Methane and nitrous oxide emissions from rice paddy fields

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Abstract

Recent field studies in rice paddy fields in Japan and China have shown that N_2O is emitted to the atmosphere not only after the application of nitrogen fertilisers under flooded conditions but also in a period from the final drainage to submergence in the following rice-growing season through nitrification or denitrification. Those results clearly indicate that CH_4 and N_2O emissions in rice paddy fields are in a trade-off relationship. In some cases, the emission rate of N_2O equivalent to CO_2 emission was higher than that of CH_4, by using global warming potential (CO_2: CH_4: N_2O = 1: 21: 310). A long-term field study in Okayama, Japan, showed that no-tilled direct seeding cultivation (N-TD) could reduce CH_4 emission for several years after the start of N-TD, compared with tilled transplanting cultivation (TT), while N_2O was emitted from N-TD more than from TT. Two field experiments which were conduced in different years and sites in China showed that the annual N_2O emission in double-rice cropping fields was much higher in the plot where Chinese milk vetch was planted in winter than in the plot with dry fallow in winter, while the CH_4 emission rate was much lower in the Chinese milk vetch plot in the rice-growing season. From these results strongly indicate that possible techniques to reduce N_2O and CH_4 emissions simultaneously from rice fields should be developed, investigating nitrogen and carbon cycles in rice paddy fields and measuring the flux of trace gases, not only in rice growing season but through a year. The introduction of methodology of life cycle inventory to agro-ecosystems indicates that the annual emission was highest in CH_4 among three greenhouse gases in rice paddy fields, and the total emission rate was much lower in rice paddy fields than in upland fields.

Keywords: rice paddy fields, methane, nitrous oxide, trade-off relationship, nitrification, denitrification, global warming potential

Introduction

Atmospheric methane (CH_4) and nitrous oxide (N_2O) are major greenhouse gases as well as carbon dioxide (CO_2), and all of these three gases have a potential contributing to global warming, since their atmospheric concentrations have been increasing in the troposphere. Agro-ecosystems are one of the major sources of atmospheric CH_4 and N_2O, as pointed out by IPCC.

It is well known that CH_4 is emitted from rice paddy fields to the atmosphere during flooded and rice-growing season, because CH_4 is produced by methanogenic bacteria in paddy soils under anaerobic conditions. N_2O is also emitted to the atmosphere from upland fields after fertilisation of chemical nitrogen (N) fertilisers and organic manures, through denitrification and/or nitrification. Many papers (Smith *et al.,*

1982; Buresh and Austin, 1988; Mosier *et al.,* 1989; Lindau *et al.,* 1990; Buresh *et al.,* 1991; De Datta *et al.,* 1991; Hasegawa *et al.,* 1998) have reported that N_2 and/or N_2O were emitted from rice paddy fields under flooding conditions after the application of chemical N fertilisers mainly through denitrification. Most of the field studies in rice paddy fields except for an experiment (Bronson *et al.,* 1997), however, were focused on either CH_4 or N_2O flux independently, while both of them are found to be emitted from rice fields if we measure the flux of CH_4 and N_2O simultaneously all the year round.

The possible sources of N for N_2O emitted from rice fields are, N fertilisers applied to paddy fields, nitrate in irrigated water, N fixed by algae in paddy water, N in precipitation deposited to rice fields, nitrogenous compounds in organic matter accumulated in soils, and green manures planted in non rice-growing season and applied to rice fields.

In this paper, the recent studies on N_2O emissions from rice paddy fields are summarized, focusing on N_2O flux in a year-round experiment, especially in drained or non rice-growing period, a trade-off relationship between CH_4 and N_2O emissions, the effect of land management in non rice-growing season on N_2O and/or CH_4 emissions in the following rice-growing season, and on the importance of evaluating the total emission rate of the greenhouse gases converting CH_4 and N_2O emissions to CO_2 emission rate by using global warming potential. Finally, an introduction of the methodology of life cycle inventory to agro-ecosystems is discussed.

Field Experiments

In this paper, many recent reports from the field measurements of N_2O flux in rice paddy fields were used and further analysed.

