Biol Fertil Soils (2002) 36:53–58
DOI 10.1007/s00374-002-0503-3

ORIGINAL PAPER

X. Xu · P. Boeckx · Y. Wang · Y. Huang · X. Zheng
F. Hu · O. Van Cleemput

Nitrous oxide and methane emissions during rice growth and through rice plants: effect of dicyandiamide and hydroquinone

Received: 18 July 2001 / Accepted: 25 March 2002 / Published online: 19 July 2002

Abstract There is growing interest in N_2O and CH_4 transport through rice plants, but very little information is available on the effects of inhibitors on these gaseous emissions during rice growth and through rice plants. The closed chamber technique was used to study the effect of the urease inhibitor hydroquinone (HQ) and the nitrification inhibitor dicyandiamide (DCD) on N_2O and CH_4 emissions. As rice plants grew, the N_2O emission through rice plants was significantly reduced in all treatments; N_2O emissions were always lower in the presence than in the absence of inhibitor(s). These variations paralleled those in NO_3^--N content of fresh rice plants. During the rice growth period, increasing NO_3^--N content in rice plants paralleled the increase in the N_2O emission through rice plants. Hence, NO_3^--N in young rice plants can substantially contribute to the plant-mediated N_2O flux. A substantial CH_4 emission through rice plants occurred at their vigorous growth stage; CH_4 emissions were always lower in the presence than in the absence of inhibitor(s). Under the experimental conditions, application of DCD, especially of DCD+HQ, could significantly improve the growth of rice, and reduce the emissions of N_2O and CH_4 during rice growth.

Keywords Dicyandiamide · Hydroquinone · Methane · Nitrous oxide · Urea

Introduction

Rice fields have been considered as one of the important sources of atmospheric CH_4 (Khalil and Rasmussen 1983; Bartlett and Harriss 1993). For permanently flooded rice fields, >80% of CH_4 is emitted from rice plants (Nouchi et al. 1990). The pattern and amount of aerenchyma in rice plants can substantially contribute to the wide variation in the CH_4 transport capacity of rice plants during different growth stages (Aulakh et al. 2000; Wassmann and Aulakh 2000). Khalil et al. (1998) showed a large N_2O emission from rice fields using N-based fertilizers. By comparing N_2O emissions in chambers with and without rice plants, Mosier et al. (1990) showed that young rice plants facilitated the emission of N_2O. In recent years there has been growing interest in N_2O and CH_4 emissions through rice plants (Yu et al. 1997; Yan et al. 2000). When soils were flooded, N_2O emissions through rice plants were substantial. The reduction of NO_3^--N in fresh plants can influence N_2O and NO_x fluxes within the plants and contribute to total N_2O through the plants (Chen et al. 1990; Klepper 1990; Rockel et al. 1996).

Under flooded conditions, dicyandiamide (DCD), a nitrification inhibitor, alone or in combination with hydroquinone (HQ), a urease inhibitor, can substantially reduce CH_4 emission during rice growth (Xu et al. 2000a) and effectively regulate the behaviour of applied urea (U)-N in a soil-plant system (Xu et al. 2000b, 2001). This could possibly affect the N loss as N_2O from rice fields after application of U, and the status of N in the rice plants.

Majumdar et al. (2000) and Kumar et al. (2000) showed that in field experiments, application of DCD together with U significantly reduced N_2O emission. In the presence of nitrification inhibitors such as DCD (Lindau et al. 1993; Xu et al. 2000a), wax-coated CaC_2 (Lindau et al. 1993; Keerthisinghe et al. 1993) and nitrapyrin (Keerthisinghe et al. 1993) and Nimin (Rath et al. 1999), CH_4 emission was significantly reduced from rice fields fertilized with U. Even so, very little information is

X. Xu (✉) · Y. Wang · Y. Huang · X. Zheng · F. Hu
State Key Laboratory of Atmospheric Boundary Layer Physics
and Atmospheric Chemistry,
Institute of Atmospheric Physics,
Chinese Academy of Sciences, Beijing 100029,
People’s Republic of China
e-mail: xingkai_xu@hotmail.com
Tel.: +86-10-82084278, Fax: +86-10-62041393

P. Boeckx · O. Van Cleemput
Laboratory of Applied Physical Chemistry,
Faculty of Agricultural and Applied Biological Sciences,
University of Ghent, 9000, Gent, Belgium

available on the effects of both inhibitors on N_2O and CH_4 emissions during rice growth and through rice plants.

