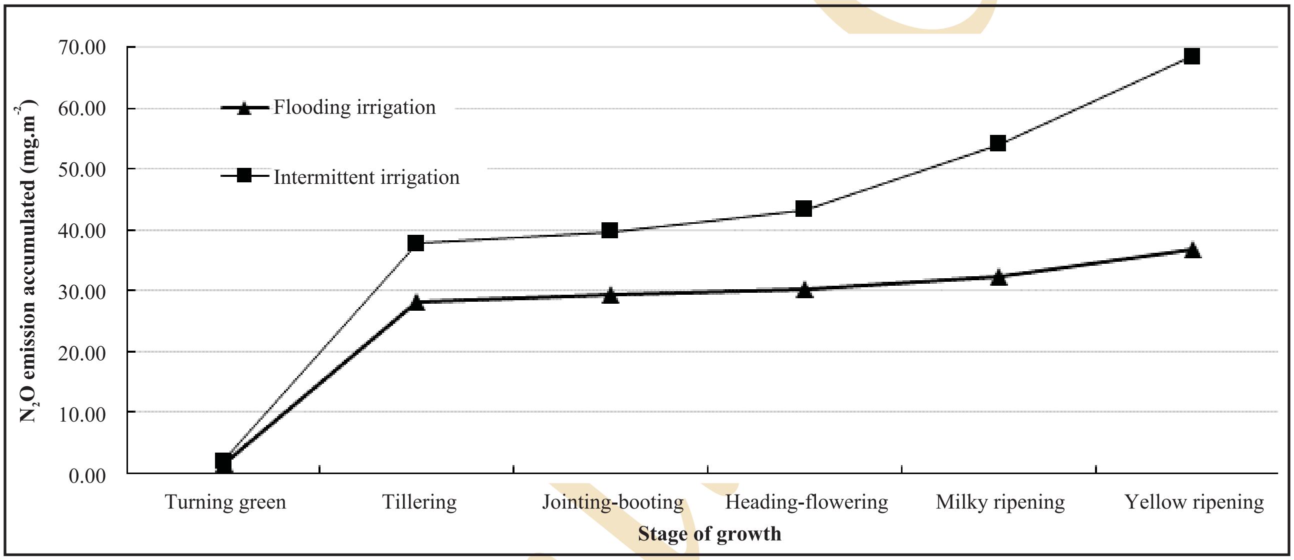

Fig. 4 : Accumulated N_2O emission for different irrigation modes

Influence of irrigation mode on N_2O emissions : The soil water status in rice fields caused by different irrigation modes not only had a significant effect on CH_4 emission, but also on N_2O emission (Usui *et al.*, 2001).

N_2O emission from paddy field soil mainly comes from nitrification and denitrification processes of microorganisms under the conditions of soil-rice system interaction (Cai *et al.*, 1997). The nitrification process needs good ventilation, and this was achieved by joint action of aerobic nitrifying bacteria and nitrobacteria. Denitrification process is reverse of nitrification, which is carried out by anaerobic denitrifying bacteria in the anaerobic environment. Both nitrification and denitrification can produce N_2O, and the respective production proportions are determined by soil water content (Bender *et al.,* 1993).

Generally, nitrification becomes weaker as soil water content increases. However, under conditions of flooding irrigation, the soil of paddy fields form strict anaerobic environment which makes denitrification process complete. It makes some N_2O emission as N_2 and other N_2O

Table 4 Greenhouse effect of CH_4 and N_2O emission of different irrigation modes

Irrigation mode	N_2O emission (mgm^{-2})	CH_4 emission (gm^{-2})	Greenhouse effect of N_2O ($kgCO_2ha^{-1}$)	Greenhouse effect of CH_4 ($kgCO_2ha^{-1}$)	Total greenhouse effect ($kgCO_2ha^{-1}$)
Flooding irrigation	36.88	6.46	114.32	1356.51	1470.83
Intermittent irrigation	68.77	5.47	213.19	1149.52	1362.71

deoxygenized as N_2 in the process of diffusion and transference. Therefore, N_2O emission under flooding irrigation condition is relatively low. Under intermittent irrigation condition, management of alternate shallow and wet condition changes the soil water content sharply, and nitrification and denitrification processes happen alternately. Hence, the amount of N_2O is produced as intermediate. At tillering and yellow ripening stage, the status is very pronounced and the emission peaks appear.

The above analysis showed that irrigation mode had a significant effect on greenhouse gas emission. Compared with flooding irrigation, intermittent irrigation or water-saving irrigation significantly decreased CH_4 emission, although it increased N_2O emission. The experimental results showed that when CH_4 emission decreased, the corresponding N_2O emission increased. For regulation of CH_4 and N_2O emission from rice fields, the complex environmental effect of different irrigation modes should be considered so that an appropriate technique can be employed to minimize the greenhouse gas emission.

