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Methane emissions associated with a green manure amendment to flooded rice in California

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Abstract. The goals of sustainable food production and mitigation of greenhouse gas emissions may be in conflict when green manures are used in flooded rice systems. A field study was initiated in early spring 1992 near Sacramento, California to quantify the potential for enhanced methane emissions following a green manure amendment to rice. Replicate flux measurements were made twice a day every 3–4 days throughout the growing season in four treatment plots: burned rice straw, spring incorporated rice straw, burned straw plus purple vetch and spring incorporated straw plus vetch. Seasonal methane emissions ranged from 66–136 g CH_4 m^{-2} and were 1.5 to 1.8 times higher from the straw plus vetch treatments relative to the straw only treatments. No significant differences in emissions were found between the two straw only treatments or the straw plus vetch treatments. Methane fluxes were exponentially related to soil temperature, but no effect of redox potential or floodwater depth were observed. The potential impact of these results on the global methane budget is discussed.

Introduction

The global average concentration of methane (CH_4) in the atmosphere has increased rapidly from 0.8 ppmv, in pre-industrial times, to the present level of 1.75 ppmv (Blake & Rowland 1988). Much concern has been expressed about the potential for global warming and ozone depletion from continued increases in atmospheric CH_4. This concern is based on the large infrared radiation absorption capacity of CH_4 (58 times greater than CO_2 on a mass basis) and its role in the tropospheric/stratospheric generation of CO_2, O_3 and water vapor (Shine et al. 1990).

The Intergovernmental Panel on Climate Change estimates that anthropogenic sources account for 70% of current CH_4 emissions, and flooded rice has been identified as an important contributor (Watson el al. 1992). Methane emissions from flooded rice are strongly dependent on soil, environmental and management factors (Cicerone & Ormland 1988). The broad range in estimated global emissions, 50–170 Tg y^{-1} (Watson et al. 1992), reflects the variability of these factors in field studies carried out to date. Much effort has been made to understand the effects of soil temperature, redox potential, carbon substrate level, fertilizer, and plant presence on the production and fate of CH_4 in flooded rice (Holzapfel-Pschorn & Seiler 1986; Patrick 1981, Seiler et al. 1984; Lindau et al. 1991; Yagi & Minami 1990; Holzapfel-Pschorn et al. 1986). However little is known of the effects of varying management and cultural practices, especially those used in Asia, where more than 90% of the world's rice is grown (FAO 1990).

Methane's short atmospheric lifetime and large infrared absorption capacity have made it a target for short-term mitigation efforts. Consequently, several strategies to reduce CH_4 emissions from flooded rice have been proposed (USEPA 1990a). At the same time, food production needs are increasing with population growth, and the demand for rice is expected to increase from 458 to 758 $\times 10^6$ mt in the next 30 years (IRRI 1989), It is anticipated that a proportional increase in CH_4 emissions will accompany increased rice production. One analysis projects an increase of 20% in the next decade (USEPA 1990b).

Additionally, rice production systems are under stress from declining soil fertility and other factors. Greater addition of organic materials to rice paddies has been recommended as a major remedial measure to protect agricultural productivity and sustainability (FAO 1993). The most practical options for increasing organic inputs in rice production systems are legume green manuring and incorporation of straw in places where it is now burned. Burning is commonly practiced where rice straw is not removed for feed, because straw incorporation alone can lead to decreased yields (Meelu et al. 1992). Generally, green manuring involves incorporating plant biomass into the soil prior to flooding and transplanting of rice. Leguminous plant species such as *Sesbania aculeata, Astragalus sinica* or *Crotalaria juncea* are used throughout Asia because of their nitrogen fixing capabilities and rapid biomass accumulation. However, the addition of organic materials to flooded rice promotes CH_4 emissions by providing a readily available carbon substrate to methanogenic bacteria. It is clear, therefore, that strategies to increase food production conflict with mitigation goals and that a better understanding of the effects of proposed agronomic practices on CH_4 emissions from rice is needed.

Several studies have shown that straw additions double CH_4 emissions from flooded rice (Schütz et al. 1989; Yagi & Minami 1990; Sass et al. 1991), but a greenhouse study carried out by us is the only report with a green manure (Lauren & Duxbury 1992). Here *Sesbania aculeata* additions equivalent to 30 mt ha^{-1} (fresh weight) increased CH_4 emissions by 2 to 3 times relative to an unamended control. Given the limitations of small experimental units and relatively controlled conditions of the greenhouse, a field-scale experiment was undertaken to more realistically assess the effects of green manuring on CH_4 emissions. The objectives of this study were 1) to quantify and compare field CH_4 emissions from flooded rice where straw was either burned or incorporated and with or without a green manure amendment; and 2) to record and evaluate how soil and environmental factors might affect CH_4 fluxes in this system.