This work reports the emissions of N_2O and CH_4 over the rice growing period. The effects of HQ and DCD were studied in pot experiments. The objective of this work is to present an effective method for the mitigation of both N_2O and CH_4 emissions during rice growth. Of additional interest was also the contribution of the NO_3^--N content of rice plants to the N_2O emission through rice plants.

Materials and methods

Soil characteristics

Samples (0–20 cm depth) of a sandy loam soil in Belgium were collected. Some properties of the soil, classified as luvisol (FAO soil classification), were measured using the methods of Kim (1995) and Keeney and Nelson (1982). The amounts of clay, silt and sand in the soil were 14.9%, 28.9% and 56.2%, respectively. Concentrations of soil total N, available N and total C were 1.5 g N kg^{-1}, 16.7 mg N kg^{-1} and 17.5 g C kg^{-1}, respectively. The soil pH was 7.6 (1:5, soil:water ratio). The soil samples were slightly air-dried and passed through a 2-mm-mesh sieve before use.

Experimental description

Pot experiments were conducted in a greenhouse. Two kilograms of soil was thoroughly mixed with 1.0 g K_2HPO_4 and 2.0 g U and placed into each pot. According to the experimental treatments, corresponding amounts of inhibitor(s) were mixed with the soil before flooding. Application rates of HQ and DCD were 0.3% and 5% of the applied U (w/w), respectively (Zhao et al. 1993; Xu et al. 2000a). Seven 20-day-old healthy rice seedlings were transplanted into the pot after 1 day of flooding. The experimental design contained four treatments with nine replicates per treatment. These treatments included U, U+HQ, U+DCD and U+HQ+DCD. During the entire experimental period a floodwater layer on the surface of the soil was 2 cm deep.

Sampling and analysis

Within an 80-day period of rice cultivation, the pots were, at regular intervals, sealed air-tight with a PVC lid (height×diameter=85 cm×30 cm) (Xu et al. 2000a) from 10:00 to 12:00 am o'clock. During this period, gas samples were taken using 10-ml vacutainers. Concentrations of CH_4 and N_2O in the gas samples were measured using a Chrompack 437 A with an ECD and a chrompack cp 9000 with a FID, respectively (De Groot et al. 1994; Boeckx et al. 1996). The emissions of CH_4 and N_2O from pots after cutting plants were also measured on days 20, 60 and 80 after fertilization, respectively, corresponding to early tiller, stem elongation and booting stages of rice plants. Fresh weight of the above-ground biomass of rice was recorded, and NO_3^--N content of the fresh rice plants was measured according to Singh (1988). NH_4^+-N and $(NO_3^-+NO_2^-)$-N concentrations in the standing floodwater were measured by the MgO-Devarda's alloy procedure (Keeney and Nelson 1982).

Calculation and statistical analysis

Gas emission was determined by collecting four headspace samples at 30-min intervals, during a 1.5-h period of closure. Results showed that the increase in the headspace gas concentration could be assumed to be time-linear. The rates of gas emissions were derived from linear regressions of concentration changes over time in the PVC cover, by the methods of Granberg et al. (1997). Only measurement sets with a R^2 value >0.90 were accepted. The N_2O and CH_4 emissions were calculated as follows: $F=V/W\times dC/dt$, where F represents the N_2O emission rate (μg N_2O-N kg^{-1} air-dried soil h^{-1}) or the CH_4 emission rate (μg CH_4 kg^{-1} air-dried soil h^{-1}); W is the weight of air-dried soil in each pot (kg); V is the available headspace volume (ml) and dC/dt is the increase in the N_2O or CH_4 concentration during dt (μg N_2O-N or CH_4 ml^{-1} h^{-1}).

All samplings were replicated 3 times. Total emissions of CH_4 and N_2O during the study period were calculated by integrating the emissions on sampling days and cumulative emissions in between the sampling days. Cumulative emissions were quantified by multiplication of the average emissions of 2 successive sampling days by the number of non-sampling days in between. The mean values and SEs were calculated. Significant differences between means were analysed using SPSS (version 9.0), with a confidence interval of 95%. Regression analysis was used to fit the independent variables in the model, which related the contribution of the NO_3^--N content of fresh rice plants to the N_2O emission.