(1) The first measurement of N_2O flux all the year-round was conducted at the Ryugasaki rice experiment station in Ibaraki prefecture, Japan between 1992-1993 (Tsuruta *et al.,* 1997). In the following rice-growing season, the flux of N_2O and CH_4 continued to be measured in the same field (Yagi *et al.,* 1996). (2) An intensive field program on N_2O and CO_2 flux measurement in a drained rice field was performed for one week in a fallow mid-winter season of 2000 in Mase, Ibaraki, Japan (Kim *et al.,* 2002). The relationship among fluxes, soil temperature and moisture, meteorological conditions was analysed. (3) A field study was performed to clarify the effect of soil redox potential and microbiological processes on CH_4 and N_2O emission from a rice paddy field in Shenyang, northern China, during March to December in 1995 and 1996 (Chen *et al.,* 1997; Hou *et al.,* 2000). (4) Another intensive field program was carried out to measure CH_4 and N_2O emissions from rice fields in rice-growing seasons at three sites of China during 1993-1994 (Xu *et al.,* 1997; Cai *et al.,* 1997; Cai *et al.,* 2000). The effect of soil texture, nitrogen fertiliser, and topography on greenhouse gas emissions was analysed in the rice field of Fengqiu, Nanjing, and Yingtan, respectively. (5) No-tilled direct seeding cultivation (N-TD) is expected to be a possible technique of mitigating CH_4 emission from rice paddy fields. A long-term field program on the flux measurement of CH_4 in rice-growing season has been carried out in rice paddy fields in Okayama, western Japan, to clarify the effect of N-DT on CH_4 emission, compared with that from the rice fields under tilled transplanting cultivation (TT), for several years since 1992 when non-tilled direct seeding cultivation started (Ishibashi *et al.,* 2001). The flux measurement of N_2O and CH_4 has started since May 1998 through all the seasons, in three rice fields of N-TD, TT, and of tilled direct seeding cultivation (TD)

(Tsuruta, 2001). (6) For better understanding of the effect of land and water managements in non rice-growing season on greenhouse gas emissions in the following rice-growing season, two different field experiments were performed in China. One was conducted to measure CH_4 flux from double-cropping rice fields in Hunan province, China during 1995-1997, where four treatments were prepared in winter, i.e., the plot of fallow (drained), fallow (flooded), and of planting Chinese milk vetch, and oil-seed rape (Cai *et al.,* 2001). The other was performed to measure N_2O flux from double-cropping rice fields in Jiangxi province, China during 1999-2000, where two treatments were prepared in winter, i.e., the plot of fallow (drained) and Chinese milk vetch (Xiong *et al.,* 2002).

Results and Discussion

N_2O flux measurements from rice paddy fields

The first field measurement of greenhouse gas emissions from a rice paddy field through one year in Japan, showed that no positive or negative flux of N_2O was observed during the rice-growing and flooded period when CH_4 was emitted from paddy fields to the atmosphere. N_2O started to be emitted into the atmosphere, however, from the final water drainage for harvest when soil redox potential drastically increaesd and the emission of CH_4 stopped (Tsuruta *et al.,* 1997). The emission of N_2O continued during the fallow season to submergence in the following rice-growing season, while CH_4 had no emission. This clearly indicates that the emission of CH_4 and N_2O showed a trade-off relationship. The flux of N_2O in the first few months after harvest was in a range of 10-50 μg N $m^{-2}h^{-1}$. In contrast, it was below 10 μg N $m^{-2}h^{-1}$ from December 1992 to Spring 1993, when soil temperature was very low. The total N_2O emission was 60.6 mgN m^{-2} in the non-flooded period, and which was 0.673% of the applied nitrogen (9 g N m^{-2}) as chemical fertiliser. The flux of N_2O was positively correlated with CO_2 flux which was also measured in the latter half of the experiment. The flux of CO_2 showed a clearly positive relationship with soil temperature at a depth of 5cm below the surface, and the emission rate was lower than that from upland fields.

The vertical profile of N_2O and CO_2 in soils in the first period showed the maximum concentration at a depth of 10 cm, indicating that a large amount of N_2O and CO_2 was produced possibly through decomposition of organic matter in the plowed layer after soils became aerobic conditions. In the latter period, N_2O (and CO_2) was possibly produced in the sub soil layer, and was transported to the atmosphere through the plowed layer by diffusion, because N_2O (and CO_2) concentration in the soils was decreased monotonically from the bottom of plowed layer (pan layer) to the soil surface. After submergence in the same field in the following season, N_2O and CH_4 fluxes continued to be measured in the rice-growing period when no emission or uptake of N_2O was observed, while CH_4 was emitted (Yagi *et al.,* 1996).

