Reduction of global warming potential contribution from a rice field by irrigation, organic matter, and fertilizer management

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[1] The major objective of this study is to find a feasible management practice to mitigate the cumulative global warming potential (GWP) from CH_4 and N_2O emission in an irrigated rice field. Nonflooding (but wet) conditions reduced CH_4 emission by 79 and 71% from the fields with and without organic matter (OM) addition, respectively. This was mainly due to the desirable soil redox status in the nonflooded fields with less CH_4 production and more CH_4 oxidation when CH_4 diffused up the soil profile. Increase in N_2O emission from the nonflooded fields offset part of the reduction in CH_4 emission, especially when OM was not added. Thus the nonflooding treatment reduced the cumulative GWP by 72% in the OM-added field but only 46% in the field without OM addition. Under flooding conditions, no OM addition reduced CH_4 emission by 57%, but rice yield was decreased by 16% in comparison with the OM-added fields. The best management practice proposed from this study is to keep the fields nonflooded but wet with OM addition, which largely reduced the GWP from the fields with no decrease in rice yield. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1615 Global Change: Biogeochemical processes (4805); *KEYWORDS:* global warming potential, redox potential, rice field

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1. Introduction

[2] Methane (CH_4) and nitrous oxide (N_2O) are the most important non-carbon dioxide (CO_2) biological greenhouse gases, contributing to about 20 and 6%, respectively, of the global mean radiative forcing. Methane is removed from the atmosphere by reacting with the hydroxyl radical (OH). Increasing emissions of CH_4 reduce the concentration of OH, a feedback that may increase methane's atmospheric lifetime. Nitrous oxide contributes to stratospheric ozone destruction with a residence time in the atmosphere of more than a century [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001]. Irrigated rice fields, especially with OM amendment, have the highest CH_4 source strength than other rice fields because of sustained reducing conditions in the soils and the presence of organic substrates. Lower CH_4 fluxes are recorded in the fields with less rice residue, multiple aeration periods, poor fertility and low fertilization, which normally results in poor rice growth and low yields [*Delwiche and Cicerone*, 1993]. Rice soils are producers of N_2O if they are not constantly flooded because ammonium (NH_4^+) and nitrate (NO_3^-) are available from fertilization and the temporary oxidizing conditions that enable nitrification (conversion of NH_4^+ to NO_3^-) to take place [*Byrnes et al.*, 1993]. Both N_2O and CH_4 production are functions of soil redox potential (Eh) and microbiological activity. Nitrous oxide can be produced from nitrification under aerobic conditions (high Eh), and denitrification (reduction of NO_3^- to N_2O and N_2) under moderately reducing conditions (lower Eh) where the reduction intensity is not strong enough to completely reduce nitrate to nitrogen gas (N_2). Significant CH_4 formation generally occurs under strictly reducing conditions (low Eh) where obligate anaerobes can grow and function. Reduced flooding duration increases N_2O production, whereas continuously flooded soils maintain anaerobic conditions that enhance CH_4 production [*Neue*, 1993]. Drainage and aeration during the rice-growing season is the most effective approach to mitigate CH_4 emission from flooded rice fields, but with a potentially adverse effect of stimulating higher N_2O emission [*Sass et al.*, 1992; *Bronson et al.*, 1997; *Wassmann et al.*, 2000]. Improved soil aeration may increase nitrogen loss as a result of stronger nitrification, and later denitrification when the soils are submerged again. Consequently, the cumulative GWP in terms of CO_2

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equivalent [*IPCC*, 2001] from both CH_4 and N_2O emission may not be significantly reduced, and may even be increased.

[3] Rice fields are a major source of CH_4 during the flooded season, and an important source of N_2O during the nonflooded season as found in numerous field studies [*Cai et al.*, 1997; *Chen et al.*, 1997; *Tsuruta et al.*, 1997; *Abao et al.*, 2000], because of the different Eh conditions required for N_2O and CH_4 formation. Four requirements have been proposed to follow in recommending an acceptable practice to reduce CH_4 emissions from flooded rice fields: (1) no decrease in rice yield, (2) some additional benefit to the farmer, (3) rice varieties used desirable for local consumers, and (4) no increase in emissions of other greenhouse gases, particularly N_2O [*Mosier et al.*, 1998]. It is a challenge to abate the production of one gas but not to enhance the production of the other without decreasing rice yield.

[4] Our recent studies using a soil microcosm technique showed a redox ''window'' of +180 to −150 mV (corresponding values at pH 7.0) where both N_2O and CH_4 production were low. Soils in this redox window were reducing enough to favor complete denitrification to N_2 (rather than stopping at the intermediate product N_2O), but were too oxidizing to initiate significant methanogenesis [*Yu et al.*, 2001; *Yu and Patrick*, 2003]. This wide Eh range with minimum N_2O and CH_4 production may provide a good opportunity to abate the GWP contribution from rice fields by proper field management regardless of soil heterogeneity. The effect of irrigation, OM addition, and fertilization were evaluated in the field study reported here with the following objectives: to (1) monitor Eh conditions in the soil profile under different treatments, (2) measure CH_4 and N_2O emission from the rice fields simultaneously, and to calculate the cumulative GWP, (3) study the effect of different management practices on rice yield, and (4) propose a feasible approach to minimize the GWP contribution from the rice fields.

2. Materials and Methods

2.1. Experimental Site and Treatment

[5] The field experiment was conducted at Shenyang Experimental Station of Ecology, Chinese Academy of Sciences (41°32′N, 122°23′E). The soil type is locally described as meadow brown. Soil OM content was 2.12 and 1.51% for the field with and without receiving organic manure (mixed manure of pig and poultry), respectively. Organic manure has been applied at about 30 ton ha^{-1} each year before rice cultivation in spring for about 10 years (Note: soil carbon and CO_2 emission was not considered in the cumulative GWP, because both respiration and photosynthesis activities contributed to CO_2 concentration change in the chamber). Soil pH (top 20 cm) fluctuated within 6.4 and 6.7 under all treatments. Other soil characteristics were reported in previous publications but were highly variable at different rice growing seasons [*Chen et al.*, 1995, 1997].

