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Release of entrapped methane from wetland rice fields upon soil drying

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Abstract. Methane emissions from Philippine rice paddies, fertilized with either urea or green manure, were monitored for several weeks after harvesting the dry and the wet season crops of 1992. The fields were still flooded during harvest but irrigation was stopped after harvest and the fields were allowed to evaporatively dry while CH_4 emissions were monitored with a closed chamber technique. In all plots we observed a sudden, strong increase of CH_4 emissions to the atmosphere for 2 to 4 days just after the soil fell dry. As soil drying continued, the soils began to crack and CH_4 emissions decreased to nil. The release of CH_4 during soil drying was observed for fields on three different soil types and both for urea or organically manured rice fields in both seasons. The absolute amounts of CH_4 emitted during soil drying differed greatly depending on fertilizer treatment. However, the ratio between the amount of CH_4 released upon soil drying and CH_4 emitted during the growing season was quite constant (0.10 ± 0.04). This suggests that about 10% of the CH_4 emitted during a full rice crop cycle is released during drying of the fields and thus needs to be included in estimates of the total CH_4 emission from rice agriculture.

Introduction

Methane (CH_4) is one of the most important greenhouse gases. Wetland rice fields emit CH_4 and are important contributors to the increasing atmospheric methane concentrations [*Cicerone and Shetter*, 1981; *Schütz et al.*, 1989a]. CH_4 emissions from wetland rice fields are often measured with the so-called closed chamber technique [e.g., *Schütz et al.*, 1989a]. Although the same technique is used in many studies, the method (e.g., manually versus automatic operation of the flux chambers) and frequency of sampling vary widely. Calculated seasonal CH_4 emissions from rice fields have to include both daily and seasonal variation in CH_4 emission. If CH_4 emissions are monitored continuously this is achieved by summing the individual flux measurements. If CH_4 emissions from rice fields are monitored at a low time resolution, for example, once every week, total seasonal CH_4 emission estimate is obtained by assuming that each measurement point is representative for a certain time window. However, low nighttime CH_4 emissions and/or peak emissions around noon or early afternoon may be missed when sampling at low time resolution. Therefore when monitoring at a low time resolution, intensive 24-hour measurement campaigns should be included. The obtained diel emission pattern can be extrapolated to other measurement points because the diel emission pattern is rather stable on a timescale of a few weeks [*Schütz et al.*, 1989a; *Denier van der Gon and Neue*, 1995]. In addition to the diel fluctuation in CH_4 emissions, agricultural practices, like weeding and post-harvest drainage, may also cause highly variable CH_4 emissions in relatively short periods [*Denier van der Gon et al.*, 1992; *Wassmann et al.*, 1994]. In this paper we present data that illustrate the dynamics of CH_4 release upon soil drying and discuss its importance for the total CH_4 emission during a complete rice crop cycle.

Materials and Methods

Measuring System

Methane emission was monitored automatically with a closed chamber technique as described by *Schütz et al.* [1989a]. The system allows 24-hour semicontinuous determination of CH_4 emission rates from different gas collector chambers. Measurements are performed in 2-hour cycles, allowing 12 flux measurements per day of each chamber. All

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chambers were made of smooth colorless Plexiglas and equipped with a Plexiglas cover which could be opened and closed by a time-controlled pneumatic cylinder. The dimensions of the chambers were 1 m x 1 m basal area and 1.2 m height or 0.6 m x 0.6 m basal area and 1.2 m height. To stabilize the chambers, each corner of a chamber has a 20-cm aluminum extension which is placed in the soil. The lower sides of the chambers were submerged, providing a gastight seal between inner and outer atmosphere. During receding floodwater and soil drying, the flux chambers were pushed 10 cm into the soil when the fields were still flooded with about 10 cm of water. After harvest of the 1992 wet season crop, water status, soil drying, reflooding, and soil cracking were recorded on a daily basis for each individual flux chamber. Air samples from the individual closed chambers were analyzed for CH_4 on a gas chromatograph equipped with a 6-port valve, sample loop, and a flame ionization detector (FID). For a schematic overview and technical details of the measurement system we refer to *Schütz et al.* [1989a]. The methane emission rate from a chamber is calculated with linear regression from the temporal increase of the CH_4 concentration in the chamber. Each emission rate is based on four measurements. The r^2 of the linear regression of the CH_4 concentration against time is typically > 0.95. CH_4 emissions from all plots were measured in duplicate.