An inverse relationship was also measured between CH_4 and N_2O emissions in a flooded rice field in Shenyang, Northeastern China (Chen *et al.,* 1997; Hou *et al.,* 2000). CH_4 was not emitted form soils where soil Eh was higher than -100 mV and N_2O was emitted from soils with soil Eh more than 200 mV. It confirmed the result of the field experiment described before.

According to an intensive field measurement of N_2O and CO_2 fluxes in a fallow drained period, the flux of N_2O and CO_2 was higher in the calm days than in the windy

days, and N_2O and CO_2 fluxes showed a positive correlation in the calm days, while no relationship was found in the windy days (Kim *et al.,* 2002).

These experiments indicate that flooded or drained conditions of paddy soils strongly affect not only CH_4 emission but also N_2O emission from rice paddy fields, and that the value of soil redox potential is an indicator of CH_4 and N_2O production. N_2O and CO_2 fluxes could be driven by a similar mechanism in the fallow and drained and field.

Trade-off relationship between CH_4 and N_2O emissions

The trade-off relationship between CH_4 and N_2O emissions from rice paddy fields was also found in the field measurements from three rice paddy fields (Fengqtiu, Nanjing, and Yingtan) in China (Xu *et al.,* 1997; Cai *et al.,* 1997; Cai *et al.,* 2000). At these three sites, N_2O flux had two peaks, i.e., one was found in a few days after the application of chemical N fertilisers and the other after the final water drainage. In contrast, N_2O flux was not observed even after the fertiliser application in Japan, possibly because the application rate was much lower in Japan than in China. The total N_2O emission rate in the rice-growing season showed a negative correlation with the CH_4 emission rate, as shown in Figure 1. The total emission rate of two greenhouse gases (CH_4 and N_2O) equivalent to the CO_2 emission rate can be calculated using the Global Warming Potential (GWP). The upper-left zone in Figure 1 is the area where N_2O emission is higher than CH_4 emission, under the same unit of g CO_2 m^{-2}. Hence, for mitigation options for greenhouse gas emissions from rice paddy fields, possible techniques to reduce CH_4 and N_2O emissions simultaneously all the year-round should be developed.

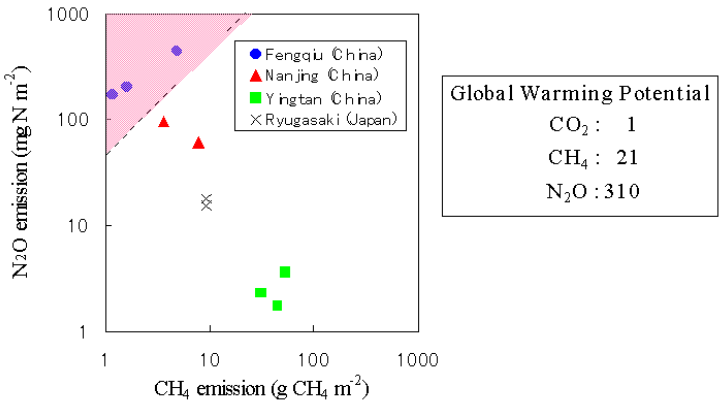

Figure 1 The emission rate of CH_4 and N_2O from rice paddy fields in rice growing season in China and Japan. See text for the explanation of the upper-left area.

Effect of non-tilled direct seeding cultivation on CH_4 and N_2O emissions from rice paddy fields

A long-term field study in rice paddy fields in Okayama, Japan has revealed that non-tilled direct seeding cultivation (N-TD) reduced the CH_4 emission rate compared with tilled transplanting cultivation (TT) for several years after non-tilled direct seeding cultivation had begun (Figure 2). The decreasing rate of CH_4 emission was closely correlated with the water percolation rate. The continuation of non-tilled direct seeding cultivation gradually increased the CH_4 emission, because part of the rice straw spread

on the rice field after harvest was accumulated on the soil surface each year to form an organic matter layer. And the thickness of the layer gradually increased year-by-year. Considering mitigation options for CH_4 emission, rice paddy fields in N-TD are expected to be tilled and transplanted again after several years. That technique, however, might increase CH_4 emission in the next rice-growing season, because the organic matter accumulated on the surface layer is incorporated into the paddy soil to produce a large amount of CH_4 after submergence in the following year. The field study in 2001 to clarify this hypothesis, however, showed that the CH_4 emission was lower in the former N-TD field than in TT, possibly because the N-TD field was tilled in winter, and part of the organic matter could be quickly decomposed before submergence (Ishibashi, 2002).