Results and discussion

Growth of rice plants

Fresh weight of the above-ground biomass of rice plants was much higher in the U+DCD and U+HQ+DCD treatments than in the other treatments throughout the experimental period (Fig. 1). However, no significant difference was found between the U+DCD and U+HQ+DCD treatments. The influence of HQ on U hydrolysis is of short duration under waterlogged conditions (Zhao et al. 1993). For this reason, it was assumed that the positive effect of the U+HQ+DCD treatment on rice growth was mainly due to DCD.

NO_3^--N content of fresh rice plants

For the treatments with inhibitor(s), especially with DCD and with DCD+HQ, the content of NO_3^--N in the plant tops of fresh rice was much lower than that in the U treatment (Fig.2). This result confirmed those by Grylls (1988), who reported that application of nitrification inhibitors together with NH_4^+-based fertilizers effectively reduced NO_3^--N content in lettuces. Kallio et al. (1982) also showed that the nitrification inhibitor, N-serve, could reduce the NO_3^--N content in the roots and leaves of red beet when fertilized with U or NH_4NO_3. As the rice plants grew, the NO_3^--N content of the fresh plants decreased significantly (Fig. 2), suggesting that an accumulation of NO_3^--N in rice plants occurred only during the early growth period.

Application of DCD and of DCD+HQ can effectively enhance the concentration ratio of NH_4^+-N to $(NO_3^-+NO_2^-)$-N in U-treated soil, and regulate the N status in plants and grains (Xu et al. 2000b, 2001). These effects can, to some extent, explain the small NO_3^--N content in the DCD-treated rice plants at the early growth stage.

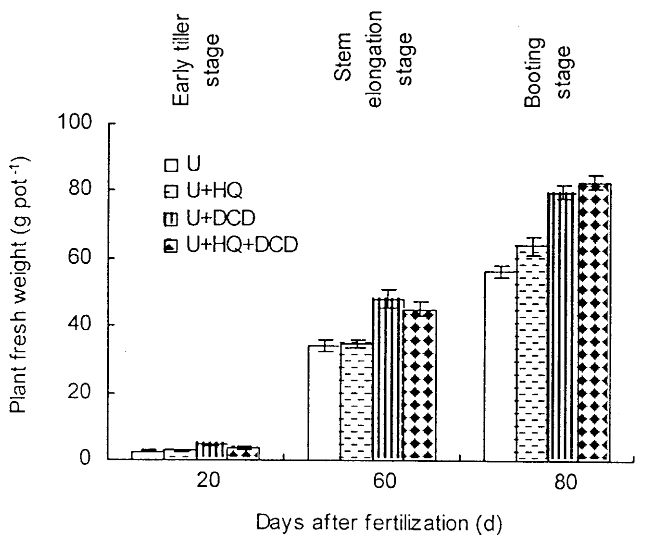

Fig. 1 Fresh weight of the above-ground parts of rice plants during different growth stages; mean±SE (*n*=3). *U* Urea, *U+HQ* U+hydroquinone, *U+DCD* U+dicyandiamide

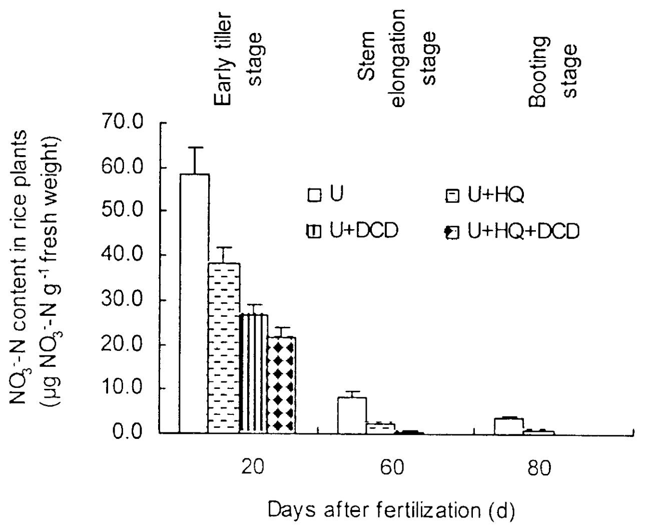

Fig. 2 NO_3^- content in the above-ground parts of rice plants during different growth stages; mean±SE (*n*=3). For abbreviations, see Fig. 1