[6] Rice, Liao Kai 79 (a major regional cultivar), was cultivated in a single crop per year with a growing season of about 120 days. Rice seedlings were transplanted the second day after flooding the fields (late May). The fields received basal fertilization of $(NH_4)_2HPO_4$ at 290 kg ha^{-1} within 3 days after transplanting. In addition, urea was broadcasted at tillering (156 kg ha^{-1}, late June) and again at heading (73 kg ha^{-1}, late August) stage. The fields were drained in late September, and harvested in early October. Four treatments with two replicates were applied to eight experiment plots (4 m × 6 m each): A, no OM addition, flooded; B, no OM addition, nonflooded; C, OM addition, flooded (this is the major management practice in this region); D, OM addition, nonflooded. In the flooded plots the level of standing water was maintained at 5–10 cm by irrigation. In the nonflooded plots, the soils remained wet with water table at approximately 0–5 cm below the soil surface. The same management of inorganic fertilization was applied to all four treatments.

2.2. Soil Eh Measurement

[7] Redox potential (Eh) in the soil profile (top 22 cm) was measured using a platinum (Pt) electrode cable with a calomel reference electrode connected to a portable millivolt meter (Digi-Sense 5938-00, Cole-Parmer Instrument Co.). All Pt electrodes were prechecked (deviation <10 mV) by using standard pH 4.0 and pH 7.0 buffer solutions saturated with quinhydrone before installation [*Bohn*, 1971]. The Pt electrode cable consisted of 6 single Pt electrodes that were located at depths of 1, 2, 4, 8, 14, and 22 cm below the soil surface. Each of the eight plots had two replicate electrode cables that were permanently installed in the fields during the study period. Effect of soil temperature and pH on Eh was not considered. The Eh values were reported after correction to the standard H_2 electrode by adding 247 mV (the correction factor for calomel reference electrode at 20°C) to the observed instrument readings.

2.3. CH_4 and N_2O Emission in the Fields

[8] Methane and N_2O emissions in the rice fields were measured at least once a week using the static chamber technique. The chamber was 1 m high with a base area of 0.8 m × 0.8 m. During the measurement, the chamber was manually operated to cover the field for 40 min, and sealed with water in the base unit. Gas samples were collected using a 30 ml syringe at 0, 20, and 40 min upon chamber closure. Methane and N_2O fluxes from the fields were calculated by a linear regression of their concentrations in the chamber against time [*Chen et al.*, 1995].

2.4. Soil Pore Water Measurement

[9] Methane, N_2O, ammonium and nitrate concentrations in the soil profile were measured using a soil pore water equilibrator (commonly called a peeper) [*Jacobs*, 2002]. The equilibrator was made of an acrylic block (40 cm long, and 18 cm wide) with 12 sampling cells. Each cell was 1 cm long and 15 cm wide (the same orientation as the block) with approximately 20 ml in volume. The cells were distributed 1 cm apart in the block to cover the top 22 cm of the soil profile when the equilibrator was inserted into the soil. The equilibrator was driven into the soil after the cells being filled up with deionized water, and then covered with a thin permeable membrane (Poretics, 0.2 micron). Such a

sampling device was left in the field for at least 2 weeks to allow the water in the cells equilibrate with the surrounding soil pore water, thus only 3 measurements were available for this study. Upon removing the device from the field, about 6 ml water was taken from the sampling cell using a syringe, and then immediately transferred into an evacuated vial (10 ml Vacutainer, Becton Dickinson, NJ, USA) for later analysis. The remaining volume of the vial was filled with pure N_2 at 1 atmospheric pressure. A single equilibrator was used for each of the four differently treated plots with duplicate water samplings from the cells. This measurement was eventually conducted at days 81 and 96 (between tillering and heading stage fertilization), and at day 112 after rice transplanting (after fertilization of heading stage at day 97). Methane and N_2O concentrations in the headspace of the vials were analyzed after shaking the vials for 4 hrs, and were reported as their concentrations in the soil pore water.

2.5. Analysis

[10] Methane and N_2O were analyzed using a HP-5890 gas chromatography (GC) with a flame ionization detector (FID), and a Shimadzu GC-14A with an electron capture detector (ECD), respectively, and were calibrated with each corresponding standard gas provided by the National Research Institute of Standard Material, China. Ammonium and nitrate contents in the water samples of the equilibrator were measured using a distillation method in the presence of MgO and Devarda's alloy [*Keeney and Nelson*, 1982].

[11] Statistical analysis (α = 0.05) was conducted using SAS (SAS Institute Inc., 1999–2001) analysis of variance (AVOVA) using PROC GLM was conducted to determine the least significant difference (LSD) between the different treatments.

3. Results

3.1. Eh in the Soil Profile

[12] Soil Eh values under the 4 treatments showed a similar seasonal pattern (Figure 1). Flooding conditions (A and C) and OM addition (C and D) facilitated developing lower Eh in the soils. After drainage, soil Eh in the upper layers of the field increased up to +450 mV in just a few days. Strictly reducing conditions (Eh < −150 mV) that were favorable for methanogenesis generally developed at 3 periods after rice transplanting: day 50 to 60 (early), day 67 to 77 (middle), and day 95 to 105 (late). Nonflooded conditions (B and D) maintained by controlled irrigation introduced more aeration to the top layers of the fields than the flooded fields (A and C), and consequently resulted in the strictly reducing zones (Eh < −150 mV) being developed 4 or 5 cm deeper than in the flooded fields.