Materials and methods

The study site was part of an existing 6-ha experiment in a rice-green manure rotation at Sills Farm in Sutter County, north of Sacramento, California. The objective of the existing experiment was to determine the effect of a green manure on rice straw decomposition as an alternative to burning. The soil was a Neuva loam classified as a fine loamy, mixed, thermic Fluventic Haploxeroll. It is characterized as somewhat poorly drained, with a hard pan at approximately 25 cm depth and a texture of 39% sand, 38% silt and 23% clay. Some selected chemical properties were: 0.9 g total $N \cdot kg^{-1}$, 10.7 g total $C \cdot kg^{-1}$, 13 to 21 $mg \cdot kg^{-1}$ bicarbonate extractable P and an unflooded pH of 4.5 to 5.0.

The existing experiment consisted of 30 hydrologically isolated basins, each assigned treatment combinations of rice straw management (fall burned, fall disked, spring disked) and green manure (purple vetch, *Vicia benghalensis L.*) or winter fallow. Methane collection was restricted to four treatments: fall burned straw and winter fallow (BC), spring disked straw and winter fallow (SC), fall burned straw plus vetch (BV) and spring disked straw plus vetch (SV). These treatments were selected to represent the extremes of potential CH_4 flux from the system.

The straw management treatments and growth of the purple vetch were initiated in the fall preceding the 1992 rice crop. On April 24, 1992, the quantities of straw and accumulated vetch biomass were determined on mowed strips. Subsamples of the collected materials were analyzed for total C and N on an Europa Scientific Roboprep C/N analyzer (Europa Scientific, Ltd.; Crewe, England). Estimates of the vetch and/or straw inputs for the selected treatments as well as the corresponding C and N contents are presented in Table 1. Distribution of the straw and vetch was variable within the treatment basins. Differences in dry weight for the straw only treatments were caused by burning, whereas differences in vetch inputs were due to planting date. Vetch was seeded just prior to rice harvest in the SV treatment and after harvest and fall burning in the BV treatment. Differences in straw inputs between the SV and SC plots may reflect enhanced decomposition of straw by vetch growth and/or heterogeneous distribution of straw within the treatment basins.

The organic materials were incorporated into the soil by disking after which the field was flooded and air-seeded with M-202, an early maturing, semi-dwarf rice cultivar. Urea N was applied at 100 kg $N \cdot ha^{-1}$ to the straw-fallow treatments only to assure sufficient nitrogen for the rice crop. Three replicate gas collection structures were installed in each of the selected treatment basins at flooding. To minimize disturbance to the agronomic experiment and to facilitate gas sampling, each set of collection structures were grouped 1.5 to 2.0 m apart at the end of a 10 m boardwalk extending into the basin. A collection structure consisted of a removable chamber suspended from a permanently installed rigid base. The chamber was a 26 cm diameter polyethylene pail open at the bottom and modified at the top to accomodate a gas

Table 1. Dry weights and C, N compositions of added straw and/or vetch materials.

Treatment	Rice straw			Purple vetch			Total
	Dry wt. (kg/ha)	% C	% N	Dry wt. (hg/ha)	% C	% N	(mt/ha)
BC	977 ± 117	39.5	1.01	0	–	–	1.0
SC	2189 ± 1461	38.0	0.98	0	–	–	2.2
BV	978 ± 103	39.5	1.01	1770 ± 447	42.6	2.96	2.8
SV	672 ± 20	38.1	1.14	3170 ± 295	44.0	2.27	3.8

sampling port, pressure release vent and a small mixing fan. The chamber extended down into the floodwater to prevent air exchange between the outside atmosphere and the head space within the chamber. Marks on the outside of the chamber made it possible to record the water level at each sampling time. As the plants grew, chamber volumes were expanded by joining extension collars to the base chamber with wide, snug rubber bands cut from tire inner tubes. Chamber volumes increased from 18 to 38 to 52 L over the course of the experiment.

