PERGAMON

Soil Biology and Biochemistry 31 (1999) 1313–1322

Soil Biology & Biochemistry

Methane pool and flux dynamics in a rice field following straw incorporation

Deborah A. Bossio[a,]*, William R. Horwath[a], Randall G. Mutters[b], Chris van Kessel[c]

[a]*Department of Land, Air and Water Resources, University of California, One Shields Avenue, Davis, CA 95616-8627, USA*
[b]*University of California Cooperative Extension, 2279B Del Oro Avenue, Oroville, CA 95965, USA*
[c]*Department of Agronomy and Range Science, University of California, One Shields Avenue, Davis, CA 95616-8515, USA*

Accepted 20 March 1999

Abstract

Concerns for air quality have led to legislation restricting rice straw burning in some parts of the world. Consequently, growers must dispose of large amounts of residual rice straw by incorporation into the soil, which may have large effects on CH_4 emissions from those fields. Our objective was to characterize how this recent change in management has affected overall CH_4 emissions in a California rice field and establish relationships between organic matter availability, CH_4 pool sizes and CH_4 fluxes. Closed chamber measurements were used to monitor diurnal and post drain fluxes, to describe the seasonal pattern of CH_4 emissions and estimate total CH_4 fluxes on a large on-farm field trial during the 1997 growing season. Soil redox, temperature and plant growth and yield were also monitored. To establish relationships between CH_4 pool sizes and fluxes, soil interstitial CH_4 concentrations were monitored in the field and available organic matter in the spring was estimated with a laboratory incubation. Redox values in the soil were found to be 50 mV lower in plots in which straw had been incorporated (−275 mV) than those in which it had been burned (−225 mV). No significant treatment differences were seen in total soil organic matter contents in the spring. However, available organic matter was 1.5 times higher in straw incorporated than straw burned plots. Methane emissions peaked between 22.00 and 23.00 h on two different diurnal sampling dates. Methane emission after draining was about 10% of the flooded period total. A 5-fold increase in total CH_4 emissions over the rice growing season was observed in plots in which rice straw had been incorporated each fall for 4 yr. Total cumulative CH_4 flux, 1 May–1 October 1997, was 8.87 g C m^{-2} in incorporated, winter flooded plots; 9.52 g C m^{-2} in incorporated, non-winter flooded plots; 1.63 g C m^{-2} in burned, winter flooded plots; and 2.25 g C m^{-2} in burned, non-winter flooded plots. Soil CH_4 concentrations at 10–15 cm depth was strongly associated with emissions to the atmosphere ($r = 0.89$). A model developed by Nouchi et al. (1994) [Nouchi, I., Hosono, T., Aodi, K., Minami, K., 1994. Seasonal variation in methane flux from rice paddies associated with methane concentration in soil water, rice biomass and temperature and it's modeling. Plant and Soil 161, 195-208.] which could predict the CH_4 flux based on soil CH_4 concentrations and temperature was fit to our data. The model was very successful at predicting flux rates and cumulative fluxes because conductance (CH_4 flux divided by CH_4 concentration in soil water) was highly correlated with soil temperature ($r = 0.88$) throughout the period of high CH_4 emissions. Organic matter availability and CH_4 pool and flux dynamics were altered by straw incorporation practices as evidenced by increased conductance at the same interstitial CH_4 concentration and increased emissions per unit available organic matter in rice straw incorporated plots. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Atmospheric concentrations of CH_4 have been increasing at the rate of 0.5–0.8% yr^{-1} since the industrial revolution began. Because CH_4 is a potent greenhouse gas and wetland rice fields account for

---

* Corresponding author. Tel.: +1-530-756-3826; fax: +1-530-756-6144.
E-mail address: dabossio@ucdavis.edu (D.A. Bossio)

0038-0717/99/$ - see front matter © 1999 Elsevier Science Ltd. All rights reserved.
PII: S0038-0717(99)00050-4

approximately 20% of global anthropogenic CH_4emissions (Denier van der Gon and Neue, 1995), there is considerable interest in understanding how land use and management affects CH_4 emissions (Sass and Fisher, 1997). In agricultural ecosystems, management practices can substantially alter organic matter availability and thus CH_4 production. However, predicting changes in CH_4 emissions directly from management is still problematic. Denier van der Gon and Neue (1995) developed a relationship which describes increases in CH_4 emissions resulting from added organic matter in rice experiments throughout the world. Deviations from this relationship were large and represent the variability in soils, such as landscape position or soil land use. Clearly, the relationship between added organic matter and CH_4 emissions is complex. Our current abilities to predict this relationship are limited by a lack of understanding in underlying processes. One cause of variability in the relationship between organic matter application and CH_4 flux may be differences in the relationships between amount of available substrate and CH_4 flux as was found in some Japanese soils (Yagi and Minami, 1990). It is not clear whether the magnitude of this type of difference will affect larger scale prediction of CH_4 fluxes.

In California, concerns over the negative air quality effects of the traditional practice of rice straw burning has led to legislation which restricts open field burning. A large field trial in which the yield effects of rice straw incorporation followed by winter flooding are compared to the traditional practice of straw burning provides an opportunity to investigate the effect of this considerable change in rice cropping system management on CH_4 dynamics. An essential difference between this experiment and earlier straw experiments is that rice straw is incorporated in the fall, 6 months before the growing season. Our objectives were to (1) determine whether recent changes in straw management changed overall CH_4 fluxes; (2) understand how straw additions affected relationships between organic matter availability and CH_4 pool sizes and fluxes; and (3) test the dependence of CH_4 fluxes on soil interstitial CH_4 and temperature using a known model.