3.2. CH_4 and N_2O Emission

[13] Major periods for CH_4 and N_2O emissions observed in this study agreed quite well with the previous measurements in the same rice field where more complete seasonal variations of CH_4 and N_2O emissions were recorded [*Chen et al.*, 1995, 1997], and remained the same under the different treatments. Major CH_4 emission occurred in three periods during the rice-growing season (Figure 2). Highest CH_4 emission was found in the treatment C (OM addition, flooded), and lowest in the treatment B (No OM addition, nonflooded). The flooded fields showed low N_2O emission, and occasional consumption of ambient N_2O. Nitrogen fertilization during the rice-growing season stimulated N_2O emission, especially in the nonflooded fields (Figure 3). Drainage at the end of the season also stimulated higher N_2O emission, but at the same time terminated CH_4 emission from the fields (Figure 2).

3.3. CH_4, N_2O, Ammonium, and Nitrate Content in the Soil Profile

[14] Dissolved CH_4, N_2O, and mineral-N in the soil pore water were measured three times (days 81, 96, and 112) during the rice-growing season (Figures 4, 5, and 6). Methane concentrations tended to be higher at lower depths of the soil. The flooded fields generally showed higher CH_4 accumulation than the nonflooded fields, except in the treatment B at day 96 (Figure 5). No clear pattern of N_2O concentrations related to the soil depths could be found in the measurement at day 81 (Figure 4) and 96 (Figure 5). However, the measurement at day 112, conducted following the application of urea at day 97 (heading stage), showed two N_2O maxima at the soil depths of 7 to 9 cm, and of 15 cm in the nonflooded fields where the N_2O concentrations were significantly higher than in the flooded fields (Figure 6). Both ammonium and nitrate varied less than 3 μM in the soil profiles, except in the treatment A at day 112 where the ammonium content at 10 to 13 cm depths of the soil reached up to 10 μM (Table 1).

4. Discussion

4.1. Soil Eh Distribution in the Rice Fields Under Different Treatments

[15] Soil Eh generally spanned a range of +700 to −300 mV in the studied rice fields. Unlike homogeneous soil suspensions, both oxidizing and reducing conditions existed simultaneously in the rice fields. This was due to heterogeneous nature of the fields, slow diffusion of oxygen (O_2) in water and soil structure, and presence of rice plant that can transport O_2 from the atmosphere into the root zone. Methane production mostly occurs in the soil microenvironment where the redox status is expected to be lower than the measured Eh [*Neue*, 1997]. However, soil Eh measurement generally reflects the redox status of the soil microenvironment. When the soil Eh is high, the reducing microenvironment in the soils will be smaller, meanwhile the oxidized microenvironment will be larger, and vice versa. Soil OM is the major electron donor in various soil redox reactions that occur at different Eh conditions [*Ponnamperuma*, 1972; *Reddy et al.*, 1989; *Patrick and Jugsujinda*, 1992]. Soil original OM (and the additional OM applied to the treated fields) was the major driving force of development of soil reducing conditions, especially for the strictly reducing zone (Eh < −150 mV) developed during the early rice-growing season (Figure 1). Release of new OM from the rice root and degradation of the dead rice root might significantly contribute to the development