On average, CH_4 flux measurements were made every 3 to 4 days, shortly after flooding until irrigation was stopped prior to rice harvest. Recognizing the diurnal nature and temperature dependence of CH_4 emissions, sampling occurred both in the early morning (~7–8 AM) and afternoon (~2–3 PM) of each sampling day. The gas collection procedure involved careful placement of a chamber onto the rigid base, stoppering the pressure vent, running the mixing fan for ~30–45 sec and withdrawing a 10 mL gas subsample from the head space with a gas syringe. Gas samples were withdrawn thereafter at 10 min intervals up to 20 min. Short collection times combined with the white, reflective surface of the chamber minimized temperature differences between the chamber interior and exterior. After each sampling period, chambers were removed and the samples, placed in a portable cooler, were transported to the laboratory for analysis. Data also were collected on soil temperature, water depth and a platinum electrode placed next to each collection structure measured the soil redox potential at 10 cm depth.

An Aerograph Model 600 gas chromatograph (Wilkins Instrument and Research, Inc.; Walnut Creek, CA) with a flame ionization detector was utilized for CH_4 analysis. A 5 mL sample was injected into a 3 mL sampling loop and separated on a 1.6 m Carbosieve S-11 column (Supelco, Inc.; Bellefonte, PA) with 30 $mL{\cdot}min^{-1}$ of N_2 carrier gas and an oven temperature of 100 °C. Signals were recorded on a Hewlett Packard Model 3390 peak integrator (Hewlett Packard Co.; Houston, TX). Peaks were calibrated with 30 and 100 ppmv CH_4 standards during each analysis run.

Methane flux values were determined using Rolston's (1986) equation:

$$f = (V/A)(\Delta C/\Delta T)$$

where f = CH_4 flux, V = head space volume, A = chamber cross-sectional area and $\Delta C/\Delta T$ = the change in CH_4 concentration during the sampling time. Some of the measurements made early in the experiment showed a non-linear increase in CH_4 concentration with time, indicating that ebullition processes dominated emissions. Such points are often excluded, because they violate the linearity assumption for a flux calculation. However as demonstrated by Seiler et al. (1984) and Lauren & Duxbury (1992), such step-wise increases in CH_4 concentration eventually show a linear trend with time.Rather than discard data sets, a linear model was assumed to calculate fluxes, even though obvious ebullition had occurred. It is important to include bubble release in the flux measurements, since exclusion would have ignored a significant transport process and seriously underestimated emissions.

Results were analyzed using PROC GLM in SAS (SAS Institute, 1990). Statistical differences between treatments were evaluated with single degree of freedom contrast comparisons.

Results and discussion

Methane flux results from the 1992 growing season are presented in Figs. 1 and 2 for morning and afternoon sampling times, respectively. Treatments are grouped in meaningful pairs for comparison purposes. Relatively high CH_4 emissions were detected from all treatments within 5 days after flooding (DAF). With the exception of a sharp drop in flux at 23 DAF associated with a brief period of cold weather, CH_4 emissions peaked early in the season and then gradually declined to lower levels, presumably because readily available carbon supplies were depleted. Variability in the measurements was high during the period of peak emissions due to ebullition.

Methane emissions were usually 1.5 to 2 times higher from straw plus vetch treatments relative to straw only treatments, especially between 25 and 85 DAF (Figs. 1c,d; 2c,d). Statistical analyses corroborate our graphical observations. Single degree of freedom contrasts comparing SV vs SC and BV vs BC treatments were highly significant ($p = 0.001$) at both sampling times. In contrast, no significant flux differences were found between the two straw treatments or the two straw plus vetch treatments (Figs. 1a,b; 2a,b). Average daily CH_4 emissions from the straw only treatments were 24 mg $m^{-2} \cdot h^{-1}$ in the morning and 39 mg $m^{-2} \cdot h^{-1}$ in the afternoon. These values are comparable to others reported for paddy rice, which range from 10 to 58 mg $m^{-2} \cdot h^{-1}$ (Schütz et al. 1989; Yagi & Minami 1990; Khalil et al. 1991). Vetch green manure amendments increased average CH_4 fluxes to 38 and 62 mg $m^{-2} \cdot h^{-1}$ for morning and afternoon sampling times, respectively representing an increase of almost 60% over the straw only treatmens. These results are consistent with those from an earlier experiment carried out in the greenhouse (Lauren & Duxbury 1992).