Soil Types

Three soils were used in this study (Table 1). Maahas is the soil originally present at the IRRI research farm. Luisiana and Pila are soils from neighbouring districts. The 0- to 20-cm topsoil from farmers fields in Luisiana and Pila was collected and transported to the IRRI research farm. The original 0- to 20-cm topsoil from 3 x 5 m plots was removed and replaced by Luisiana or Pila soil. The newly placed soils were separated from the original subsoil by a plastic sheet. Field preparations and other agricultural practices were the same for all three soils. Luisiana and Maahas are clay soils, whereas Pila is a calcareous sandy loam. The rice fields were fertilized with urea or green manure (Table 2 and 3). An additional treatment in the 1992 wet season was an addition of gypsum to a plot with Maahas clay.

Table 1. Some Characteristics of the Three Soils Used in the Field Experiment

	Pila	Louisiana	Maahas
pH 1:1 H_2O	7.8	4.5	5.9
CEC, meq/100 g	27.2	24.9	40.2
Organic Carbon, %	1.47	1.84	1.97
Total N, %	0.182	0.180	0.166
Clay, %	21	56	66
Silt, %	40	40	28
Sand, %	39	4	6

Potential CH_4 Production in Soil Columns

Duplicate soil cores of about 10-cm length were taken from each treatment between the rows (10 cm from a hill), using 4.4-cm inner diameter acrylic core tubes with a length of 25 cm. Soil cores were collected at 26, 52, and 94 days after transplanting, corresponding to three growth stages of the rice plant, tillering, panicle initiation, and ripening, respectively. The cores were sliced into 2.5-cm thick segments resulting in four different depth intervals; 0 to 2.5 cm, 2.5 to 5 cm, 5 to 7.5 cm, and 7.5 to 10 cm. Each segment was mixed with 30 mL of demineralized water and transferred to a 125-mL erlemeyer flask of a known total volume. The flasks were sealed with suba-seals, flushed with N_2, and placed in a waterbath shaker (T = 30°C) for preincubation overnight. The following day the flasks were purged with N_2. Six headspace gas samples were taken with intervals of about 1 hour and analyzed for CH_4. After each sampling, the headspace volume was readjusted by injecting a sample volume of N_2 in to the erlemeyer flask. CH_4 production rates were calculated, after correction for dilution, from the increase over time of CH_4 in the headspace.

Soil-Entrapped CH_4

In the 1992 dry season, the amount of CH_4 entrapped in the soil was measured in each treatment just before harvest, 98 days after transplanting. Triplicate soil cores of 10 cm length were collected from each treatment using 4.4-cm inner diameter acrylic core tubes with a length of 25 cm. The top of the tube is sealed with a rubber stopper with a septum. During sampling a gas collector bag is connected to the headspace of the tube via the septum to collect excess gases which may contain CH_4 released during sampling. Next, the tube is sealed at the bottom with a rubber stopper, the gas collector bag is disconnected, and the tube is vigorously shaken for 2 hours. The headspace of the tube and the gas in the gas collector bag were analyzed for CH_4 on a gas chromatograph with FID. The concentrations were recalculated to micrograms CH_4 using the known volumes and summed to give an estimate of the amount CH_4 entrapped in the soil.

Results

Cutting the plants during harvest did not affect CH_4 emission (Figure 1). Pushing the flux chambers into the soil disturbed CH_4 emission by releasing entrapped CH_4 via ebullition. However, after 1 to 2 days the CH_4 emission pattern was the same as before inserting the boxes. In the 1992 dry season the level of the floodwater above the soil surface in the plots with Maahas and Luisiana soil dropped from 10 to 0 cm in about 6 days after irrigation was stopped. In the Pila plot, drying took somewhat longer because the floodwater layer was about 15 cm when irrigation was stopped. Percolation was negligible in all three soils because of a plastic sheet below the Pila and Luisiana soils and an impermeable traffic pan at about 18 cm depth in Maahas soil. So, drying of the soils was mainly by evaporation. The normal diurnal pattern of CH_4 emission continued until floodwater had receded completely. Next, the macropores of the soils became air-filled (but the soils had not cracked yet) and a large flush of CH_4 was measured from the soils. CH_4

Table 2. Soil, Fertilizer Type, and CH_4 Emission During the Growing Season, Soil Drying, and Post-Harvest in the 1992 Dry Season