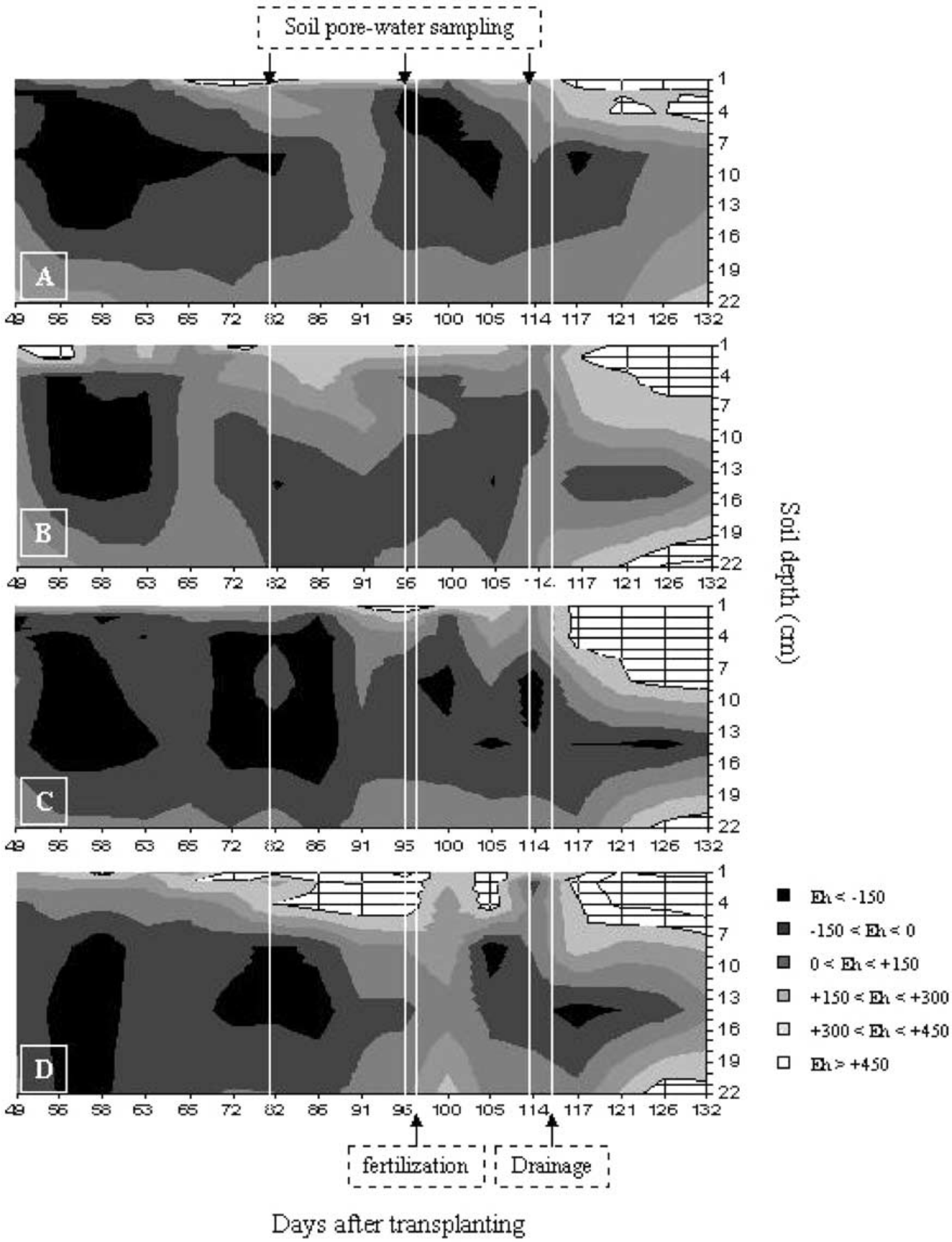

Figure 1. Soil redox potentials (Eh) under different treatments. Treatments are as follows: A, no OM addition, flooded; B, no OM addition, nonflooded; C, OM addition, flooded; D, OM addition, nonflooded.

of the middle and the late strictly reducing zones, respectively [*Schutz et al.*, 1989]. The reducing zones in the middle season were not well developed in the fields without added OM, probably because of lower initial soil OM contents and less root exudates from the rice plants of relatively poor growth (with lower rice yields; see Table 2). Studies using isotopic analysis indicated that a large fraction of the OM that supported methanogenesis was derived from recently fixed carbon [*Minoda and Kimura*, 1994]. Oxygen diffusion through the rice plant root might

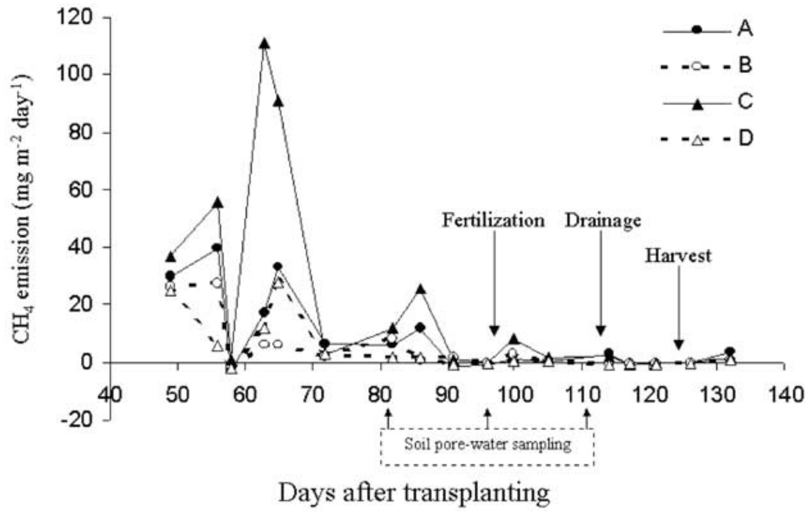

Figure 2. Methane emissions under different treatments. Treatments are as follows: A, no OM addition, flooded; B, no OM addition, nonflooded; C, OM addition, flooded; D, OM addition, nonflooded.

play a significant role in elevating the soil Eh status between the three strictly reducing zones, although effect of different treatments on the development of aerenchyma system in the rice plants remained unknown.

[16] Irrigation and OM management practice showed a significant impact on the Eh distribution in the soil profile. Under the flooding conditions, reducing soils (e.g., Eh < 0 mV) accounted for 63 and 50% bulk of the soil in the fields with (treatment C) and without (treatment A) OM addition, respectively. The nonflooding management enlarged the portion of the soil with higher Eh, and in compensation reduced the portion with lower Eh (Figure 7). The lower water table in the treatment B and D aerated the soil surface layers, thus strictly reducing conditions could only be established at deeper layers of the soil where the reducing intensity was strong enough to initiate significant CH_4 production.

[17] Mechanism for gas emission from rice fields includes diffusion through the soil profile, ebullition, and transport through the aerenchyma system of rice plants [*Holzapfel-Pschorn et al.*, 1985]. Transport through the rice plants is the major pathway for both CH_4 and N_2O emission [*Yu et al.*, 1997]. Prior to the development of the aerenchyma system in rice plants, significant amounts of CH_4 can be emitted from the rice fields to the atmosphere by diffusion and ebullition because of lower CH_4 solubility in water (1.48 mM in saturation at 20°C). Significant N_2O emission by ebullition is unlikely because the N_2O solubility in water (30.1 mM in saturation at 20°C) is higher. The detailed mechanism of CH_4 and N_2O emission was not investigated in this study. However, the nonflooded treatments were expected to significantly reduce CH_4 emission, because of less CH_4 production in the smaller portion of the reducing soil, and more CH_4 oxidation along its path upward from

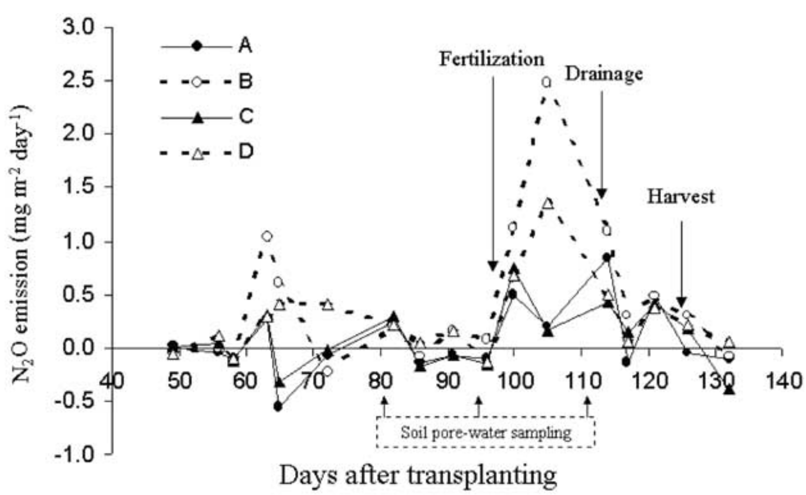

Figure 3. Nitrous oxide emissions under different treatments. Treatments are as follows: A, no OM addition, flooded; B, no OM addition, nonflooded; C, OM addition, flooded; D, OM addition, nonflooded.