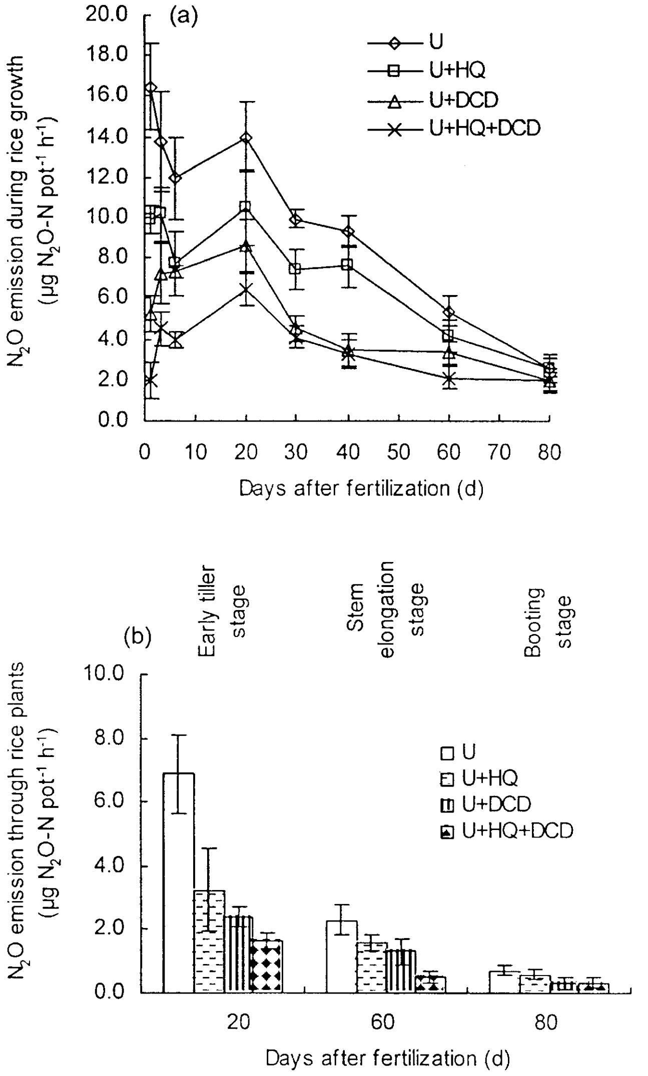

Fig. 3 **a** Dynamics of N_2O emission during rice growth; **b** dynamics of N_2O emission through rice plants; mean±SE (*n*=3). N_2O emission through rice plants=N_2O emission from pots–N_2O emission from pots after cutting plants. For abbreviations, see Fig. 1

Table 1 Total amount of the N_2O and CH_4 emissions during rice growth. Values are the means and SEs (*in parentheses*) of three replicates. *Within each column*, means followed by *different letters* are significantly different at *P*<0.05. *U* Urea, *U+HQ* U+hydroquinone, *U+DCD* U+dicyandiamide

Treatments	CH_4 emission (mg CH_4 pot^{-1})	N_2O emission (mg N_2O-N pot^{-1})
U	190.3 (15.9) c	17.3 (2.1) b
U+HQ	133.0 (10.7) b	13.2 (1.1) b
U+DCD	89.2 (7.9) a	9.1 (0.8) a
U+HQ+DCD	79.5 (10.1) a	6.5 (0.6) a

N_2O emissions during rice growth and through rice plants

N_2O emissions during rice growth and through rice plants are shown in Fig. 3a, b. The N_2O emission during rice growth in any treatment decreased with time (Fig. 3a). All treatments with inhibitor(s), especially with HQ+DCD, presented smaller N_2O emissions than the U treatment during the entire experimental period, thus resulting in a substantial reduction of total N_2O emission during rice growth (Table 1). A combined application of DCD and HQ gave the smallest N_2O emission during rice growth within a 20-day period after fertilization (Fig. 3a). The total N_2O emission in the U+HQ+DCD treatment was about one-third of that in the U treatment (Table 1). The synergistic effect of the two inhibitors on the N_2O emission in wetland rice cultivation occurred immediately after application of U. A similar synergistic effect was also observed under well-drained conditions (Xu et al. 2000b). Inhibition of the

N_2O emission during rice growth by addition of DCD was in accordance with that shown by Majumdar et al. (2000) and by Kumar et al. (2000).