Rice yields in the current experiment were high (8.9–10 mt ha^{-1}) with no

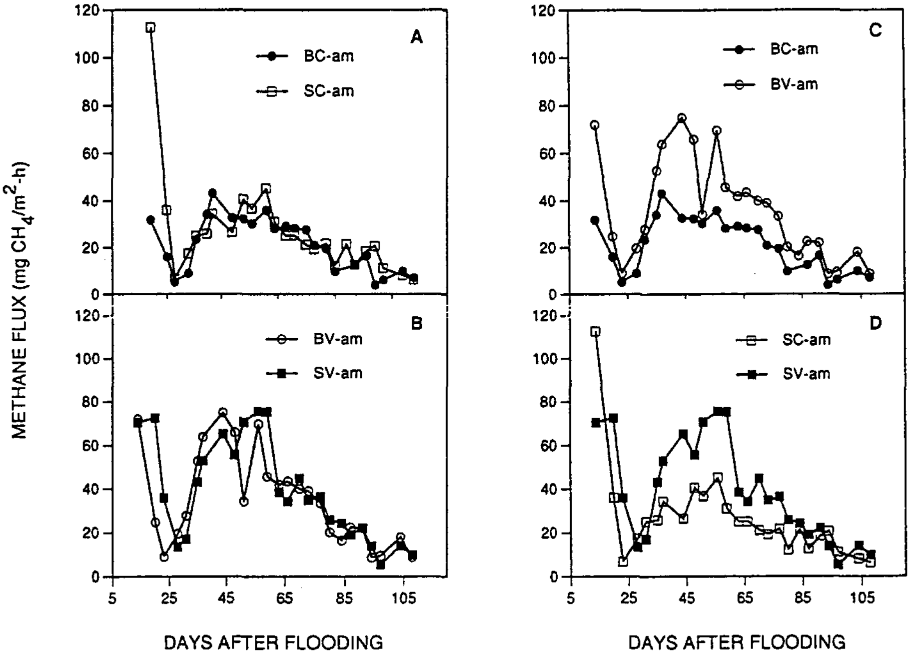

Fig. 1. Comparison of CH_4 flux values from morning samplings between (A) BC and SC, (B) BV and SV, (C) BC and BV, (D) SC and SV treatments.

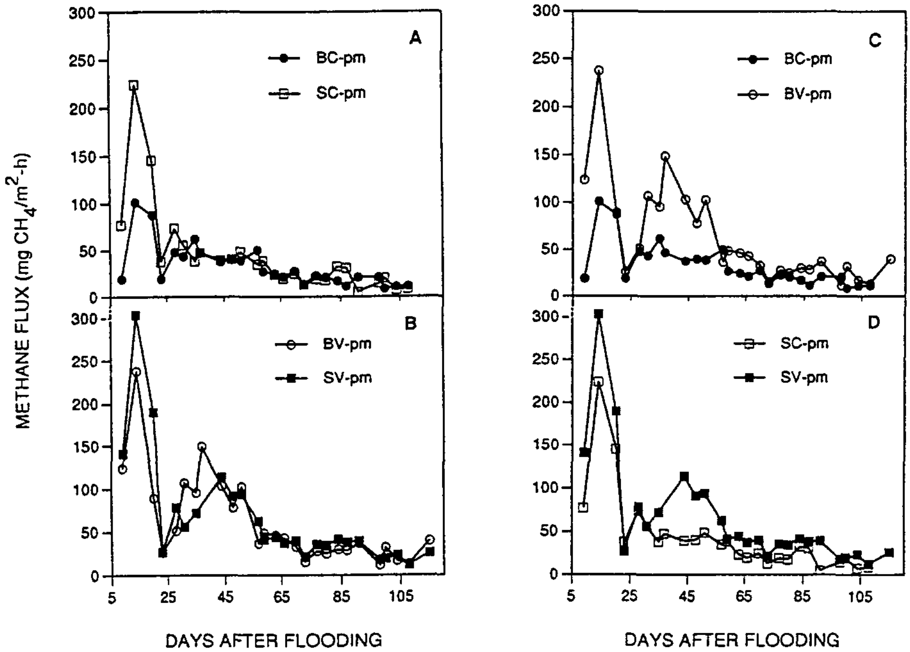

Fig. 2. Comparison of CH_4 flux values from afternoon samplings between (A) BC and SC, (B) BV and SV, (C) BC and BV, (D) SC and SV treatments.