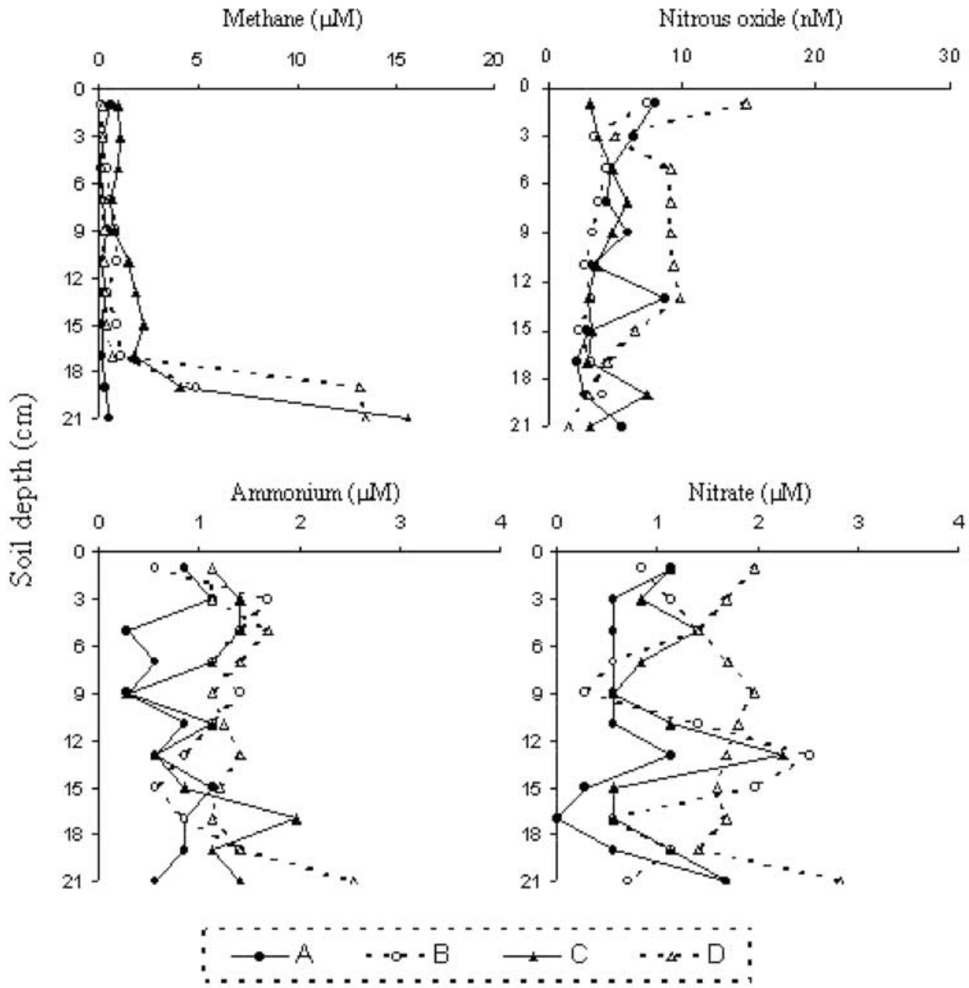

Figure 4. Measurement of the soil profile at day 81 after rice transplanting. Treatments are as follows: A, no OM addition, flooded; B, no OM addition, nonflooded; C, OM addition, flooded; D, OM addition, nonflooded.

the deeper layers of the soil where most of the CH_4 was produced.

4.2. Best Management Practice (BMP) to Reduce Cumulative GWP Without Decreasing Rice Yield

[18] The three periods with major CH_4 emission in the rice fields (Figure 2) corresponded to the seasonal development of strictly reducing conditions in the soils (Figure 1), indicating a close relationship between soil Eh and methanogenesis activity. No clear correlation of N_2O emission from the rice fields and soil Eh could be found during the study period (Figure 3). Nitrification and denitrification contribute to N_2O production at different Eh conditions, and both the denitrification rate (higher at lower Eh) and the N_2O to N_2 ratio (smaller at lower Eh) must be known to evaluate the N_2O emissions through denitrification.

[19] The results of the soil profile measurements showed that CH_4 concentrations in the soil pore water were supersaturated with respect to the atmosphere under all treatments (Table 1), making the rice field a potentially significant source of atmospheric CH_4 during the growing season. Most of the CH_4 produced in the anoxic environments was oxidized in the aerobic soil surface [*Conrad and Rothfuss*, 1991] and rice plant rhizosphere [*Denier van der Gon and Neue*, 1996]. The measurement at day 81 was conducted in the second period (middle) when the strictly reducing conditions developed in the soils. The results of this measurement showed that most of the time the soil N_2O concentrations was below the atmospheric level (Figure 4 and Table 1), providing an explanation and evidence of potential consumption of the atmospheric N_2O in the rice fields (Figure 3). However, consumption of the atmospheric N_2O occurred only occasionally when the reducing conditions in the soils were intense enough. The measurements at day 96 and 112 when Eh was higher showed that the soil N_2O concentrations were higher than the atmospheric level (Figures 5 and 6 and Table 1). Fertilization in the rice-growing season significantly stimulated N_2O emission (Figure 2). The soil profile measurements at day 112 showed that the soil N_2O concentrations were significantly elevated, especially in the nonflooded fields (Figure 6 and Table 1). Nitrification activity was