Soil	Fertilizer	Growing Season CH_4 Emission[a], g m^{-2}	Soil-Entrapped CH_4 Before Harvest[b], µg g^{-1}	CH_4 Emitted During Soil Drying, g m^{-2}	Ratio CH_4 Emission During Soil Drying to Growing Season CH_4 Emission	Post-Harvest CH_4 Emission[d], g m^{-2}
Maahas	urea	17.2	18.5 (7.3)	1.7	0.10	2.9
Maahas	GM[c]	87.1	32.4 (2.3)	5.9	0.07	9.4
Luisiana	urea	23.6	21.0 (3.3)	2.9	0.12	5.1
Pila	urea	30.5	12.5 (3.0)	1.6	0.05	5.6

[a]CH_4 emitted in the period from transplanting up to harvest.
[b]Average of three samples collected 98 days after transplanting, standard deviation in parentheses.
[c]GM is green manure; *Sesbania rostrata.*
[d]In the 1992 dry season post-harvest emission equals emission during fallow period because CH_4 emission from the fields had stopped completely 2 weeks after harvest.

Table 3. Soil, Fertilizer Type, and CH_4 Emission During the Growing Season, Soil Drying, and Fallow Period in the 1992 Wet Season

Soil	Fertilizer	Growing Season CH_4 Emission[a], g m^{-2}	CH_4 Emitted During Soil Drying, g m^{-2}	Ratio CH_4 Emission During Soil Drying to Growing Season CH_4 Emission	Fallow Period CH_4 Emission[d], g m^{-2}
Maahas A[c]	GM[b]	47.1	4.6	0.10	8.5
Maahas B[c]	GM	42.0	3.6	0.09	6.4
Maahas + gypsum	GM	12.1	2.4	0.20	5.0
Pila	GM	42.3	3.8	0.09	9.4

[a] CH_4 emitted in the period from transplanting up to harvest.
[b] GM is green manure; *Sesbania rostrata.*
[c] Plots presented separately because of the different drying pattern (see Figures 4a and 4c).
[d] Includes post-harvest CH_4 emission and CH_4 emission during soil drying.

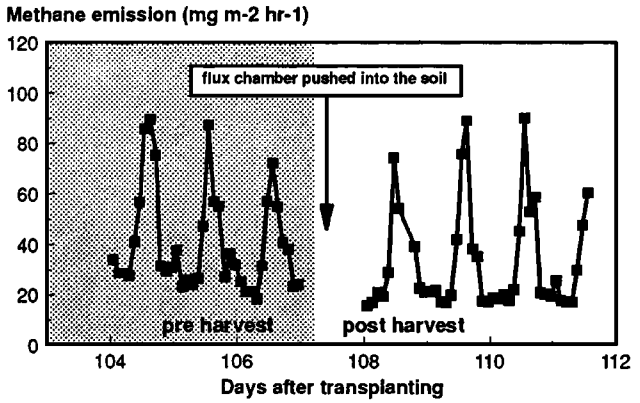

Figure 1. Methane emissions from a continuously flooded rice field as measured with a closed chamber before and after harvest in the 1992 dry season.

emission stopped only after the soil was fully aerated (Figure 2a, 2b, 2c, and 2d). Interruptions of the curves in Figure 2 indicate periods when technical problems prohibited data collection. Table 2 lists the amounts of CH_4 released during the growing season, the amount of soil-entrapped CH_4 just before harvest, CH_4 released during soil drying only and total post-harvest CH_4 emission.