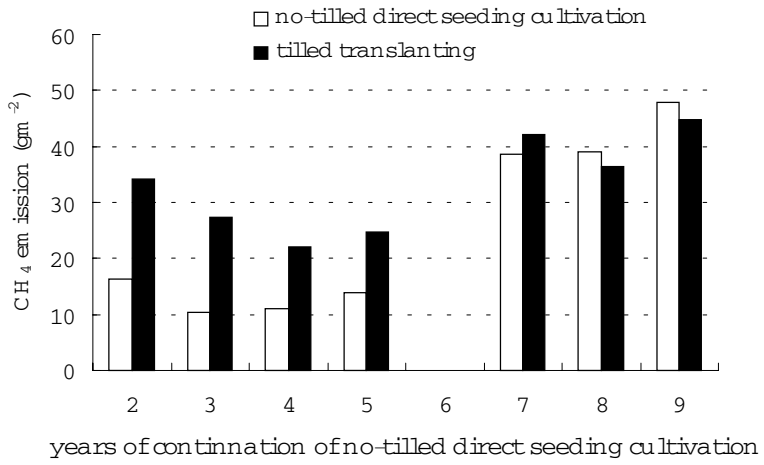

Figure 2 Effect of continuation of no-tilled direct seeding cultivation on CH_4 emission in rice growing season from rice paddy fields in Okayama, Japan.

The flux of N_2O in N-TD was greatly enhanced for about a month after fertilisation in late May 1998 when CH_4 showed no emission, because the surface soil was under aerobic conditions before submergence (Figure 3). On the contrary, no N_2O flux in that period was found in TT, because the period was before fertilisation. As a result, the annual emission ratio of N_2O to the applied nitrogen was much higher in N-TD than in TT. The N_2O flux for a month after fertilisation in late May 1999 in N-TD drastically decreased in comparison with that in the same period in 1998, due to the application of controlled slow-release fertilisers, as shown in Figure 3. The annual N_2O-N emission ratio to the applied nitrogen fertiliser in the rice paddy fields was in a range of 0.5-2.3%, which was almost equal to that measured in upland crop fields all over Japan during 1992-1994 (Tsuruta, 1998). The flux of CH_4 and N_2O clearly showed a trade-off relationship in N-TD, as shown in Figure 3. The annual CH_4 emission rate in 1998 was still a little bit higher in TT than in N-TD, while the annual N_2O emission rate was much higher in N-TD. The total emission rate equivalent to the CO_2 emission rate using GWP showed that the sum of the CH_4 and N_2O emissions was almost equal between N-TD and TT several years after continuation of non-tilled direct seeding cultivation.