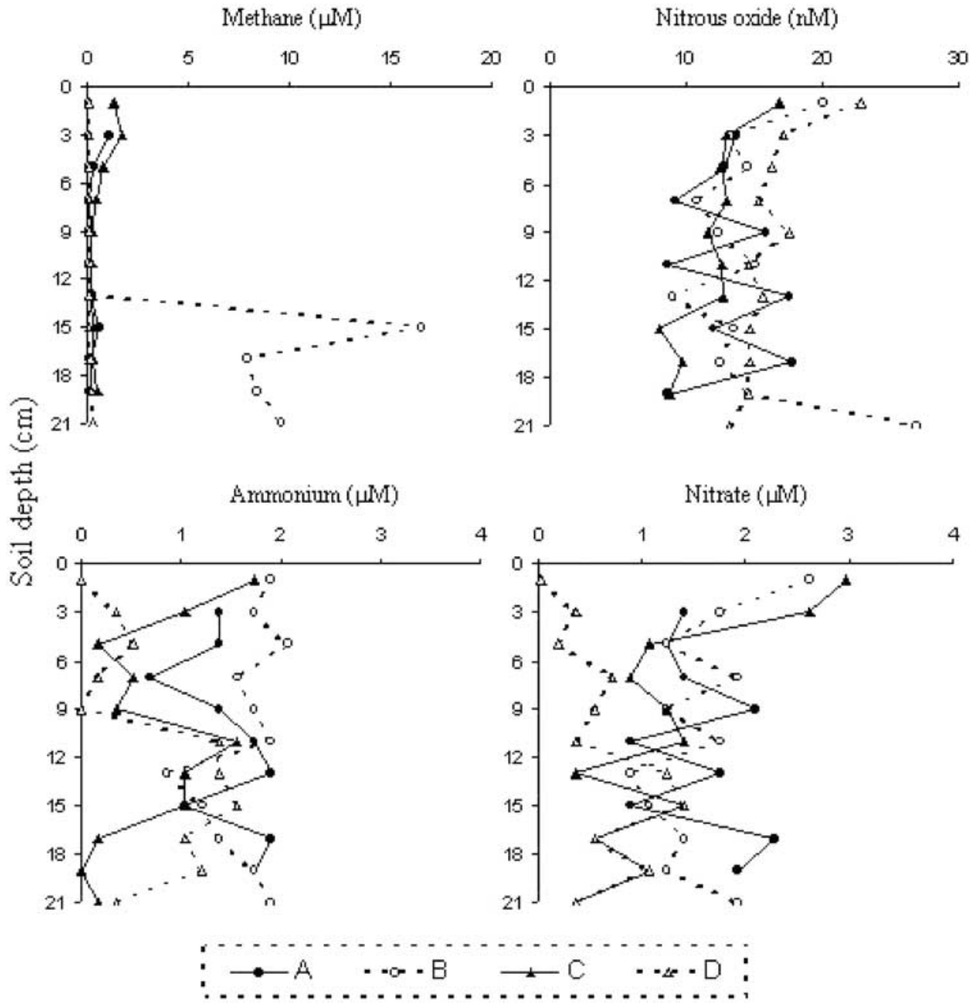

Figure 5. Measurement of the soil profile at day 96 after rice transplanting. Treatments are as follows: A, no OM addition, flooded; B, no OM addition, nonflooded; C, OM addition, flooded; D, OM addition, nonflooded.

stronger in the nonflooded fields where more oxidizing conditions existed at the soil surface, and consequently transformed more ammonium to nitrate for stronger denitrification activity at deeper layers of the soils. Coupled nitrification and denitrification at the two aerobic/anaerobic interfaces, water/soil and rice plant rhizosphere/bulk soil, is an important mechanism of N loss and N_2O production in rice fields [*Patrick and Reddy*, 1976; *Reddy et al.*, 1989; *Arth et al.*, 1998]. Nitrous oxide produced in the more oxidizing conditions, as in the nonflooded rice fields, is more likely to be emitted to the atmosphere, because the only known biological mechanism for consumption of N_2O is denitrification wherein N_2O can be reduced to N_2. Irrigation and OM addition management will also affect rice plant physiology and yield. The highest soil ammonium contents found in treatment A may be due to less uptake by the rice plants and weaker nitrification activity under flooded conditions (Figure 6).

[20] Table 2 summarizes the major results of this study. Irrigation showed a critical impact on controlling the soil Eh conditions, as well as the CH_4 and N_2O production and emission. Addition of OM played an essential role in the rice yield. Rice plants showed a more healthy growth as observed in the field and higher yield at harvest when additional OM was provided before the rice cultivation regardless of the two irrigation treatments, probably due to the additional nutrients in the organic manure and the generally beneficial effect of OM on soil fertility. Compared with the local traditional management (treatment C), the rice yield was decreased by 16% in the field without added OM (treatment A), and by another 9% if the field was maintained nonflooded by irrigation (treatment B). Therefore application of organic manure should be included in the field management practice, at least for this region, because of the top priority for higher rice yield. Under flooding conditions, CH_4 emission was reduced by 57% if no additional OM was provided. In the fields without OM addition, nonflooding management reduced the cumulative GWP by 46%, where about one third of the reduction of CH_4 emission (176.6 CO_2 equivalent m^{-2} d^{-1}) was offset by the increase in N_2O emission (56.2 CO_2 equivalent m^{-2} d^{-1}). In the OM-added fields, nonflooding management reduced the overall GWP by 72% with the reduction of CH_4 emission by 458.2, and the increase in N_2O