In the 1992 wet season, soil drying after ceasing irrigation was slower due to rain (Figure 3). Table 3 gives the amounts of CH_4 released during soil drying only and the total amounts of CH_4 released from harvest until the CH_4 emission had completely ceased. The CH_4 emissions immediately after harvest showed the same diel pattern and levels as before harvest, as was also observed in the dry season (Figure 1). In Figure 4 these periods with a constant diel emission pattern (up to 14 days after harvest in Figures 4a and 4c, up to 26 days after harvest in Figures 4b and 4d) are omitted to allow more detailed graphical representation of the periods with drastic changes in CH_4 emission. At 16 days after harvest, the soil surface in box 2 of the Maahas plot A (Figure 4a) fell dry and CH_4 emission peaked, apparently due to release of soil-entrapped CH_4. One day later, high CH_4 emissions were also observed from the other box in Maahas plot A (Figure 4a) and the gypsum-amended Maahas soil (Figure 4c). Heavy rain on day 19-21 after harvest interrupted soil drying and caused reflooding of the soils. CH_4 emissions decreased and stopped at 21 days after harvest at the end of the 2-day rain period. (The soil surface of all but one chamber (box 2 of Maahas plot A) showed no cracks yet.) CH_4 emissions from the reflooded plots did not return to the previous diel emission pattern and were negligible with the exception of box 1 of Maahas plot A where the diel emission pattern observed before soil drying returned after 1 week. At 27 days after harvest the soil surface in box 1 and 2 of Maahas plot A and box 1 of the gypsum-amended plot fell dry again, release of entrapped CH_4 resumed 1-2 days later. The largest CH_4 release was observed from box 1 of Maahas plot A which had emitted relatively little CH_4 during the first period of drying. The soil surface of box 2 of the gypsum-amended plot fell dry on 29 days after harvest, and release of entrapped CH_4 started 1 day later. The soils of Maahas

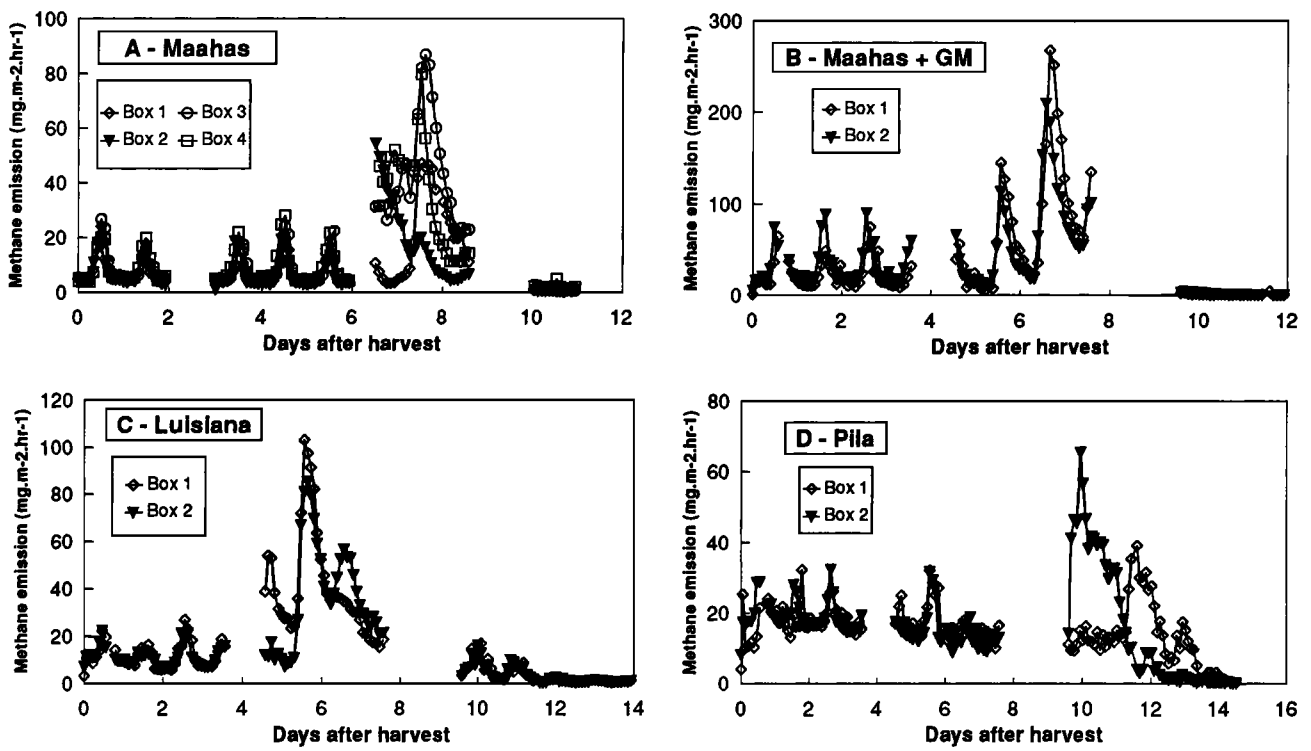

Figure 2. Post-harvest methane emissions from rice fields fertilized with urea (2a, 2c, and 2d) or green manure (2b) on different soil types; Maahas (2a and 2b), Luisiana (2c), and Pila (2d) in the 1992 dry season.