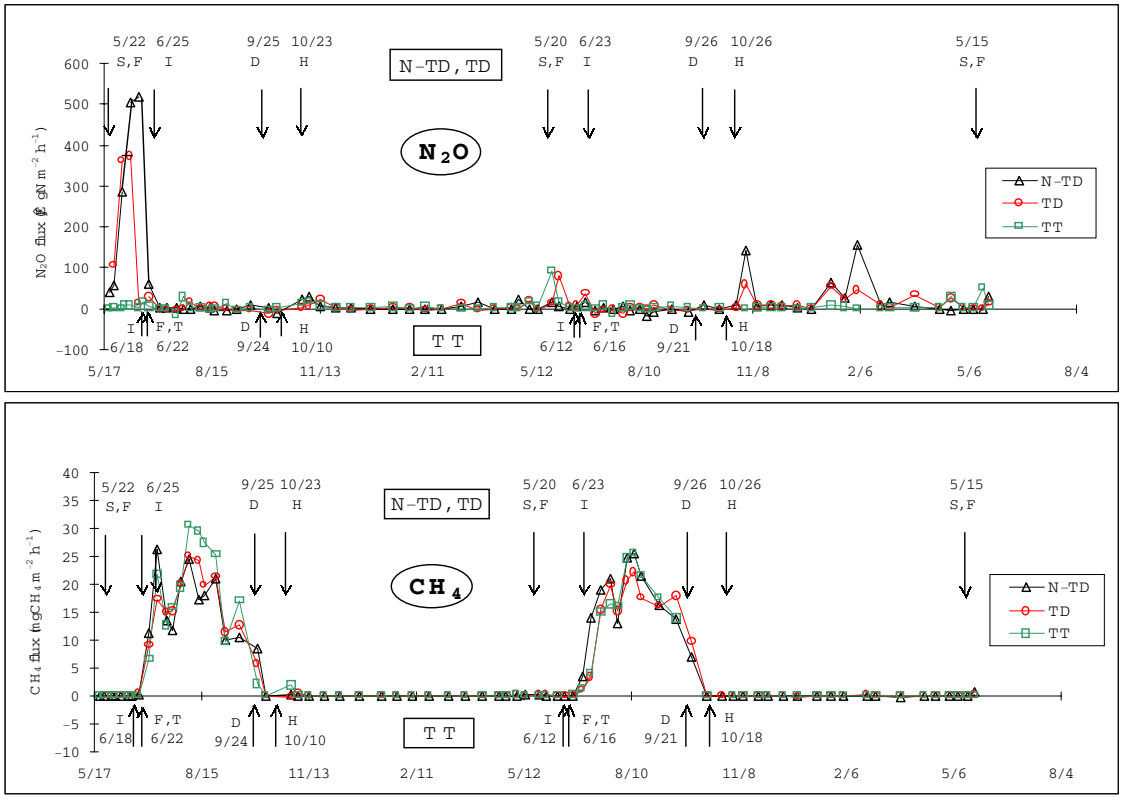

Figure 3 Time series of CH_4 and N_2O fluxes from no-tilled direct seeding (N-TD), tilled direct seeding (TD), and tilled transplanting (TT) cultivations in rice paddy fields in Okayama, Japan during May 1998-May 2000. Allows show the date of S (seeding), I (submergence), F (fertilisation), T (transplanting), D (final drainage), and H (harvest).

Effect of land management in non rice-growing period on CH_4 and N_2O emissions from rice paddy fields

A field study on CH_4 emission from four treatments in double-cropping rice fields in Hunan, China, showed that the annual-mean CH_4 emission was lowest in the plot where Chinese milk vetch had been planted in winter and incorporated before early-rice transplanting, and highest in the plot flooded in the fallow winter season (Cai *et al.,* 2001), as shown in Figure 4. Another study in a pot experiment indicates that CH_4 emission in the rice-growing season from the plot planted with winter wheat was as low as that from the plot with dry fallow in winter, compared with that from the plot flooded in winter (Xu *et al.,* 2000). These results suggest that winter cropping in rice fields can mitigate CH_4 emission in the following rice growing season.

Another field study on N_2O emission from double-cropping rice fields showed that N_2O emission in winter was lower in the plot of Chinese milk vetch than in the fallow plot as shown in Figure 5, possibly because nitrogen in the soil was absorbed by plants (Xiong *et al.,* 2002). The emission of N_2O in the following rice growing season, however, was much higher in the Chinese milk vetch plot than in the fallow plot, possibly because a large amount of green manure was incorporated into the plot, and

N_2O production could be greatly enhanced by an interaction between green manure and chemical nitrogen fertiliser applied to the paddy field.

From these two field measurements which were conducted in different years and sites, we can conclude that the annual N_2O emission in double-rice cropping fields was much higher in the plot with Chinese milk vetch planted in winter than in the plot with dry fallow in winter, while the CH_4 emission rate was much lower in the Chinese milk vetch plot, which was described previously. It also demonstrated that the CH_4 and N_2O emissions were in a trade-off relationship. Hence, further study should be conducted on the effect of crop rotation in agricultural fields on the total emission of the three greenhouse gases including CO_2 derived from carbon budget for a few years.

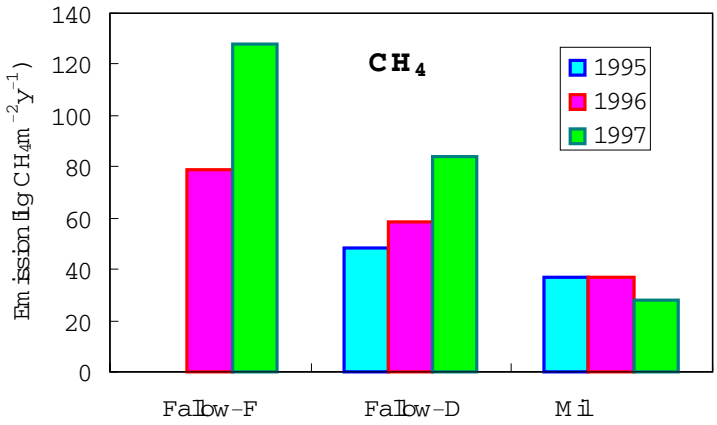

Figure 4 Annual CH_4 emission rate from double-rice cropping fields with three different treatments in winter in Hunan province, China. Fallow-F (Flooded), Fallow-D (Drained) and Chinese milk vetch during 1995-1997.