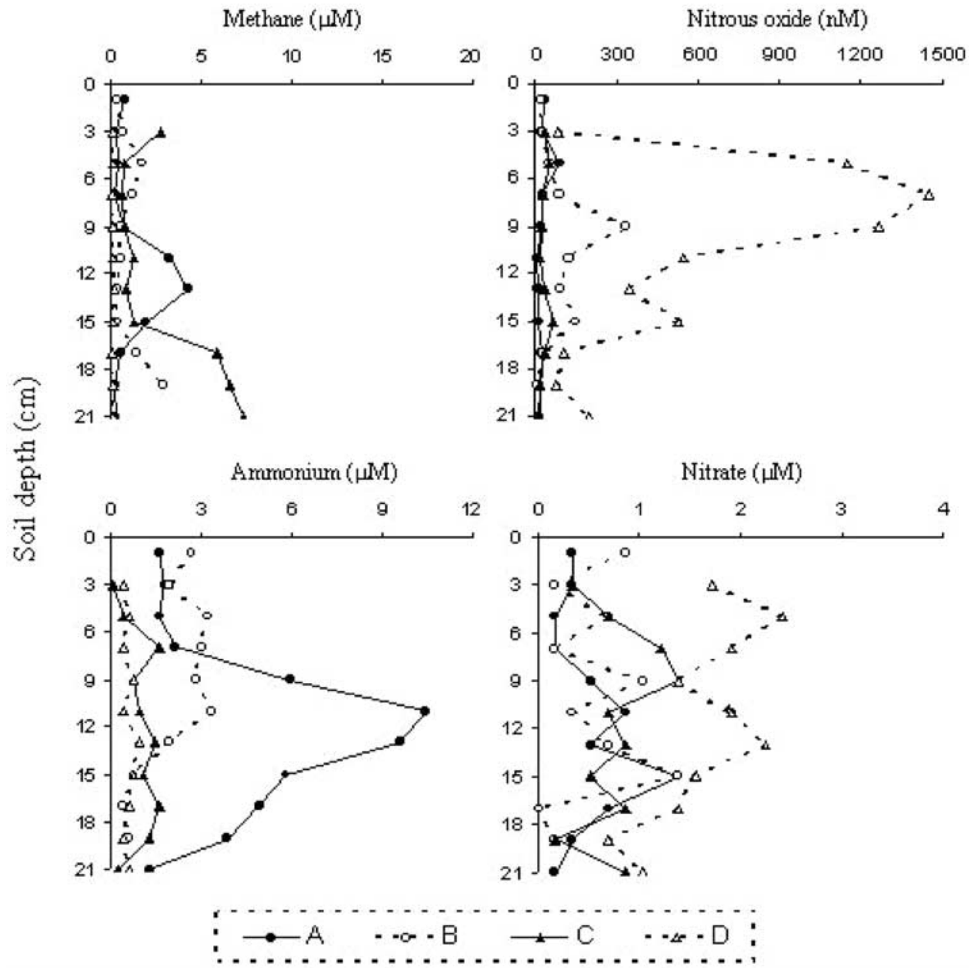

Figure 6. Measurement of the soil profile at day 112 after rice transplanting. Treatments are as follows: A, no OM addition, flooded; B, no OM addition, nonflooded; C, OM addition, flooded; D, OM addition, nonflooded.

emission by 29.6 CO_2 equivalents m^{-2} d^{-1}. Although the local traditional management (treatment C) showed the highest GWP contribution from the rice fields, appropriate management of irrigation (treatment D) could effectively reduce the overall GWP by a significant reduction of the CH_4 emission with little offset by the increase in N_2O emission. Because of higher availability of O_2 under the nonflooding conditions, a larger portion of the easily degraded OM was converted to CO_2 by aerobic and/or anaerobic microbial activities, instead of being converted to CH_4 by methanogenesis under strictly anaerobic conditions. Therefore the BMP proposed from this study to reach a minimum GWP contribution without decreasing rice yield is to keep the fields nonflooded with OM addition (treatment D). This is just a minor modification of the current local management practice, which makes it more practically feasible in application. Less water will be needed under the nonflooding treatment, which may provide some additional benefits to the farmers with less labor, water, and electricity expenses, although weed control will have to be considered. This management approach will be also feasible for rice fields with no available information on the seasonal varia-

Table 1. Mean Values of the Soil Profile Measurement Under Different Treatments[a]

Date	Measurement	Treatment A	Treatment B	Treatment C	Treatment D	Least Significant Difference (n = 11)
Day 81	CH_4 (μM)	0.3	1.0	2.8	2.6	3.1
Day 81	N_2O (nM)	4.9	3.8	4.1	7.4	2.1
Day 81	NH_4^+ (μM)	0.7	1.1	1.1	1.4	0.3
Day 81	NO_3^- (μM)	0.7	1.1	1.1	1.8	0.4
Day 96	CH_4 (μM)	0.3	3.9	0.6	0.1	2.7
Day 96	N_2O (nM)	12.9	14.8	11.9	16.0	3.2
Day 96	NH_4^+ (μM)	1.5	1.6	0.7	0.7	0.5
Day 96	NO_3^- (μM)	1.5	1.6	1.3	0.6	0.5
Day 112	CH_4 (μM)	1.2	1.0	2.8	0.2	1.4
Day 112	N_2O (nM)	27.2	95.8	33.0	575.9	236.0
Day 112	NH_4^+ (μM)	4.5	2.1	1.0	0.6	1.6
Day 112	NO_3^- (μM)	0.5	0.6	0.8	1.6	0.4

[a]Treatments are as follows: A, no OM addition, flooded; B, no OM addition, nonflooded; C, OM addition, flooded; D, OM addition, nonflooded. Data represent concentration in the soil pore water. At 20°C, CH_4 and N_2O concentrations in water are 0.0026 μM and 9.04 nM, respectively, in equilibrium with the atmospheric CH_4 (1.75 ppm) and N_2O (0.3 ppm).

Table 2. Summary of Mean CH_4 and N_2O Emissions, Eh Values, and Rice Yields Under Different Treatments[a]

Measurement	Treatment A	Treatment B	Treatment C	Treatment D	Least Significant Difference (n)
CH_4,[b] mg m^{-2} d^{-1}	10.80 (95)	3.12 (51)	25.20 (98)	5.28 (75)	13.32 (17)
N_2O,[b] mg m^{-2} d^{-1}	0.04 (5)	0.23 (49)	0.04 (2)	0.14 (25)	0.15 (17)
GWP[c]	260.24	139.84	591.44	162.88	306.47 (17)
Eh, mV					
Before drainage	20.2	114.1	8.7	150.0	72.1 (72)
After drainage	247.6	311.4	291.8	324.6	205.9 (30)
Yield, t ha^{-1}	9.7	8.8	11.5	10.9	1.6 (4)

[a]Treatments are as follows: A, no OM addition, flooded; B, no OM addition, nonflooded; C, OM addition, flooded; D, OM addition, nonflooded.
[b]Data in parenthesis denote the relative contribution (%) of CH_4 or N_2O in the cumulative GWP.
[c]Global warming potential (GWP) was calculated on the basis of mass factors of 23 for CH_4 and 296 for N_2O of 100-year time horizon and expressed in mg CO_2 equivalent m^{-2} d^{-1}.

tion of CH_4 and N_2O emissions, because irrigation control is adjusted according to the wetness of the soil surface, instead of any information from instrumental measurement.