2. Materials and methods

2.1. Field study

A 35 ha field study of rice straw incorporation methods was initiated in October 1993 on a commercial farm near Maxwell, CA. The soil is a Willows clay, a fine, montmorillonitic, thermic, Typic Pelloxerert, with a pH of 6.8–7.0 and 51% clay. The experimental design was a randomized complete block, split-plot experiment with four replicates. The main plot treatments were winter flood or no winter flood and the split-plot treatments were two rice straw management methods (burned or incorporated). Rice straw was chopped and disced into the soil to a depth of 15 cm at an average rate of 9.8 Mg ha^{-1} in October 1996 and 0.7 Mg ha^{-1} straw remained as standing residue on the straw burned plots. Winter flooded plots were re-flooded in November and water was held on these plots until late March 1997. The measurements presented here began after draining of the winter flooded plots in the spring of 1997. Preplant aquaNH_3 at a rate of 150 kg ha^{-1} was applied to all plots 1 d prior to flooding. Fields were flooded and the rice aerially seeded during the first week in May.

2.2. Soil and plant parameters

Soil temperature was monitored at a depth of 2 cm in the four treatment plots located in block 1 (Optic StowAway Temp, Onset). Reduction–oxidation potential of the soil was measured continually with modified, commercially available platinum electrodes (Broadley-James). Probes and companion copper–constantan thermocouples were inserted to a depth of 15 cm in one straw incorporated and one straw burned plot. Probes were calibrated at the beginning, end and frequently over the course of the study with saturated solutions of hydrone quinone buffered at pH 4.0 and 7.0. Measurements were taken every 15 min between 24 July 1997 and soil draining, averaged and stored as hourly values (model 21X, Campbell Scientific). Total carbon and nitrogen (including detrital material) in surface soils (0–15 cm), were determined with an elemental analyzer (model NA 1500 NCS, Fisons) on pre-flood spring samples from 22 April 1997. Soil bulk density (0–15 cm) was measured mid season (1 July) using intact soil cores.

Available organic matter was measured in a 58 d aerobic laboratory incubation study in which 25 g of dry soil from the 22 April samples were wetted to 28% moisture and incubated at 27°C in 0.90 l bottles. CO_2 evolution was monitored every 3–5 d by analyzing a headspace gas sample using a g.c. equipped with a TCD detector (model 8601A, SRI). After each sampling, bottles were vented, soil moisture was adjusted if necessary and bottles were resealed.

Shoot biomass within each gas sampling ring and root biomass for each treatment plot were determined at physiological maturity. Grain yields were measured at harvest.

2.3. Methane flux and interstitial gas sampling

Closed, vented chambers (Livingston and Hutchinson, 1995), with a diameter of 25 cm and height of 60 or 90 cm (depending on plant height), were used to quantify methane fluxes from all plots during the rice growing season in 1997. Three permanent rings were placed below water level to create a seal in each treatment plot and chambers were temporarily placed on these rings to measure gas fluxes. Fans installed inside the chambers were run for 1 min before each gas sample was withdrawn to ensure mixing of air within the chamber. Twelve ml gas samples were withdrawn from the chambers every 10 min over a 40–60 min period and stored in evacuated glass containers (Labco). Flux sampling was done at intervals of approximately 7–14 d throughout the rice growing season. Change in CH_4 concentrations remained linear throughout the sampling period. Ebullition of CH_4 gas bubbles was monitored by looking for discontinuity in the linear flux relationship in all early season samples (Holzapfel-Pschorn and Seiler, 1986).

Soil interstitial (pore) water CH_4 concentrations were measured during each flux sampling by withdrawing soil solution from 10 to 15 cm below the soil surface (Rejmankova and Post, 1996). Soil water samples were stored in evacuated glass containers. Just prior to analysis half of the soil water was replaced with atmospheric air and samples were shaken for 2 min. CH_4 concentrations were then measured in 1 ml headspace samples. Gas concentrations were quantified with a g.c., equipped with an FID detector (model 8610A, SRI).

Diurnal variation in fluxes and interstitial CH_4 concentrations were determined twice, 16–17 June and 19–20 August 1997, by taking closed chamber flux measurements at 3 h intervals over a 30 h period. Methane release during the post draining period was quantified by measuring the flux between 12.00 and 16.00 h each day for 8 d during the soil drying period in each treatment plot in block 1. Cumulative CH_4 flux was corrected for diurnal variation in flux and for the CH_4 release during dry down.

A model developed by Nouchi et al. (1994) was modified to fit the soil water CH_4 and soil temperature data. In the model, diffusion of CH_4 through the rice plants is controlled by the conductance of the rice plant and is based on an empirical relationship between conductance (CH_4 flux divided by soil water CH_4 concentration) and air temperature. In this study, soil temperature at 2 cm depth was substituted for air temperature as follows:

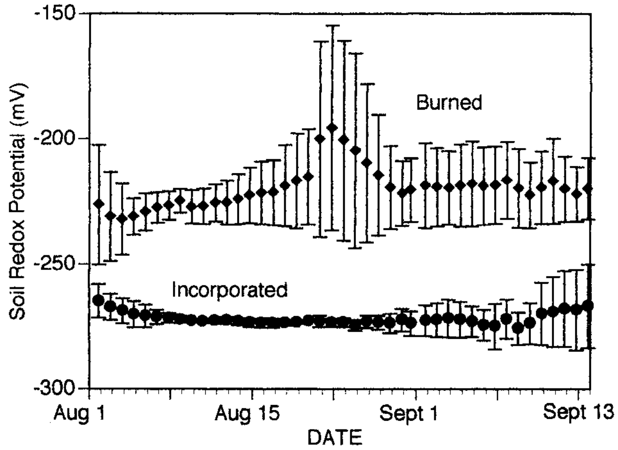

Fig. 1. Soil redox values in burned and incorporated plot over a 6 week period in 1997.

$$F = 10C_s(aT - b),$$

where F is the CH_4 flux in mg C m^{-2} h^{-1}; C_s is the CH_4 concentration in mg C l^{-1}; and T is the surface soil temperature in °C. The model was fit to straw incorporated and straw burned plot data in which winter flooded and non-winter flooded plots were combined, so that on each date the value of CH_4 flux and interstitial water CH_4 concentration was the mean of eight replicate plots for each treatment.

3. Results

3.1. Soil and plant variables

In the early growing season, average surface soil temperatures (2 cm) ranged from 22 to 28°C and diurnal variation could reach 8°C. As the rice canopy closed and shading of the soil surface increased, soil temperatures and diurnal variation slowly decreased. Just prior to draining, soil temperature averaged 19°C and diurnal fluctuations were reduced to less than 1°C.

Soil redox values were stable during the growing season and averaged −250 mV for all plots. There was a clear treatment effect on redox potential such that

Table 1
Total soil carbon, nitrogen and bulk density of flooded soil as affected by straw management

Treatment	Total carbon (g kg^{-1} dry soil)[a]	Total nitrogen (g kg^{-1} dry soil)	Bulk density (kg m^{-3})
Incorporated	1.96 (0.28)	0.17 (0.02)	590 (20)
Burned	1.86 (0.22)	0.16 (0.02)	630 (20)

[a] Values are means of eight replicates with standard deviations in parentheses.

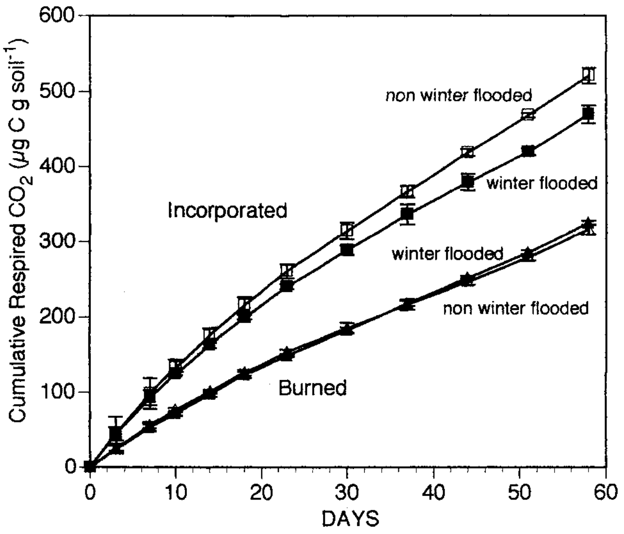

Fig. 2. Available organic matter as measured by CO_2 respired in a laboratory incubation experiment using soils collected from the different straw management plots.

the straw incorporated plot had a redox value of −275 mV, 50 mV lower than the straw burned plots (data shown for a 6 week period, Fig. 1). Total soil organic carbon and nitrogen, measured before the spring flood, did not differ significantly between straw incorporated and straw burned plots, but tended to be higher in straw incorporated plots (Table 1). Available carbon as measured by soil respiration, however, was approximately 1.5 times higher in the straw incorporated plots (Fig. 2).

Plant biomass within individual gas sampling rings varied (CV = 20%), but there was no trend with straw management treatment and plant root biomass and rice grain yields were similarly unaffected by treatment (Table 2).

3.2. Methane pools and fluxes

Methane flux increased over time during the growing season (Fig. 3), except for one week when the field was drained for aerial herbicide application. After 100% heading (mid August), fluxes began to decline. Peak flux rates were found at between 22.00 and 23.00 h during both diurnal samplings (Fig. 4). In June, peak flux rates were 41% higher than the lowest observed flux rates. August flux rates overall were higher and the diurnal variation was larger with 73% difference from lowest to highest flux rates. Diurnal flux rates appeared to trend with soil temperature in June (Fig. 4). In August, however, there was no diurnal variation in soil temperature while flux rates showed strong diurnal variation. Apparently, diurnal fluxes, although often correlated with temperature, were not determined by temperature at this site.

Table 2
Dry weight (g m^{-2}) of rice root and shoots at physiological maturity and grain yield at harvest

Treatment	Shoot (g m^{-2})[a]	Root (g m^{-2})[a]	Grain yield (g m^{-2})[a]
Incorporated	866 (165)	148 (12)	1130 (70)
Burned	896 (195)	134 (24)	1100 (80)

[a] Values are means of eight replicates with standard deviations in parentheses.