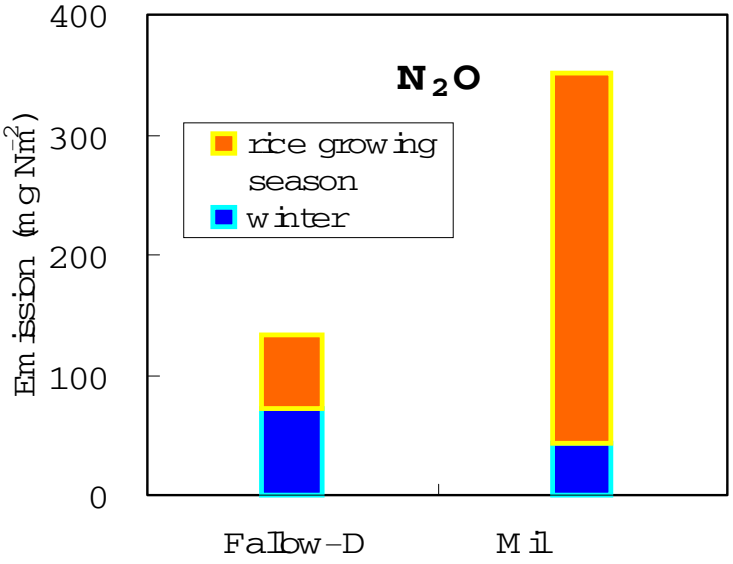

Figure 5 Annual N_2O emission rate from double-rice cropping fields with two different treatments in winter in Jiangxi province, China. Fallow-D (Drained), and Chinese milk vetch during 1999-2000.

Life cycle inventory for the emission of greenhouse gases

Three greenhouse gases (GHGs) of CH_4, N_2O and CO_2 should be measured simultaneously in rice paddy fields for all the seasons, because a field experiment for carbon budget all the year-round demonstrated that the dominant GHG of CO_2 is also emitted from rice paddy fields (Koizumi, 1997). Methodology of life cycle inventory was introduced into agro-ecosystems, to estimate the total emission of three GHGs from rice and upland fields with the unit of g CO_2 m^{-2} y^{-1} using global warming potential, although the emission rate of three GHGs used was measured in different fields in Tsukuba, Japan (Tsuruta *et al.,* 1998). The case study indicates that, in rice paddy fields the annual emission of CH_4 is largest and the smallest is N_2O among three GHGs. And the total annual emission rate of three GHGs was much lower in rice paddy fields, than in upland fields.

Conclusion

Recent field experiments in rice paddy fields in Japan and China showed that N_2O was emitted not only in flooded and rice-growing season but also in non-rice growing season through denitrification or nitrification. N_2O was emitted mainly after the final drainage in the rice fields with low input of nitrogen fertilisers, while CH_4 stopped to emit, because soil was drastically changed from anaerobic conditions to aerobic conditions. And soil redox potential could be an indicator of CH_4 or N_2O emission from paddy fields. In the drained and fallow period, CO_2 in addition to N_2O was emitted from rice fields, and N_2O and CO_2 fluxes could be driven by a similar mechanism in the fallow and drained field. No-tilled direct seeding cultivation (N-TD) reduced CH_4 emission, compared to tilled transplanting cultivation (TT), for several years after N-TD started. After several years, however, CH_4 emission rate in N-TD was almost equal to that from TT, because organic matter layer was accumulated on the soil surface due to the spread of rice straw at harvest every year. And N_2O emission was higher in N-TD than TT, because N_2O was emitted from N-TD after fertilisation during one month before submergence. The annual N_2O emission in double-rice cropping fields in China was much higher in the plot with Chinese milk vetch planted in winter than in the plot with dry fallow in winter, while the CH_4 emission rate was much lower in the Chinese milk vetch plot, although these two field experiments were conducted in different years and sites

These field experiments clearly showed that N_2O and CH_4 emissions showed a trade-off relationship. In some cases, N_2O emission rate was higher than CH_4 emission, converting to CO_2 emission rate by using global warming potential. These results strongly indicate that possible techniques to reduce N_2O and CH_4 emissions simultaneously from rice fields should be developed, investigating nitrogen and carbon cycles in rice paddy fields and measuring the flux of trace gases, not only in rice growing season but through a year.

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