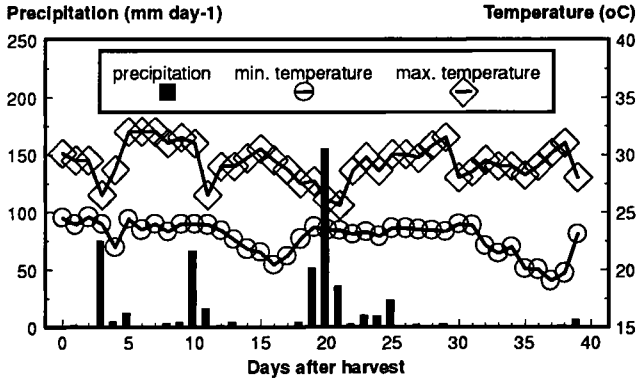

Figure 3. Daily precipitation, minimum temperature, and maximum temperature at the IRRI research farm for the first 40 days after harvest in the 1992 wet season.

plot A and Maahas plus gypsum started to crack at 31 and 32 days after harvest, respectively. However, the release of CH_4 from the soils had more or less stopped by then.

Maahas plot B and the Pila plot were continuously flooded the first month after harvest and showed the normal diel emission pattern in this period (data not shown). The soil surface of Maahas plot B and Pila fell dry 29 and 31 days after harvest, respectively, and large amounts of CH_4 were released to the atmosphere 1-2 days later (Figures 4b and 4d). Soil cracking in Maahas plot B and Pila started 34 and 35 days after harvest, respectively.

Discussion

CH_4 emissions did not change after harvest because the plants were cut above the floodwater layer and thus remained a good conduit for CH_4 transport. Owing to spatial heterogeneity within the plots, the timing of drying differed among individual chambers. Therefore emission patterns should be considered for each chamber separately. To facilitate the discussion, we propose the following terminology: (1) "emission during the growing season" covers the period from transplanting up to harvest, (2) "post-harvest emission" is reserved for emission during the initial 2 weeks after harvest, (3) total emission after harvest (including post-harvest emission) is referred to as "fallow emission", and (4) "emission upon/during soil drying" covers the period of drastic changes in CH_4 emission when the soil falls dry (this may happen more than once during a fallow period).

The sharp increase in CH_4 emission during soil drying is a very dynamic process. We observed that the release of entrapped CH_4 starts 1-2 days after the soil surface fell dry but before the soils started to crack. This pattern indicates that soil cracking by itself is not a prerequisite for the release of entrapped CH_4 and that peak emissions upon soil drying may also be expected from soils that do not or only slightly crack (sandy soils, e.g., Pila soil). Our observations indicate that the critical moment that causes the release of soil-entrapped CH_4, is when the macropores become air-filled. The diffusion of CH_4 through the gas phase is about 4 orders of magnitude faster than through the water phase. So,