Table 3
Measured and predicted seasonal cumulative CH_4 fluxes (g C m^{-2}) in the different straw management plots

Treatment	Pre-drain (g C m^{-2})		Total including post-drain (g C m^{-2})	
	measured	predicted	measured	predicted
Incorporated				
Winter flooded	7.92		8.87	
Non-winter flooded	8.50		9.52	
All plots	8.21	8.22	9.20	9.21
Burned				
Winter flooded	1.53		1.63	
Non-winter flooded	2.11		2.25	
All plots	1.82	2.18	1.94	2.32

Methane flux was approximately 5 times higher in straw incorporated than straw burned plots (Table 3). Total cumulative CH_4 flux, 1 May–1 October 1997 was 8.87 g C m^{-2} in incorporated, winter flooded plots; 9.52 g C m^{-2} in incorporated, non-winter flooded plots; 1.63 g C m^{-2} in burned, winter flooded plots; and 2.25 g C m^{-2} in burned, non-winter flooded plots. Methane released in the 10 d after draining was found to be an additional 12% of the total seasonal emissions in incorporated plots and 7% in burned plots (data not shown).

Soil interstitial CH_4 showed the same pattern as was observed for CH_4 fluxes, which increased over time up to 100% heading, with the exception of the short drained period (Fig. 3). Ebullition of CH_4 gas was found to be negligible (data not shown), likely because CH_4 concentrations in the soil were low until after the rice plants had attained sufficient size to dominate transport. Flux rates from individual sampling rings were not related to plant shoot biomass within the ring, despite large variation in biomass.

Interstitial water CH_4 concentration and CH_4 flux rates were strongly correlated ($r = 0.86$), as were surface soil temperature and conductance ($r = 0.78$, Fig. 5). A modified model which predicts flux based on interstitial CH_4 concentrations and soil temperature (Nouchi et al., 1994) was able to predict CH_4 flux with a high degree of accuracy, accounting for 95% of the variation in flux data over the growing season (Fig. 6).

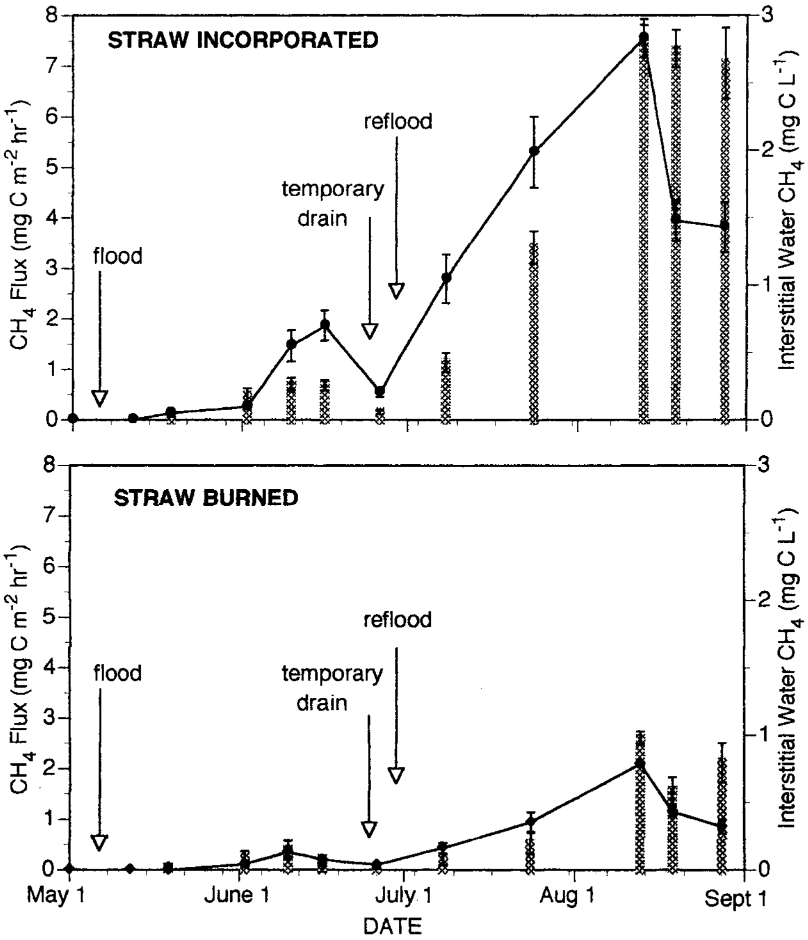

Fig. 3. Methane flux rates and interstitial water CH_4 concentrations in straw incorporated and straw burned plots over the 1997 growing season. Values are means of eight replicate plots with winter flooded and winter non-flooded combined. Lines are fluxes and bars are interstitial CH_4 concentrations.

Overestimation of fluxes in the early part of the season (Fig. 6), resulted in an overestimation in cumulative fluxes for the burned treatment, but was unimportant in estimation of cumulative flux from the incorporated plots (Table 3).

Soil interstitial CH_4 concentration was a dominant controlling factor in CH_4 emissions, particularly during the later season (July and August). During this period, the relationship between conductance and interstitial CH_4 was strong ($r^2=0.93$ for incorporated and $r^2=0.83$ for burned) and differed between burned and incorporated plots (Fig. 7), such that incorporated plots had a higher conductance per unit of interstitial CH_4.

Cumulative CH_4 emissions were plotted against available organic carbon from the 58 d laboratory incubation in order to examine the relationship between available soil organic matter and seasonal emissions (Fig. 8). Although the variability in available organic carbon, particularly in the straw burned treatment plots was low, it is apparent that at similar amounts of available carbon, higher CH_4 emissions were found in the rice straw incorporated plots.