Based on the foregoing account it is concluded that the average CH_4 emission flux under the condition of intermittent irrigation is less than flooding irrigation in paddy fields, which is opposite to the average N_2O emission flux. The emission peaks are seen at the tillering stage for both CH_4 and N_2O, and another peak of N_2O emission appearing at the yellow ripening stage. Therefore, intermittent irrigation during the tillering stage of rice can suppress green house gases emissions and decrease the total green house effect of CH_4 and N_2O.

Acknowledgments

The authors acknowledge the National Natural Science Foundation of People's Republic of China (Grant No.51379078, 51579101, 51409103 and 51379079), Science-tech Innovation Talents in University of Henan Province (Grant No.15HASTIT044) and Postal Financial Project of Heilongjiang Province (Grant No. LBH-Z12041).

References

Bender, M. and R. Conrad : Kinetics of methane oxidation in oxic soil. *Chemosphere*, **26**, 687-696 (1993).

Bhatia, A., H. Pathak, N. Jain, P.K. Singh and A.K. Singh : Global warming potential of manure amended soils under rice-wheat system in the Indo-Gangetic plains. *Atmosph. Environ.*, **39**, 6967-6984 (2005).

Bosse, U. and P. Frenzel : Methane emissions from rice microcosms: The balance of production, accumulation and oxidation. *Biogeochemistry*, **41**, 199-214 (1998).

Buendia, L.V., H.U. Neue, R. Wassmann, R.S. Lantin, A.M. Javellana, J. Arah, Z. Wang, L. Wanfang, A.K. Makarim, T.M. Corton and N. Charoensilp: An efficient sampling strategy for estimating methane emission from rice field. *Chemosphere*, **36**, 395-407 (1998).

Cai, Z.C. : Effects of water regime on CO_2, CH_4 and N_2O emissions and overall potential for greenhouse effect caused by emitted gases. *Acta Pedol. Sin.*, **36**, 484-491(1999).

Cai, Z., G. Xing, X. Yan, X. Hua, H. Tsuruta, K. Yagi and K. Minami: Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilisers and water management. *Plant Soil*, **196**,7-14 (1997).

Ghosh, S., D. Majumdar and M.C. Jain: Methane and nitrous oxide emissions from irrigated rice of North India. *Chemosphere*, **51**, 181-195 (2003).

Hou, A.X., G.X. Chen, Z.P. Wang, O.V. Cleemput and W.H. Patrick: Methane and nitrous oxide emission from a rice field in relation to soil redox and microbiological processes. *Soil Sci. Soc. Am. J.*, **64**, 2180-2186 (2000).

Huang, Y. : Carbonitriding exchange between soil-atmosphere system-from experiment to model [M]. Beijing: China Meteorological Press (2003).

IPCC Climate Change : Radiative Forcing of Climate Change and an Evaluation of the IPCC IS90 Emission Scenarios [M]. Cambridge, UK:Cambridge University Press (1994-1995).

Kanno, T., Y. Miura, H. Tsuruta and K. Minami : Methane emission from rice paddy fields in of Japanese prefecture - Relationship between emission rates and soil characteristics, water treatment and organic matter application. *Nutr. Cycl. Agroecosys.*, **49**, 147-151 (1997).

Li, D.: Regularity of methane emission from paddy fields and its influence mechanism under rice controlled irrigation [D]. Nanjing: Hohai University (2007).

Li, J., M. Wang and D. Chen : Time selection for non-continuous measurements of methane emission from rice paddy fields. *J. Grad. Sch., Academia Sinica*, **15**, 24-29 (1998).

Usui, T., I. Koike and N. Ogura: N_2O production, nitrification and denitrification in an estuarine sediment. *Estuar. Coas. Shelf Sci.*, **52**, 769-781(2001).

Wang, B., H.U. Neue and H.P. Samonte : Role of rice in mediating methane emission. *Plant and Soil*, **189**, 107-115 (1997).

Xu, H., Z. Cai and X. Li : Study on regularity of CH_4 emission from paddy soil. *Soil Environ. Sci.*, **8**,193-197 (1999).

Yuan, W., C. Cao, J. Cheng and N. Xie: CH_4 and N_2O Emissions and their GWPs assessment in intermittent irrigation rice paddy field. *Scientia Agricultura Sinica*, **41**, 4294-4300 (2008).

Yuan, W., C. Cao, C. Li, M. Cai, M. Zhan, and J. Wang: Methane and nitrous oxide emissions from rice-fish and rice-duck complex ecosystems and the evaluation of their economic significance. *Scientia Agricultura Sinica*, **42**, 2052-2060 (2009).

Yue J., W. Liang, J. Wu, Y. Shi, G. Huang: CH_4 and N_2O emissions from phaeozem rice field and their mitigative measures. *Chinese J. Appli. Ecol.* , **14**, B2015-2018 (2003).