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Fallow season straw and water management effects on methane emissions in California rice

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Abstract. In response to legislative mandate to reduce postharvest straw burning and environmental concerns to restore wetland habitat for Pacific flyway waterfowl, California rice growers are incorporating straw into soil and flooding rice fields in winter. These changes were hypothesized to alter soil carbon cycling pathways across the region. The principal objective of this study was to determine how various winter fallowed straw and water management changes would affect year-round methane emissions. Main plots were winter flood and nonflood, and subplots had straw treatments: burned, soil incorporated, or rolled (partially soil incorporated). Results showed the principal factor controlling methane emissions was the interaction of flooding and straw amendments. The presence of either water or straw alone led to low emissions. Winter emissions accounted for 50% of annual totals in straw-amended treatments despite lower temperatures and the presence of plants in summer. Summer emissions were significantly influenced by winter straw amendments but not by winter flood. Postdrain peaks after winter drain accounted for 10–13% of annual emissions in treatments with amended straw. Although rolled and incorporated treatments had similar straw inputs, methane fluxes from rolled treatments were higher than from incorporated treatments. Measurements of methane should be conducted year-round to capture fallow and postdrain fluxes and improve global emission estimates. Regional emission estimates showed that 2.6 times more methane was emitted after flooding plus incorporation was implemented than before the legislative mandate was enacted.

1. Introduction

The recent rise in atmospheric methane concentrations is unprecedented over the last 160,000 years [*Raynaud et al.*, 1993] and is reportedly due to anthropogenic activities, especially cattle and rice production [*Khalil and Rasmussen*, 1994]. *Prather et al.* [1995] estimated that flooded rice contributes 16% of anthropogenic methane emissions and 11% of total methane emissions, accounting for 20–100 Tg yr^{-1} of methane. Emissions are expected to rise over the next 30 years as rice production is intensified to provide food to an ever-expanding human population [*Anastasi et al.*, 1992].

Neue et al. [1990] listed six soil factors contributing to methane fluxes from rice paddies: water regime, carbon supply, Eh/pH buffering, temperature, texture and mineralogy, and salinity. Additionally, the presence or absence of plants substantially affects emissions through photosynthetic effects due to solar radiation [*Sass et al.*, 1991b], plant and root biomass [*Sass et al.*, 1990; *Chanton et al.*, 1997], and rice cultivar [*Kludze and DeLuane*, 1995]. These influence the pathway for diffusion of methane from the soil to the atmosphere [*Nouchi et al.*, 1990; *Denier van der Gon and Breemen*, 1993]. Plants are the principal route of methane emissions to the atmosphere [*Cicerone and Shetter*, 1981; *Holzapfel-Pschorn et al.*, 1986], although diffusion from the water surface, ebullition [*Sass et al.*, 1991b; *Nouchi et al.*, 1994], and postdrain fluxes [*Denier van der Gon et al.*, 1996; *Yagi et al.*, 1996] can be significant.

In rice cultivation, straw management and flooding can substantially affect methane emissions [*Bouwman*, 1991; *Delwiche and Cicerone*, 1993]. After harvest, rice straw is disposed of by removing from the field, incorporating into the soil, or burning. In California, burning is common because it is easy and inexpensive and there are no markets for straw. Recent legislation to reduce agricultural waste burning (AB 1378, Rice Straw Burning Reduction Act of 1991) has prompted growers to decompose straw in situ using various methods of soil incorporation. At the same time, some fields have been flooded in winter to provide substituted wetlands for waterfowl along the Pacific flyway [*Brouder and Hill*, 1995]. These two practices represent a significant change in regional straw management. Considering that ∼200,000 ha of land in California is in rice production, these practices could have significant impacts on methane emissions.

Methane fluxes have been measured almost exclusively during the rice-growing season because it has been assumed that

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Table 1. Soil Characteristics for Willows Silty Clay, 0–15 cm Depth

Soil Characteristics	Values
Clay, %	50.5
Silt, %	45.0
Sand, %	4.5
Fe, mg kg^{-1}	171
SO_4-S, mg kg^{-1}	159
pH	6.6
Na, cmol kg^{-1}	1.02
EC, dS m^{-1}	1.36
N, %	0.16
C, %	1.74

fluxes are low during the fallow. This assumption is valid only where plant residue additions are low or the fallow period is dry. When plant residue is added to saturated or flooded soils, methane emissions could become significant even without the presence of vegetation [*Sass et al.*, 1990; *Cicerone et al.*, 1992; *Nouchi et al.*, 1994; *Wassmann et al.*, 1996; *Bronson et al.*, 1997].