In flooded rice fields oxic-anoxic interfaces are found at the floodwater-soil interface and in the rhizosphere of rice plants, where N_2O can be produced after application of U, via nitrification of NH_4^+ and the following denitrification. Addition of DCD and of DCD+HQ can effectively inhibit the oxidation of NH_4^+-N produced in the flooded surface soil and in the floodwater immediately following the hydrolysis of U, with a consequent reduction in the (NO_3^-+NO_2^-)-N concentration (data not shown). The inhibition of nitrification may reduce N_2O emission immediately after fertilization.

In the presence of DCD and of DCD+HQ, the fresh weight of rice plants was much higher than in the absence of inhibitor(s) (Fig. 1), indicating probably that the amount of available soil N absorbed by plants was higher during the rice growing period. This can extensively reduce gaseous N losses (e.g. N_2O) from rice fields amended with U. Williams et al. (1992) discussed that soil NO or N_2O emission rates depended on the soil N content and water availability.

N_2O emissions through rice plants are calculated as the differences between emissions from pots and those from pots after cutting plants. On days 20 and 60 after fertilization, the rice plants entered their early tiller and stem elongation stages, respectively. During these periods, the treatments with inhibitor(s), especially with HQ+DCD resulted in a small N_2O emission through rice plants (Fig. 3b). No significant differences in N_2O emissions among all treatments were observed on day 80.

As rice plants grew, the N_2O emission through rice plants was significantly reduced in all treatments (Fig. 3b); N_2O emission was always lower in the presence than in the absence of inhibitor(s) (Fig. 3a). These changes paralleled those in the NO_3^--N content of fresh rice plants (Fig. 2). Regression analysis showed a significant and positive correlation between the N_2O emission through rice plants and the NO_3^--N content of fresh rice plants (Fig. 4). Such a relation also occurred in young upland plants (Chen et al. 1997). By comparing N_2O emission in chambers with and without rice plants, Mosier et al. (1990) demonstrated that young rice plants facilitated the emission of N_2O. At low light density, the NO_3^--N content of fresh plant organs can be reduced probably due to N_2O and NO emissions (Klepper 1990; Rockel et al. 1996). Chen et al. (1990) also reported that plants might emit N_2O when stressed. Accordingly, under the experimental conditions, NO_3^--N of fresh rice plants can substantially contribute to the plant-mediated N_2O emission.

CH_4 emissions during rice growth and through rice plants

Figure 5a shows the CH_4 emission during rice growth. In contrast to the N_2O emission (Fig. 3a), the CH_4 emission increased with time in all treatments, and reached its maximum value on day 50 after fertilization (Fig. 5a), when the rice plants entered their vigorous vegetation growth stage. This peak of CH_4 emission probably resulted from some substances released by rice roots (Kimura et al. 1991; Thomas et al. 1995; Wassmann and Aulakh 2000).

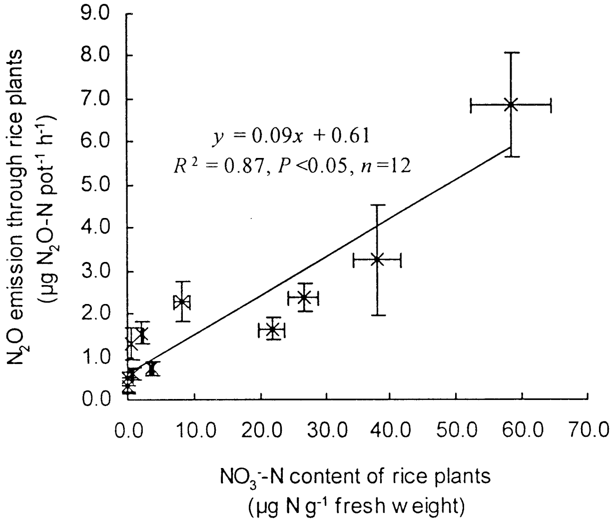

Fig. 4 Relation between N_2O emission through rice plants and NO_3^--N content of rice plants at three sampling periods. The *solid line* is the linear regression of N_2O emission through rice plants, *y*, against NO_3^--N content of rice plants, *x*. The *horizontal* and *vertical bars* represent SEs of the NO_3^--N content and the N_2O emission (n=3), respectively. N_2O emission through rice plants=N_2O emission from pots–N_2O emission from pots after cutting plants

All treatments with inhibitors, especially with DCD and with DCD+HQ, could substantially reduce CH_4 emission during the entire experimental period, and consequently the total CH_4 emission (Table 1). Lindau et al. (1993) found that CH_4 emissions from rice fields decreased by 35% and 14% after application of encapsulated CaC_2 and DCD, respectively. Rath et al. (1999) suggested that the use of nitrification inhibitors such as Nimin could be considered as a suitable option for mitigating CH_4 emissions from rice fields.