4. Discussion

Spring incorporation, or high organic matter availability in general, often result in an early season peak in CH_4 emissions (Schutz et al., 1989; Lauren et al., 1994), followed by a second, late season, peak attributed to root exudates and litter (Schutz et al., 1989). However, at this site the organic material was incorporated half a year before the growing season and the early peak was absent. The slow rise in CH_4 flux and the single late-season peak in CH_4 emissions observed at this experiment site (Fig. 3) would indicate that there is relatively little readily decomposable organic material in the soil in the spring, even in straw incorporated plots. Apparently the rice residue, especially the labile components, is degraded over the winter months, despite low temperatures. In addition to the

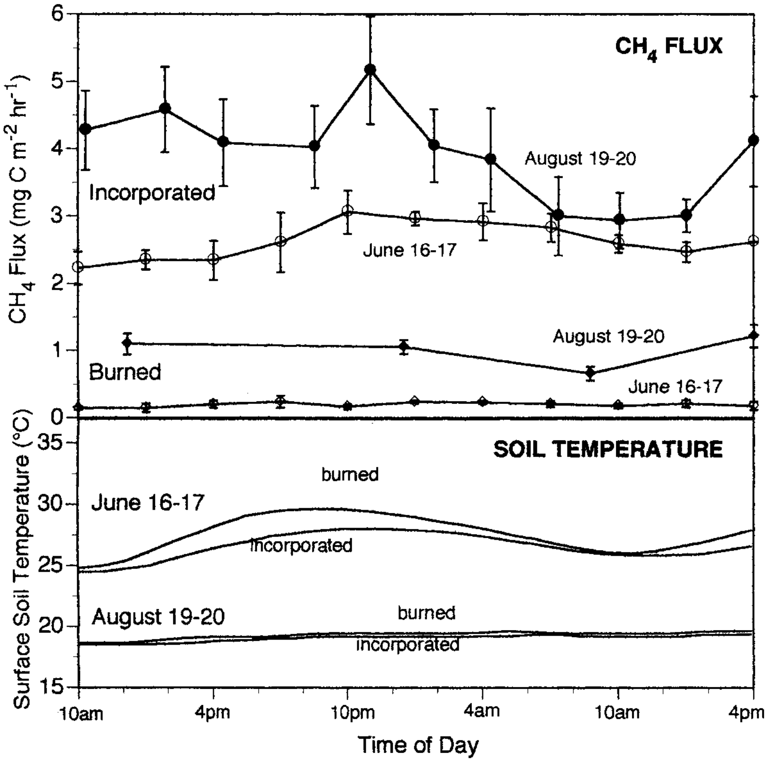

Fig. 4. Diurnal patterns in methane flux rates and soil temperature during two sampling periods.

early season peak in CH_4 emissions, straw incorporation has been associated with decreases in rice yields (Sass et al., 1991) attributed to the production of organic acids which reduce seedling root growth. However, rice yields in this study have not been affected by straw incorporation. Fall incorporation and over-winter decomposition of the straw is likely responsible for both the lack of an early season peak in CH_4 emissions and the lack of negative effects of incorporation on yields observed in this study.

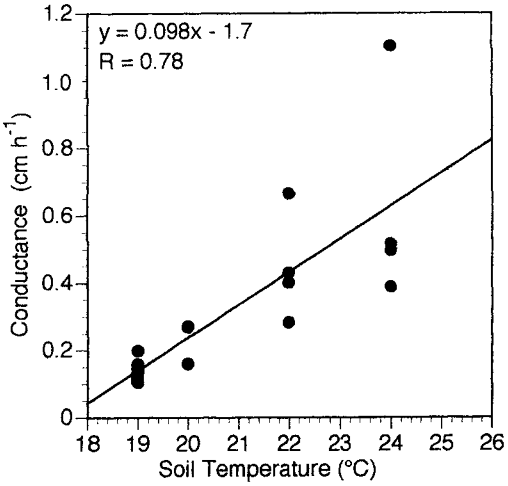

Fig. 5. Relationship between conductance (calculated as CH_4 flux divided by CH_4 concentration in soil water) and soil temperature, during the later season (8 July–29 August 1997).

Organic matter availability is a major factor controlling CH_4 emissions from rice paddies (Yagi and Minami, 1990). Many studies have demonstrated the often considerable increases in CH_4 emissions when rice straw is incorporated (Schutz et al., 1989; Yagi and Minami, 1990; Sass et al., 1991). The 5-fold increase in CH_4 emissions found at this site (Table 3) was almost double that expected from the relationship found by Denier van der Gon and Neue (1995) which summarized the effects of organic matter addition in various studies from around the world. A previous study, included in the Denier van der Gon and Neue (1995) analysis, also found an unusually large increase in CH_4 emissions due to organic matter inputs in a California rice field (Cicerone et al., 1992). This departure from expected increases can be attributed to the generally low organic matter contents in the California soils and very low amounts of seasonal CH_4 emissions without straw (Denier van der Gon and Neue, 1995; Neue, 1997).