significant differences between treatments. Hence, enhanced CH_4 emissions in the straw plus vetch treatments were due to the larger quantity of added organic material. The results may also reflect differing decomposition rates and metabolic by-products of the straw and vetch substrates. The decomposition rate of plant materials is dependent on the C to N ratio, being faster at low values (Reddy et al. 1986). Hence, the green manure, with a much lower C to N ratio than the straw (17:1 vs. 37:1) should be more readily metabolized by soil microorganisms. Furthermore, anaerobic decomposition by-products can also differ with the type of organic addition. In field studies, Tsutsuki and Ponnamperuma (1987) demonstrated that rice straw applications favored phenolic acid formation, whereas a volatile fatty acid, isovaleric acid, accumulated with a *Gliricidia sepium* green manure addition. Slightly higher percentages of added C were recovered as CH_4 with *Gliricidia* relative to straw, implying that differing anaerobic decompostion by-products associated with the decomposition process may influence CH_4 production.

Higher CH_4 emissions were observed in the afternoon relative to the morning samplings (Fig. 3), consistent with the temperature dependant diurnal pattern demonstrated by many investigators (Seiler et al. 1984; Yagi & Minami 1990; Sass et al. 1991). Contrasts comparing all morning and afternoon data were statistically different at the $p = 0.001$ level for each treatment.

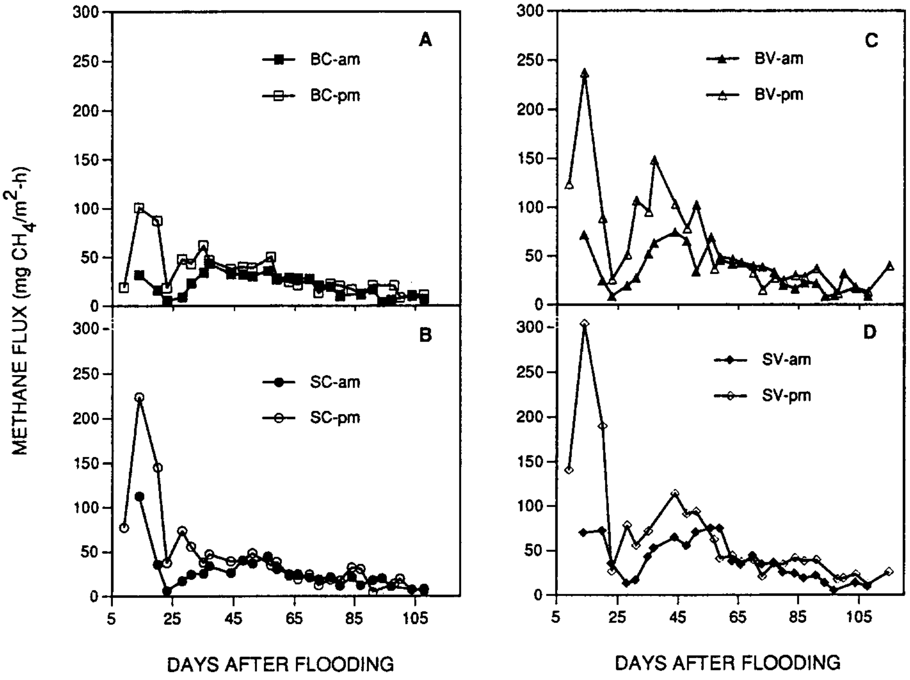

Fig. 3. Comparison of CH_4 flux values between morning and afternoon samplings for the (A) BC, (B) SC, (C) BV, (D) SV treatments.

Differences were greatest shortly after flooding; a response that may have been caused by the combination of high available carbon supplies as well as the temperature differential between morning and afternoon (see Fig. 4). Eventually differences in CH_4 flux between the morning and afternoon disappeared as the both the temperature differential and available substrate declined.