CH_4 emissions from pots after cutting plants were much higher in the presence than in the absence of inhibitor(s) (Xu et al. 2000a). This is apparently contrary to the CH_4 emissions during rice growth (Fig. 5a). Addition of DCD could significantly improve rice growth (Fig. 1), and the total amount of root exudate C was closely related to the root dry weight (r^2=0.92) and to the aboveground biomass (r^2=0.95) (Wassmann and Aulakh 2000). Aulakh et al. (2001) showed that in the anoxic rice soils, the proportion of root exudate C converted to CH_4 ranged from 61% to 83%. These results indicated that the CH_4 production in the rhizosphere of rice plants was higher in the presence than in the absence of DCD. Since the CH_4 efflux is the net result of production and oxidation of CH_4, the reduction of CH_4 emission in the wetland rice cultivation probably resulted from the inhibition of the conversion of root exudates to CH_4. This phe-

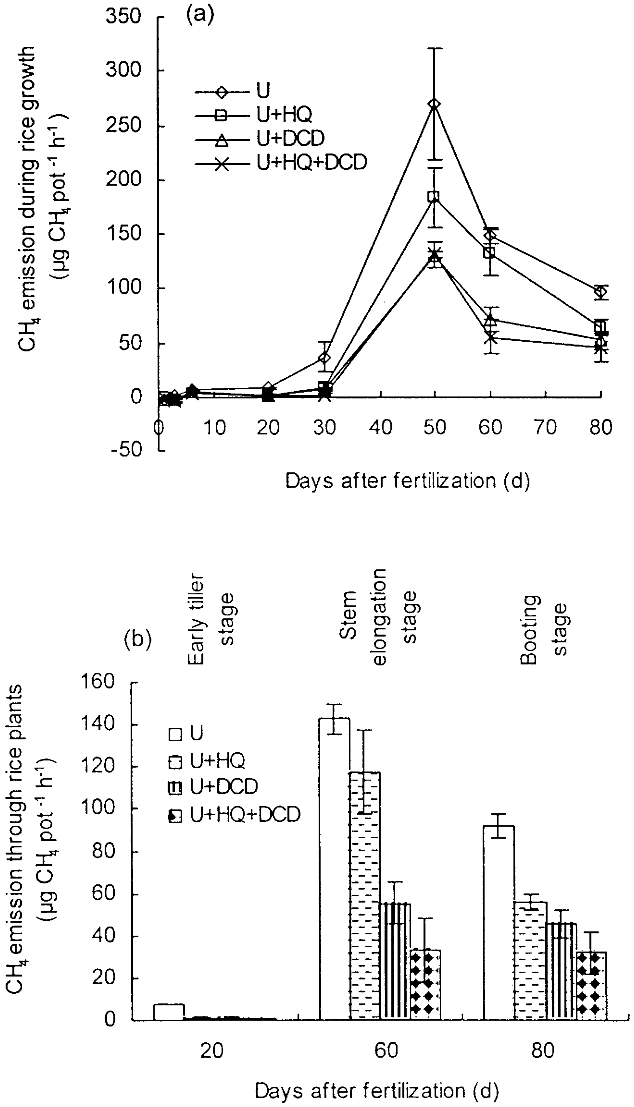

Fig. 5 **a** Dynamics of CH_4 emission during rice growth; **b** dynamics of CH_4 emission through rice plants; mean±SE (n=3). CH_4 emission through rice plants=CH_4 emission from pots–CH_4 emission from pots after cutting plants. For abbreviations, see Fig. 1

nomenon was possibly related to the variation of the Eh potential in the root zone. According to our previous rhizosphere experiments, the Eh value in the rhizosphere of rice plants was significantly higher in the presence than in the absence of DCD, particularly when the rice plants entered their vigorous growth stage (data not shown). The quantity and quality of root exudates can be affected by many factors such as N status and presence of toxic substances in the rhizosphere (Aulakh et al. 2001). Hence, it is necessary to study further the variations in the root exudates and in the aerenchyma of the roots after application of U and inhibitor(s).