4.3. Potential Modification of the Current BMP

[21] An increase in N_2O production and emission can significantly offset CH_4 reduction during the drainage practice of submerged rice fields in mitigation of CH_4 emission, resulting in low efficiency of overall GWP reduction. In this study, approximately 32% of the CH_4 reduction in the field without OM addition was offset by the increase in N_2O emission. In such nonflooded fields, N_2O emissions accounted for almost half of the cumulative GWP (Table 2). However, higher N_2O production and emission was only associated with N fertilization during the rice growing season. Application of a urease inhibitor and a nitrification inhibitor showed a significant effect on minimizing N_2O emission following urea fertilization [*Xu et al.*, 2002]. Besides of the possible option to use slow released N fertilizers, our results suggest a possibility to reduce the short-term stimulated N_2O emission by temporarily flooding the fields upon fertilization (only applied to ammonium-

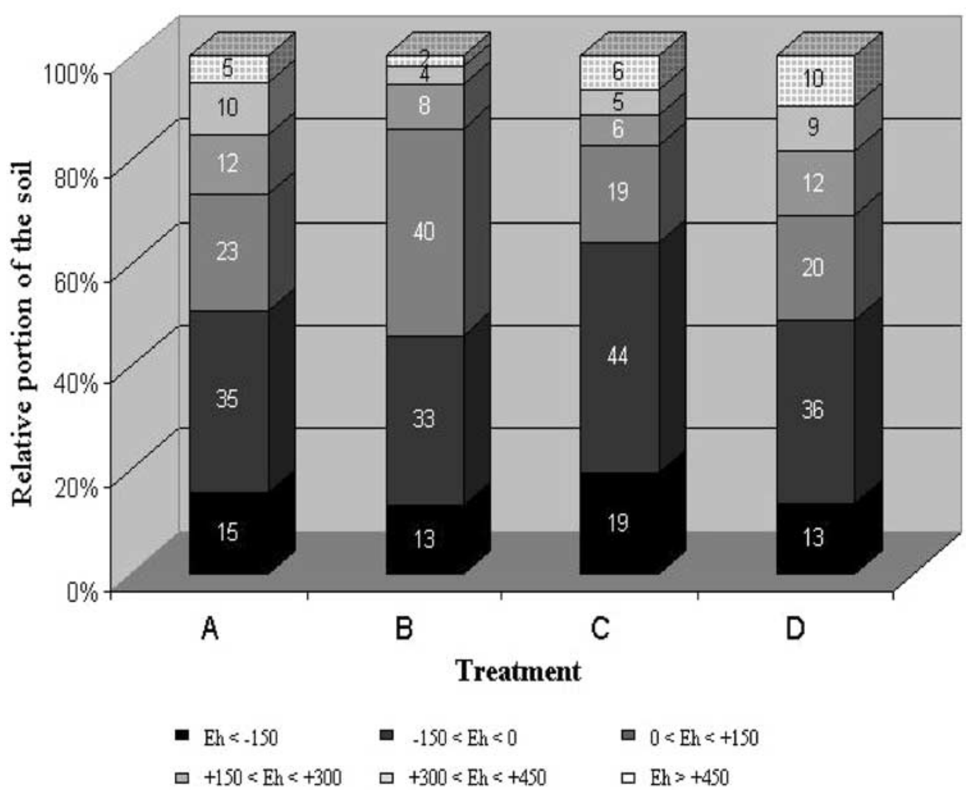

Figure 7. Relative portion of the soil at each Eh range under different treatments. Treatments are as follows: A, no OM addition, flooded; B, no OM addition, nonflooded; C, OM addition, flooded; D, OM addition, nonflooded.

based fertilizers). Such temporary flooding conditions may prevent the undesirable nitrification and N_2O production and emission as found under the flooding treatment (Figures 3 and 6 and Tables 1 and 2) without introducing significant CH_4 emission (Figure 2). This modification will not affect the feasibility of the field management, but how long the field should be kept flooded after fertilization deserves further investigation.

5. Conclusions

[22] The wide Eh range (+180 to −150 mV) with minimum N_2O and CH_4 production found in laboratory studies [*Yu et al.*, 2001; *Yu and Patrick*, 2003] provides information to maximize the reduction of the cumulative GWP from the rice fields. Although the entire soil profile cannot be regulated within such an Eh range, proper irrigation management can control soil Eh in a favorable way to largely reduce CH_4 emission with least increase in N_2O emission. The optimum Eh conditions in the fields should minimize significant methanogenesis and nitrification, while favoring complete denitrification with N_2 as the end product especially for the period following N fertilization. The recommended management practice (nonflooded, with OM addition) with a potential modification (temporary flooding following fertilization) from this study showed an effective reduction of cumulative GWP from both CH_4 and N_2O emission without decreasing the rice yield. This management option is practically feasible, because irrigation control is according to the field wetness rather than any instrumental measurements, and may also provide some benefit to the farmers. Best management practices should be field specific in general, however, it is recommended to apply this management approach to the rice fields where no specific information on seasonal variations of CH_4 and N_2O emission is available. Effective mitigation of GWP from rice fields will greatly compensate the expected higher CH_4 and N_2O emissions from projected future increase in rice cultivation area and intensity, which will help the rice ecosystem to be environmentally sustainable.

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