Winter flooding led to a small decrease in CH_4 emissions during the summer months, by about 0.6 g C m^{-2} in both straw treatments (Table 3) and caused an apparent decrease in available organic carbon in the incorporated treatment (Fig. 2). Organic matter decomposition was enhanced under continuous flooded conditions over the winter, compared with the natu-

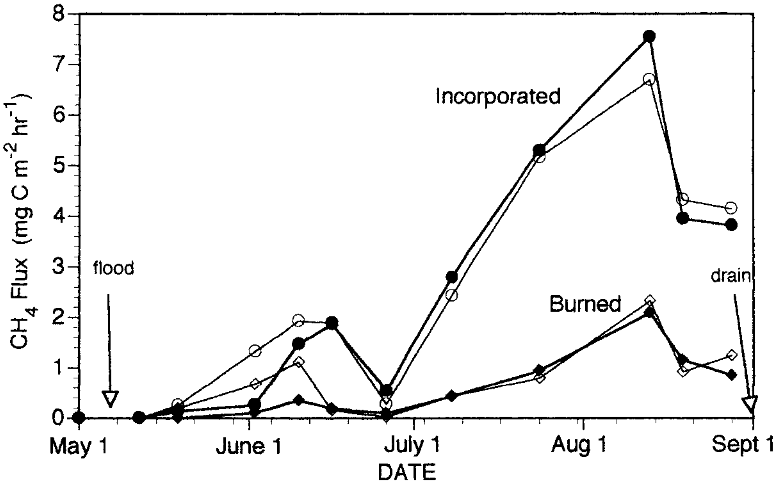

Fig. 6. Seasonal distribution of flux rates as predicted from soil interstitial water CH_4 concentration and soil temperature (open symbols) and flux rates measured in the field (closed symbols), for incorporated (●) and burned (◆) treatments. Predicted fluxes based on the model: $F = 10C_s(0.082T–1.40)$. Measured flux rates are means of eight treatment plots.

rally alternating drained and sporadic flooded conditions found in the non-winter flooded treatment. This was also found in a buried bag straw decomposition study at the same site (Bossio and Scow, 1997). Yearly CH_4 emissions, however, double as a result of winter flooding, because methane emissions during the flooded winter and early spring months (November–March) can be equal to or even higher than those found during the growing season (G. Fitzgerald, personal communication).

Release of trapped CH_4 after draining was about 10%. In field studies, Denier van der Gon et al. (1996) found an additional 10% CH_4 released in the dry down period in three different soils. In a pot study, an additional 7–10% CH_4 emissions with rice straw and 4–5% without rice straw was found after draining (Watanabe et al., 1994) and Wassmann et al. (1996b) reported a significant release of CH_4 during the post drain period. Our results concur with these previous researchers that estimates of total CH_4 emissions which ignore the post drain period can be in error by approximately 10%.

Like Wassmann et al. (1996a) and Nouchi et al. (1994), we found a strong correspondence between soil entrapped CH_4 and CH_4 emissions and like Hosono and Nouchi (1997) we found a strong relationship between soil temperature and conductance (Fig. 5). By separating effects of soil and air temperature on CH_4 transport, Hosono and Nouchi (1997) found that transport was predominantly determined by soil and not air temperature. At our site we found soil temperature was more strongly related to conductance (CH_4

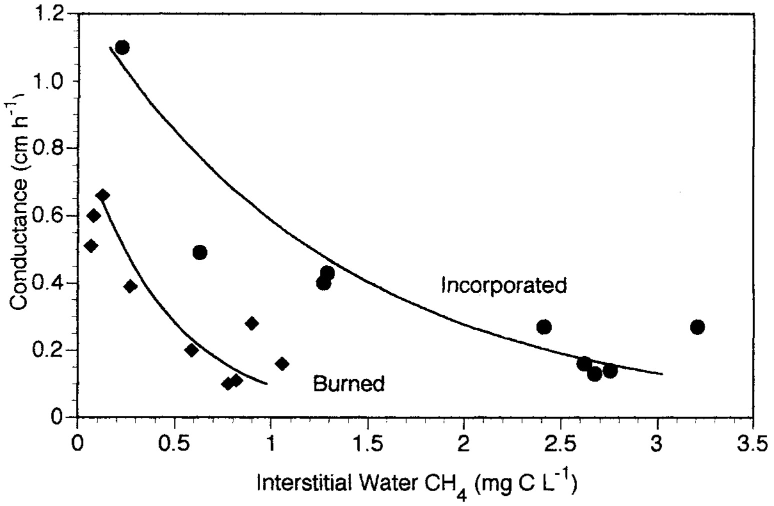

Fig. 7. Relationship between conductance (calculated as CH_4 flux divided by CH_4 concentration in soil water) and CH_4 concentration in interstitial water. Logarithmic curves are fit to the late season data (8 July–20 August 1997), incorporated (●) and burned (◆).

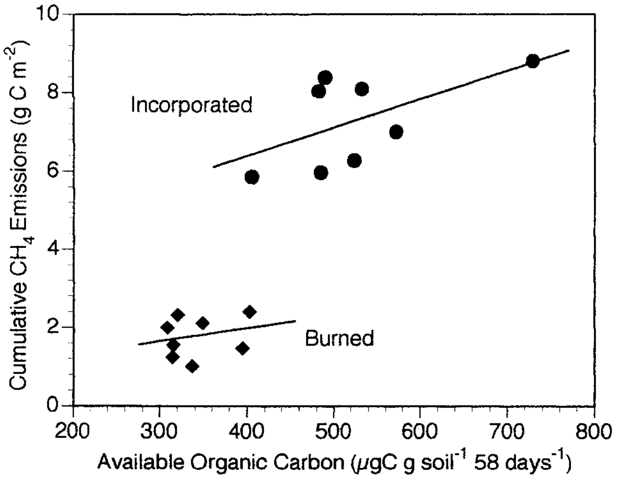

Fig. 8. Relationship between available organic carbon released in a 58 d aerobic incubation and cumulative CH_4 emissions from straw incorporated (●) and straw burned (◆) plots.

flux/soil CH_4 concentration) than air temperature and was therefore used in the model. Soil CH_4 concentration and temperature alone were able to account for 95% of the variability in flux data. Some overestimation in flux rates in the early season resulted in a 20% (0.40 g C m^{-2}) overestimation of total flux in the burned treatment, but was insignificant in the incorporated treatment.