CH_4 emission through rice plants can be calculated as the difference between emissions from pots and those from pots after cutting plants (Fig. 5b). At the early tiller stage, a small CH_4 emission through rice plants occurred in each pot. However, when the rice plants entered their vigorous growth stage (e.g. stem elongation stage), substantial emission of CH_4 occurred through rice plants (Fig. 5b), probably as the result of the development of aerenchyma tissue (Wassmann and Aulakh 2000). The pattern of the plant-mediated CH_4 emission during rice growth was different from that of the plant-mediated N_2O emission (Fig. 5a). Indeed, these emissions were not significantly correlated (r=–0.28, P>0.05).

In the presence of DCD, 60.4–86.7% of CH_4 emission occurred through rice plants, and was smaller than the percentage (94.2–96.3%) of the U treatment (Fig. 4a, b). Hence, the combined application of U and DCD caused a small CH_4 emission through rice plants.

In conclusion, in the presence of floodwater, the N_2O and CH_4 emissions through rice plants presented an apparent difference during rice growth. As rice plants grew, the N_2O emission through rice plants decreased significantly. However, a substantial CH_4 emission through rice plants occurred at their vigorous growth stage. Both emissions from the flooded soil were related to the conduit of rice plants, and the NO_3^--N content of fresh rice plants could substantially contribute to the plant-mediated N_2O emission. DCD and DCD+HQ together with U appeared to be effective tools in reducing emissions of N_2O and CH_4 during rice growth. This paper provides interesting results on how to reduce CH_4 and N_2O emissions in wetland rice cultivation, but further field experiments will be needed in order to attain the objective of an effective method for mitigating both N_2O and CH_4 emissions.

Acknowledgements This work was funded partly by the National Natural Sciences Foundation of China (agreement no. 29907004) and by the knowledge Innovative Program of the Chinese Academy of Sciences (approved no. KZCX1-SW-01B) and by the Hundred Talents Program of the Chinese Academy of Sciences. We also acknowledge financial support from ABOS, Ministry of Foreign Affairs, Belgium, through VLIR-Own Initiatives.

References

Aulakh MS, Wassmann R, Rennenberg H, Fink S (2000) Pattern and amount of aerenchyma relate to variable methane transport capacity of different rice cultivars. Plant Biol 2:182–194

Aulakh MS, Wassmann R, Bueno C, Rennenberg H (2001) Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa L.*) on methane production in a paddy soil. Plant Soil 230:77–86

Bartlett KB, Harriss RC (1993) Review and assessment of CH_4 emissions from wetlands. Chemosphere 26:211–230

Boeckx P, Van Cleemput O, Villaralvo IDA (1996) Methane emission from a landfill and the methane oxidising capacity of its covering soil. Soil Biol Biochem 28:1397–1405

Chen G, Shang S, Yu K, Wu J, Wang Y (1990) Investigation on the emission of nitrous oxide by plant. Chin J Appl Ecol 1:94–96

Chen X, Shen SM, Zhang L, Wu J (1997) Effect of nutritional condition on N_2O emission by crop seedlings – a sand-liquid cross culture study. Chin J Appl Ecol 8:177–180

De Groot CJ, Vermoesen A, Van Cleemput O (1994) Laboratory study of the emission of N_2O and CH_4 from a calcareous soil. Soil Sci 158:355–364

Granberg G, Mikkelä C, Sundh I, Svensson BH, Nilsson M (1997) Sources of spatial variation in methane emission from mires in northern Sweden – a mechanistic approach in statistical modeling. Global Biogeochem Cycles 11:135–150

Grylls JP (1988) Effect of nitrogen fertilizer type and nitrification inhibitor on the nitrate content of glasshouse lettuce. Acta Hortic 222:189–191

Kallio H, Kyyro M, Evers AM, Korkman J (1982) Distribution of nitrate in red beet roots and leaves fertilized with urea on ammonium nitrate. Ann Agric Fenn 21:131–136

Keeney DR, Nelson DW (1982) Nitrogen – inorganic forms. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis. Part 2. Chemical and Microbiological Properties, 2nd edn. America Society of Agronomy, Madison, Wis. pp 643–687