Maximum and minimum air temperatures over the growing season (Fig. 4) showed much variability, yet on average were 32 °C and 15 °C, respectively. Soil temperatures were substantially buffered by the floodwater but, nevertheless were 4 to 8 °C higher in the afternoon up to 70 DAF. The convergence of morning and afternoon soil temperatures and a downward trend in soil temperature observed between 65 DAF and the end of the experiment is attrbuted to shading from the rice canopy. Methane flux was found to be exponentially related to soil temperature (Fig. 5), consistent with models proposed by Holzapfel-Pschorn & Seiler (1986) and Schütz et al. (1989). However Seiler et al. (1984) and Khalil et al. (1991) determined that a linear relationship best described their data. Perhaps other factors such as

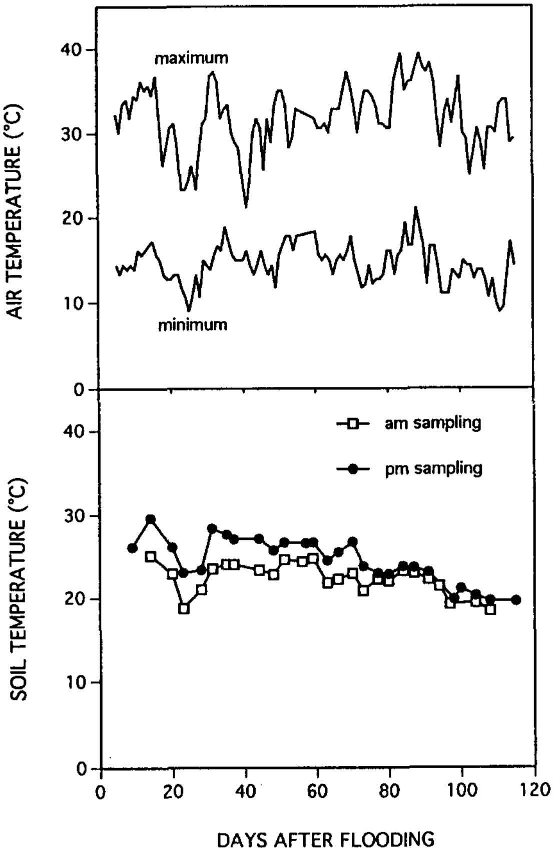

Fig. 4. Air and mean soil temperatures at field site during 1992 growing season.

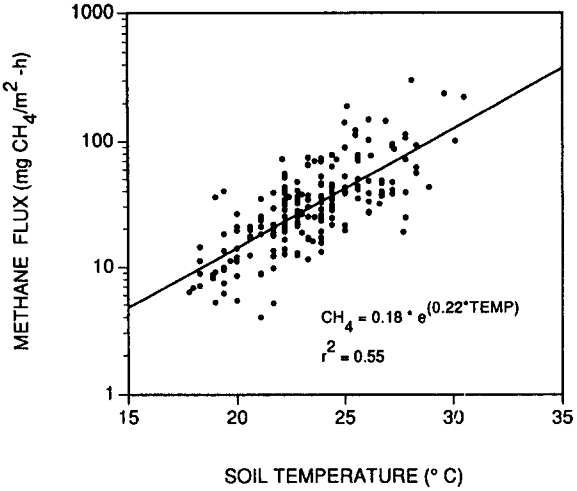

Fig. 5. Observed CH_4 emissions as a function of soil temperature.

soil type, rice variety, organic matter levels, or CH_4 oxidation control the CH_4 flux-temperature relationship.

Floodwater depths in the experimental basins ranged from 13 to 21.5 cm over the growing season (Fig. 6) with little variation within a day. Lower water levels early in the season provided for good stand establishment and higher levels at mid-season protected developing panicles from cool night temperatures. While it has been suggested that water depth may regulate CH_4 flux (Bouwman 1990), no trends were found between the two parameters in this experiment. Sebacher et al. (1986) also made this observation in natural

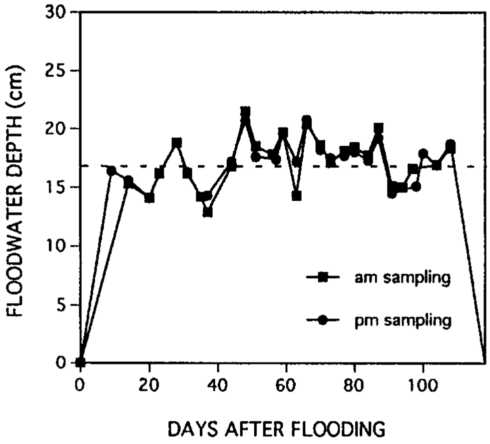

Fig. 6. Mean floodwater depths during morning and afternoon samplings throughout the experiment.

wetlands and concluded that water levels greater than 10 cm have little impact on CH_4 emissions.