Early season and small late season discrepancy between predicted and measured flux rates can be attributed to seasonal changes in the rice plant which are not taken into account in the model. In the early season, the capacity of the rice plant for transport may not keep up with potential transport predicted by soil CH_4 concentration and temperature alone. Nouchi et al. (1994) used leaf area of the rice plants to predict emissions during the early part of the growing season and only used soil CH_4 concentration and temperature to predict fluxes when variations could no longer be explained by leaf area. At our site, however, because conductance was highly correlated with soil temperature throughout the period of high CH_4 emissions, applying the temperature and soil CH_4 model to the entire season was successful. Late season overestimation is likely due to reduced transport as a result of rice plant aging (Arikado et al., 1990; Watanabe et al., 1994). Transport of CH_4 to the atmosphere in the post-drain pulse is unrelated to the rice plants and thus the model cannot be extended to include this period. However, seasonal predictions based on an expected 10% release after drainage is possible. We found, as suggested by Wassmann et al. (1996a), that the pattern of emergence of the CH_4 was shifted under growing conditions in the field from that predicted based solely on soil CH_4 concentrations. Regardless, the success of this model demonstrates that soil CH_4 concentrations and temperature are dominant factors determining overall CH_4 emissions. Measurement of soil interstitial CH_4 is easier to carry out than flux measurements and based on our results holds promise as an index of potential emission rates. Increasing the geographic representation of this data could simplify other studies, when major constraints in measuring seasonal fluxes are the cost and time involved.

Two lines of evidence suggest that straw incorporation has resulted in a change in carbon cycling and, therefore, CH_4 flux dynamics between the burned and incorporated treatments. First, the relationship between soil CH_4 concentration and conductance differed between the two treatments such that a smaller proportion of soil CH_4 reached the atmosphere in the burned treatments (Fig. 7). Differences in conductance may be due to differences in plant gas transport, soil gas transport or methane oxidation. In lieu of any measured differences in rice shoot or root biomass (Table 2), which may alter oxygen conditions in the soil and transport rates, or differences in bulk density (Table 1) which might indicate differences in soil gas transport, we hypothesize that the microbial community is more efficient at oxidizing available CH_4 in the burned treatment. Methane oxidation may be less effective in the incorporated treatment because methanotrophs face more competition with heterotrophs for available oxygen. It is also possible that low E_h in the incorporated treatment results in increased porosity of the rice plant and so enhances gas transport (Kludze et al., 1993).

Secondly, we found that the relationship between soil available carbon and CH_4 emissions differed between the two systems (Fig. 8). A higher proportion (approximately 2.5 times) of available carbon was released as CH_4 in the straw incorporated treatment. Yagi and Minami (1990) found that the relationship between readily mineralizable carbon and CH_4 emission differed between different soil types. High organic matter peat soils emitted approximately 2.5 times as much CH_4 per unit of readily available carbon as lower organic matter content Andosols (Yagi and Minami, 1990). Thus we observed that management practices may induce changes in CH_4 flux dynamics which are of the same magnitude as differences found among different soil types.

Yagi and Minami (1990) hypothesize that differences in the relationship between available carbon and CH_4 emissions result from a change in the ratio of CH_4 to CO_2 produced per unit of organic carbon and that this ratio depends on the redox conditions in the soil. A lower slope in the burned plot data (Fig. 8) indicates a lower CH_4 to CO_2 ratio of the decomposition products due to a relatively higher E_h in the burned plots. Our data supports this hypothesis as the burned plots in this study had consistently higher E_h by about 50 mV.

Soil E_h is dependent on the balance between electron donors (available organic matter) and electron acceptor input (oxygen released by roots), thus increased organic matter inputs results in lower E_h (Segers and Kengen, 1998). This effect can then result in higher CH_4 to CO_2 ratio of the decomposition products. In a controlled experiment, Wang et al. (1993) found that CH_4 production was exponentially related to change in E_h between −160 and −220, such that small decreases in E_h caused large increases in CH_4 production.

Earlier studies at this site found that straw incorporation increased the overall size of the microbial community (Bossio and Scow, 1997; 1998). This increase in size is likely to result in faster turnover rates for soil carbon in the straw incorporated treatment, resulting in increased availability of organic matter and may contribute to lowered E_h in incorporated plots. At this site, it is apparent that organic matter inputs have changed not only substrate availability, but also CH_4 dynamics such that the relationships between available carbon, conductivity and emissions have changed due to rice straw incorporation. Comparison of these results to those of Yagi and Minami (1990) suggest that differences in CH_4 dynamics caused by management on this soil are of similar magnitude as differences among some soil types. Management, therefore, is likely to be as important as soil type in predicting larger scale emissions. The modeling exercise demonstrated that despite differences in CH_4 dynamics, soil interstitial CH_4 by integrating differences in substrate availability and E_h and soil temperature can provide reasonable estimates of expected seasonal CH_4 fluxes.