Keerthisinghe DG, Freney JR, Mosier AR (1993) Effect of wax-coated calcium carbide and nitrapyrin on nitrogen loss and methane emission from dry-seeded flooded rice. Soil Biol Biochem 16:71–75

Khalil MAK, RJ Rasmussen (1983) Sources, sinks and seasonal cycles of atmospheric methane. J Geophys Res 88:5131–5144

Khalil MAK, Rasmussen RA, Shearer MJ, Chen ZL, Yao H, Yang J (1998) Emissions of methane, nitrous oxide, and other trace gases from rice fields in China. J Geophys Res 103: 25241–25250

Kim HT (1995) Soil sampling, preparation and analysis. Dekker, New York

Kimura M, Murakami H, Wada H (1991) CO_2, H_2 and CH_4 production in rice rhizosphere. Soil Sci Plant Nutr 37:55–60

Klepper L (1990) Comparison between NO_x evolution mechanisms of wild-type and mutant soybean leaves. Plant Physiol 93:26–32

Kumar U, Jain MC, Pathak H, Kumar S, Majumdar D (2000) Nitrous oxide emission from different fertilizers and its mitigation by nitrification inhibitors in irrigated rice. Biol Fertil Soils 32:474–478

Lindau CW, Bollich PK, Delaune RD, Mosier AR, Bronson KF (1993) Methane mitigation in flooded Louisiana rice fields. Biol Fertil Soils 15:174–178

Majumdar D, Kumar S, Pathak H, Jain MC, Kumar U (2000) Reducing nitrous oxide emission from an irrigated rice field of north India with nitrification inhibitors. Agric Ecosys Environ 81:163–169

Mosier AR, Mohanty SK, Bhadrachalam A, Chakravoti SP (1990) Evolution of dinitrogen and nitrous oxide from the soil to the atmosphere through rice plants. Biol Fertil Soils 9:61–67

Nouchi I, Mariko S, Aoki K (1990) Mechanism of methane transport from the rhizosphere to the atmosphere through rice plants. Plant Physiol 94:59–66

Rath AK, Swain B, Ramakrishnan B, Panda D, Adhya TK, Rao VR, Sethunathan N (1999) Influence of fertilizer management and water regime on methane emission from rice fields. Agric Ecosys Environ 76:99–107

Rockel P, Rockel A, Wildt J (1996) Nitric oxide (NO) emission by higher plants. In: Van Cleemput O (ed) Progress in nitrogen cycling studies. Kluwer, Dordrecht, pp 603–606

Singh JP (1988) Rapid method for determination of nitrate in soil and plant extracts. Plant Soil 110:137–139

Thomas KL, Price D, Lloyd DA (1995) Comparison of different methods for the measurement of dissolved gas gradients in waterlogged peat cores. J Microbiol Meth 24:191–198

Wassmann R, Aulakh MS (2000) The role of rice plants in regulating mechanisms of methane emissions. Biol Fertil Soils 31: 20–29

Williams EJ, Hutchinson GL, Fehsenfeld FC (1992) NO_x and N_2O emissions from soil. Global Biogeochem Cycles 6:351–388

Xu XK, Wang YS, Zheng XH, Wang MX, Wang ZJ, Zhou LK, Van Cleemput O (2000a) Methane emission from a simulated rice field ecosystem as influenced by hydroquinone and dicyandiamide. Sci Total Environ 263:243–253

Xu XK, Zhou LK, Van Cleemput O, Wang ZJ (2000b) Fate of urea-^{15}N in a soil-wheat system as influenced by urease inhibitor hydroquinone and nitrification inhibitor dicyandiamide. Plant Soil 220:261–270

Xu XK, Huang Y, Zhou LK, Huang GH, Van Cleemput O (2001) Effect of dicyandiamide and hydroquinone on the transformation of urea-nitrogen-15 in soil cropped to wheat. Biol Fertil Soils 34:286–290

Yan X, Shi S, Du L, Xing G (2000) Pathways of N_2O emission from rice paddy soil. Soil Biol Biochem 32:437–440

Yu KW, Wang ZP, Chen GX (1997) Nitrous oxide and methane transport through rice plants. Biol Fertil Soils 24:341–343

Zhao XY, Li SD, Zhou LK, Wu GY (1993) Fate of [^{14}C]hydroquinone and [^{15}U]urea in a soil-rice system: a pot trial. Soil Biol Biochem 25:143–146