Within a week of flooding, redox potentials in all treatments dropped rapidly due to the accumulation of electron donors from the added organic materials. During the first 30 DAF, redox values in vetch treatments were lower by roughly 50 mV relative to straw only treatments, reflecting differences in the quantity and composition of the organic amendments. Similar results with green manures have been reported by Qixiao & Tiaren (1988) and Swarup (1988). Early in the experiment, potentials were clearly less than –200 mV, which has been identified as the minimum level for CH_4 formation (Patrick 1981). However throughout the experiment CH_4 fluxes were observed over a range of redox potentials between –150 and –250 mV. This result suggests that redox measurement in the field is not a reliable predictor of CH_4 emissions.

Seasonal CH_4 emissions were estimated from the morning and afternoon emission data using linear interpolation (Table 2). These values represent a minimum and maximum range of emissions for each treatment. Averages of these ranges were also calculated for comparison purposes. Averages from the straw treatments are similar to other reports of seasonal flux following straw amendments, which range from 10–77 g m^{-2} (Schütz et al. 1989; Yagi & Minami 1990; Sass et al. 1991). Seasonal fluxes from the straw plus vetch treatments were higher still.

Given the heterogenous distribution of the vetch and straw residues, the seasonal totals are reasonably consistent with the quantities of organic materials added in each treatment (see Table 1). Methane emissions differed between SC vs BC and SV vs BV treatments by 22 and 14 g $CH_4 \cdot m^{-2}$, respectively and reflect the additional straw in the SC and SV treatments. Likewise, vetch amendment increased CH_4 emissions over the straw by 48–56 g $CH_4 \cdot m^{-2}$. These increases represent 39–53% of the added vetch carbon. Lack of an untreated control in the experiment prevented calculation of the proportion of added straw C emitted as CH_4.

An estimate of the current contribution of green manuring in flooded rice

Table 2. Maximum and minimum CH_4 emissions integrated over the 1992 growing season for the four straw/green manure treatments.

Treatment	Morning (Minimum)	Afternoon (Maximum) (g CH_4/m^2)	Average
BC	48 (13)	84 (16)	66
SC	60 (13)	117 (26)	88
BV	82 (12)	161 (12)	122
SV	90 (7)	181 (8)	136

( ) represents standard deviation

to the global CH_4 budget can determined using the seasonal flux values attributed to the green manure addition in this experiment. Although little data is available, it appears that < 5% of rice area in Asia or 6×10^6 ha currently receives additions of green manures (Garrity & Flinn 1988; Lizhi 1988). Consequently, we estimate that 2.9–3.4 Tg CH_4 y^{-1} comes from this agricultural practice. While currently not extensive, green manure use is anticipated to expand especially in poorer countries because of the rising demand for and costs of inorganic fertilizer (Meelu et al. 1992). More importantly, green manure use is being advocated as a sustainable agriculture practice to regenerate depleted soil resources and boost declining yields. This approach may be especially pertinent in South and Southeast Asia, where rice wheat systems are showing significant yield reductions due to intensive cropping practices (Flinn & DeDatta 1984; Giri et al. 1993). Green manuring may also shift straw management towards incorporation rather than burning, indirectly exacerbating CH_4 emissions. The combination of green manure and straw can give higher rice yields than any other management practice (Meelu et al. 1992). Based on the green manure effect measured in this study, we estimate that CH_4 emissions from paddy rice could increase by 55% where straw is incorporated or 85% where straw is burned.

However, it is also important to recognize that CH_4 emissions from green manure-rice systems in Asia may differ substantially from those in this experiment because of differing environmental conditions or management practices. For example, Khalil et al. (1991) pointed out that the larger CH_4 emissions measured in China relative to Europe or the US may be a reflection of the higher soil temperatures in China. Likewise, Lizhi (1986) reported green manure application rates of 3–6 mt ha^{-1} (dry weight) for rice in China compared with the 1.8–3.2 mt ha^{-1} rate used in this experiment. Yet another factor to consider is floodwater depth. In this experiment, no trends were observed between CH_4 emissions and floodwater depth, presumably because of the relatively deep water levels. However under shallow water conditions in natural wetlands, emissions appear to be linearly related to floodwater depth (Sebacher et al. 1986). This is an important factor to evaluate in Asian rice systems, where water distribution and management problems limit control of floodwater depth (Garrity et al. 1986). It is clear that much more field data from Asia, under farmer production conditions, is needed to properly quantify the contribution of flooded rice to global CH_4 budgets.

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