Acknowledgements

We would like to thank Steven Denis of Canal Farms, Maxwell, CA, for participating in this project, Steve Scardaci and Marian Llagas for management of the field site and laboratory and Mark Minto for untiring dedication to data collection in all its forms. This work was supported by a grant from the California Energy Commission Farm Energy Assistance Program and Ducks Unlimited as part of the Sacramento Valley Ricelands/Wetlands Conjunctive Use Study of the California Central Valley Joint Venture Program, which is funded by the US Department of the Interior, Bureau of Reclamation.

References

Arikado, H., Ikeda, K., Taniyama, T., 1990. Anatomico-ecological studies on the aerenchyma and the ventilating system in rice plants. Bulletin Faculty Bioresources, vol. 3. Mie University, pp. 25–39.

Bossio, D.A., Scow, K.M., 1997. Management changes in rice production alter microbial community. California Agriculture 51, 33–40.

Bossio, D.A., Scow, K.M., 1998. Impacts of carbon and flooding on soil microbial communities: phospholipid fatty acid profiles and substrate utilization patterns. Microbial Ecology 35, 265–278.

Cicerone, R.J., Delwiche, C.C., Tyler, S.C., Zimmerman, P.R., 1992. Methane emissions from California rice paddies with varied treatments. Global Biogeochemical Cycles 6, 233–248.

Denier van der Gon, H.A.C., Neue, H.U., 1995. Influence of organic matter incorporation on the methane emission from a wetland rice field. Global Biogeochemical Cycles 9, 11–22.

Denier van der Gon, H.A.C., van Breemen, N., Neue, H.U., Lantin, R.S., Aduna, J.B., Alberto, M.C.R., Wassmann, R., 1996. Release of entrapped methane from wetland rice fields upon soil drying. Global Biogeochemical Cycles 10, 1–7.

Holzapfel-Pschorn, A., Seiler, W., 1986. Methane emission during a cultivation period from an Italian rice paddy. Journal of Geophysical Research-Atmospheres 91, 11803–11814.

Hosono, T., Nouchi, I., 1997. The dependence of methane transport in rice plants on the root zone temperature. Plant and Soil 191, 233–240.

Kludze, H.K., DeLaune, R.D., Patrick, W.H., 1993. Aerenchyma formation and methane and oxygen exchange in rice. Soil Science Society of America Journal 57, 386–391.

Lauren, J.G., Pettygrove, G.S., Duxbury, J.M., 1994. Methane emissions associated with a green manure amendment to flooded rice in California. Biogeochemistry 24, 53–65.

Livingston, G.P., Hutchinson, G.L., 1995. Enclosure-based measurement of trace gas exchange: applications and sources of error. In: Matson, P.A., Harriss, R.C. (Eds.), Biogenic Trace Gases: Measuring Emissions from Soil and Water. Blackwell Science, Cambridge, pp. 14–51.

Neue, H.U., 1997. Fluxes of methane from rice fields and potential for mitigation. Soil Use and Management 13, 258–267.

Nouchi, I., Hosono, T., Aodi, K., Minami, K., 1994. Seasonal variation in methane flux from rice paddies associated with methane concentration in soil water, rice biomass and temperature and its modeling. Plant and Soil 161, 195–208.

Rejmankova, E., Post, R.A., 1996. Methane in sulfate-rich and sulfate-poor wetland sediments. Biogeochemistry 34, 57–70.

Sass, R.L., Fisher Jr, F.M., 1997. Methane emissions from rice paddies: a process study. Nutrient Cycling in Agroecosystems 49, 119–127.

Sass, R.L., Fisher, F.M., Harcombe, P.S., Turner, F.T., 1991. Mitigation of methane emissions from rice fields: possible adverse effects of incorporated rice straw. Global Biogeochemical Cycles 5, 275–287.

Schutz, H., Holzapfel-Pschorn, A., Conrad, R., Rennenberg, H., Seiler, W., 1989. A 3-year continuous record on the influence of daytime, season and fertilizer treatment on methane emission rates from an Italian rice paddy. Journal of Geophysical Research-Atmospheres 94, 16405–16416.

Segers, R., Kengen, S.W.M., 1998. Methane production as a function of anaerobic carbon mineralization: a process model. Soil Biology & Biochemistry 30, 1107–1117.

Wang, Z.P., Delaune, R.D., Masscheleyn, P.H., Patrick, W.H., 1993. Soil redox and pH effects on methane production in a flooded rice soil. Soil Science Society of America Journal 57, 382–385.

Wassmann, R., Neue, H.U., Alberto, M.C.R., Lantin, R.S., Bueno, C., Llenaresas, D., Arah, J.R.M., Papen, H., Seiler, W., Rennenberg, H., 1996a. Fluxes and pools of methane in wetland rice soils with varying organic inputs. Environmental Monitoring and Assessment 42, 163–173.

Wassmann, R., Shangguan, X.J., Tölg, M., Cheng, D.X., Wang, M.X., Papen, H., Rennenberg, H., Seiler, W., 1996b. Spatial and seasonal distribution of organic amendments affecting methane emission from Chinese rice fields. Biology and Fertility of Soils 22, 191–195.

Watanabe, A., Murase, J., Katoh, K., Kimura, M., 1994. Methane production and its fate in paddy fields. V. Fate of methane remaining in paddy soil at harvesting stage. Soil Science and Plant Nutrition 40, 221–230.

Yagi, K., Minami, K., 1990. Effect of organic matter application on methane emission from some Japanese paddy fields. Soil Science and Plant Nutrition 36, 599–610.