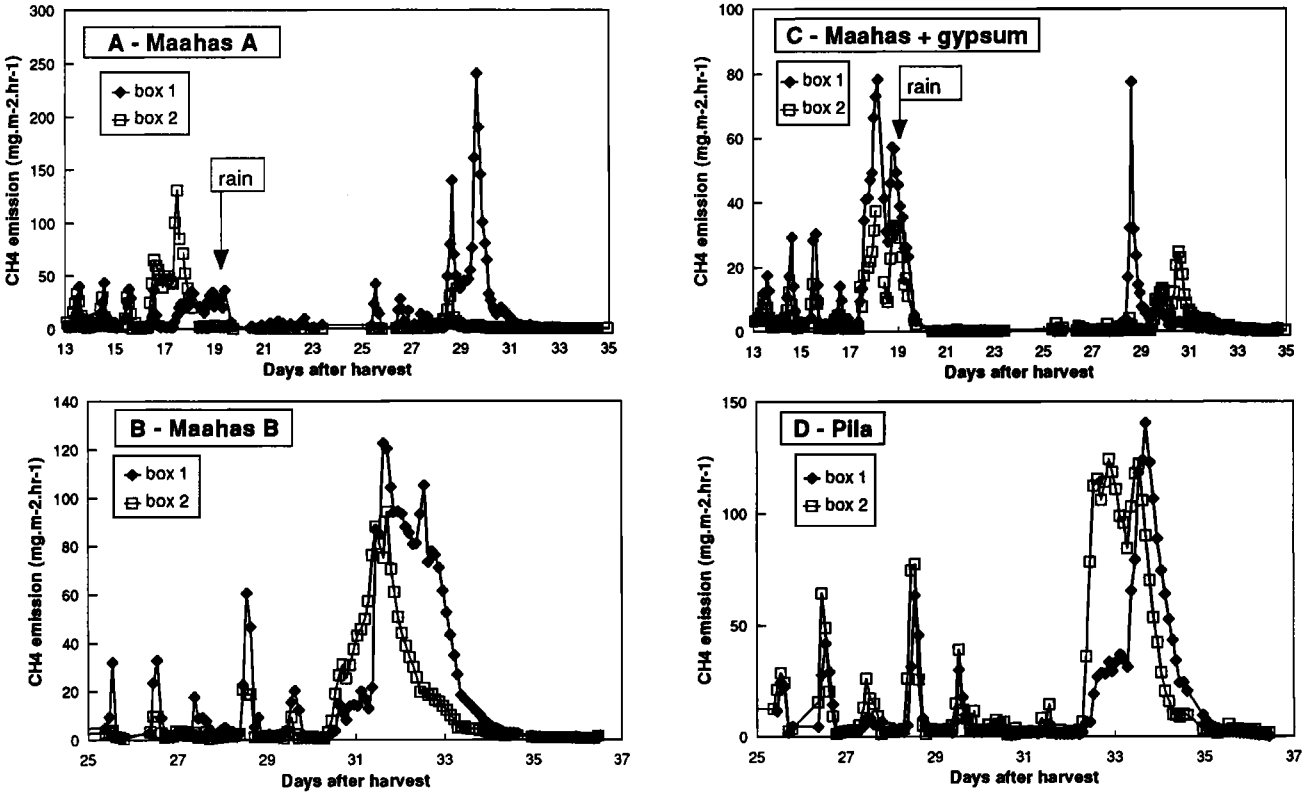

Figure 4. Methane emissions after harvest (fallow period) from rice fields fertilized with green manure before and during soil drying on different soil types; Maahas plot A (2a), Maahas plot B (2b), Maahas with gypsum (2c), and Pila (2d) in the 1992 wet season.

presence of air-filled macropores in a soil could strongly enhance transport of CH_4 from soil to atmosphere. On the other hand, air in the soil macropores would cause the soil to oxidize, creating a good environment for CH_4 oxidizing bacteria. The amount of CH_4 entrapped in the soil per square meter of rice field after the growing season of the 1992 dry season can be estimated using the soil-entrapped CH_4 data given in Table 2. Assuming a bulk density of 900 kg m^{-3} and a puddled layer of 17.5 cm, the amount of CH_4 entrapped in Maahas (urea), Maahas (green manure), Luisiana, and Pila would be 2.9, 5.1, 3.3, and 2.0 CH_4 g m^{-2}, respectively. Comparison with the amount of CH_4 emitted during soil drying (Table 2) indicates that on average, about 64% of the CH_4 entrapped in the soil was released to the atmosphere during soil drying (and thus escaped oxidation in the soil).

CH_4 emission throughout the growing season from plots fertilized with green manure was about 4 times higher than from comparable urea-fertilized plots (Table 2). Likewise the amount of soil-entrapped CH_4 and the amount of CH_4 released during soil drying from fields with green manure application is higher than from comparable urea-fertilized plots. CH_4 emission from gypsum-amended fields was reduced by 50-72%, probably due to competition between sulfate-reducing bacteria and methanogens [*Denier van der Gon and Neue*, 1994]. Again, a similar reduction is observed when the amount of CH_4 released upon soil drying is compared for fields with and without gypsum amendment (Table 3). These results suggest that in soils planted to rice, the amount of soil-entrapped CH_4 and the amount of CH_4 released upon soil drying is mainly controlled by the CH_4 productivity of the soil and is therefore influenced by measures that enhance or depress CH_4 production (e.g., green manure incorporation or gypsum application, respectively). In a recent greenhouse study, *Byrnes et al.* [1995] found that CH_4 release upon soil drying from pots planted to rice accounted for 7-8.5% of the total seasonal emission for both soil types studied. This is in good agreement with our field observations where CH_4 release upon soil drying accounted for about 10% of the total emission (Tables 2 and 3).

A laboratory study with 16 unplanted, flooded rice soils showed that a higher clay content resulted in a higher percentage soil-entrapped CH_4 and a lower percentage CH_4 emitted to the atmosphere [*Wang et al.*, 1993]. *Wang et al.* [1993] suggested that physical characteristics associated with high clay contents help to reduce CH_4 emissions to the atmosphere. However, it is doubtful whether the amount of CH_4 emitted from rice soils is really depressed by a clayey texture because (1) plant-mediated gas transport is the main transport mechanism for CH_4 from paddy fields to the atmosphere, not ebullition [*Cicerone and Shetter*, 1981; *Schütz et al.*, 1989b] and, (2) our results show that at least part of the entrapped CH_4 is released to the atmosphere upon soil drying. Furthermore, we did not observe a significant difference between the amount of CH_4 released from clayey soils or a sandier soil. However, *Sass and Fisher* [1994] reported an inverse relation between CH_4 emission from Texan rice fields and clay content. Clearly, the influence of soil texture on CH_4 emission from rice fields and the mechanism potentially causing this influence deserve further study.

At 20 days after harvest, the high CH_4 emissions of the Maahas plot A and Maahas plus gypsum (Figures 4a and 4c) were interupted because rain reflooded the soils. Considerable amounts of CH_4 were still present in the soils, indicated by the release of CH_4 during the final soil drying event around 30 days after harvest. In between the two soil drying events, CH_4 emissions did not return to levels observed before soil drying, or only after about a week as in box 1 of Maahas plot A (Figure 4a). Why CH_4 emissions do not return to predrying values (or somewhat lower values) but are negligible, although CH_4 was still present in the soil, is not fully understood. Possibly the (short) presence of O_2 poisoned the methanogens and a build-up of CH_4 in the soil to levels that support continuous emission is prohibited. The short drying period at 20 days after harvest in Maahas plot A and Mahaas plus gypsum significantly affected the CH_4 emissions from the rice field and suggests drainage and reflooding before the rice plants suffer from drought stress as a possible mitigation option if water supply is sufficient. Indeed, *Sass et al.* [1992] showed that floodwater management is an effective instrument in mitigating CH_4 emission from rice fields. *Sass et al.* [1992] obtained the lowest seasonal total CH_4 emission by applying a multiple aeration treatment. However, when evaluating the efficiency of floodwater management as a means of reducing CH_4 emissions from rice fields, the amount of CH_4 emitted during soil drying has to be taken into account. High-frequency monitoring of CH_4 emissions from rice fields during soil drying events is essential because the full process of release of the soil-entrapped CH_4 lasts only for a few days and can easily be missed if sampling is done at low time resolution. Because appreciable amounts of CH_4 are emitted just after the fields fell dry, the chambers used for monitoring CH_4 emissions during this period need to have a gastight seal between the chamber bottom and the soil, extending to about 10 cm depth to prevent leakage via cracks.

Conclusions

In all plots, both in the wet season and the dry season, we observed very high emissions of CH_4 to the atmosphere during the early phase of soil drying. *Cicerone et al.* [1992] also reported significant release of CH_4 during soil drying but did not quantify this release. *Sass et al.* [1991, 1992] observed no significant CH_4 release after drainage. Whether this is due to the drainage method or (partly) due to low time resolution sampling at the time of the drainage event cannot be concluded from the available data. The absolute amount of CH_4 emitted upon soil drying in our fields depended on the fertilizer and/or soil amendment. However, the ratio between the amount of CH_4 released during soil drying and CH_4 emitted during the growing season from our paddy fields was rather constant (0.10 ± 0.04), irrespective of the absolute amount of CH_4 emitted. Therefore CH_4 escaping to the atmosphere upon soil drying is a significant part of the total amount of CH_4 emitted from a rice field. In studies on CH_4 emission from wetland rice fields where CH_4 emission during drying of the fields was not included, the total CH_4 emission during a rice crop cycle may be underestimated by about 10 %.

In the 1992 wet season, drying of the rice fields was prevented by rain and CH_4 emissions continued well in to the fallow period at a similar level as before harvest. This indicates that considerable production and emission of CH_4 may occur in/from rice fields during a wet fallow period as was also found in a greenhouse study [*Trolldenier*, 1995]. To minimize production and emission of CH_4, a dry fallow period is recommended. However, a wet, or partially wet, fallow period cannot always be prevented, for example, when frequent rains do not allow soil drying.

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