The major objective of this research was to determine how winter fallowed straw and water management affects year-round methane emissions. Specifically, greater straw amendments and flooded conditions in winter were hypothesized to increase methane emissions during fallow and summer cropping periods. In this study we (1) characterized the effects of winter (fallow) straw and water management on winter and summer methane emissions over a 2-year period, (2) determined the relative importance of straw amendments and vegetation on emissions, and (3) studied the contribution of postdrain methane fluxes to the total methane budget.

2. Materials and Methods

Methane emissions were measured for 2 years in a commercial rice field near Maxwell, California (longitude 122°9′00″W, latitude 39°17′30″N), in the Sacramento Valley. The field was divided into 32 0.7 ha plots. Rice had been grown previously for several years using standard local practices. The soil was a Willows silty clay, moderate alkali classified as a thermic Sodic Endoaquert with poor drainage. Soil characteristics are shown in Table 1. A semidwarf variety of rice, M-202, was seeded by aircraft into water in early May each year, managed using standard cultural practices (Table 2), and harvested in October.

Beginning in 1993, six treatments were imposed in a randomized complete block split plot design with three blocks. Main plots were winter flood (F) and nonflood (NF). Subplots had three straw treatments randomized within the main plots: burn (B), incorporate (I), and roll (R). The measured treatments were FB, FI, FR, NFB, NFI, and NFR. Straw was incorporated into the soil using disc or chisel in FI and NFI. In FR and NFR a tractor-drawn cage roller pressed the straw into the soil surface to achieve partial straw incorporation. Residue was burned in FB and NFB without tillage. The straw in R and I treatments was chopped to 10–20 cm lengths. In R and I treatments, approximately the same amount of straw was amended. Placement in I was in the upper 20 cm of soil. In R, most of the straw remained on the soil surface with some buried to 10 cm depth. Winter water was maintained at 5–15 cm depth except during heavy rains in January 1995 when water depths reached 20–25 cm. Treatments were imposed following the October crop harvest and maintained until drainage for spring tillage (Table 2). Between 6000 and 8500 kg ha^{-1} straw were incorporated into the I and R treatments in autumn. Approximately 1650–2800 kg ha^{-1} straw remained after burning in the B treatment. Prior to planting in May, all treatments were soil incorporated and subsequently flooded during the rice-cropping season in summer. Summer plant density was 300 plants m^{-2} for both years. Aqueous ammonium (NH_4+) was applied at a rate of 135 kg N ha^{-1} and

Table 2. Maxwell Cultural Practice Dates, Flooding Duration, and Gas Sampling Periods

Practice	1994–1995	1995–1996
Autumn straw management	October 15–31, 1994	October 15–31, 1995
Begin winter flood	October 25–27, 1994	November 1–3, 1995
Drain winter flood	February 27 to March 1, 1995	March 2–4, 1996
Spring straw management	April 15 to May 12, 1995	April 12 to May 4, 1996
Spring flood and seeding	May 18–21, 1995	May 5–7, 1996
50% heading (flowering)	August 13–16, 1995	August 1–3, 1996
Summer drain	September 15–17, 1995	August 31 to September 2, 1996
Harvest	October 8–12, 1995	September 22–27, 1996
Winter flood duration	125 days[a]	122 days
Summer flood duration	120 days	118 days
Crop period	140 days	138 days
Gas sampling, winter	133 days December 15, 1994, to April 26, 1995	164 days November 13, 1995, to April 24, 1996
Gas sampling, summer	132 days May 18 to September 27, 1995	145 days May 5 to September 27, 1996

[a] Number of days computed from beginning of one activity to the beginning of the next (e.g., autumn flood, 1994–1995: October 25 to February 27 is 125 days).

injected to a depth of 5–10 cm (2–4 inches) before flooding in the spring both years.

Methane was sampled using closed chambers [*Lauren et al.*, 1994]. The chambers were 25-cm-diameter white plastic with volumes varying from 13,000 cm^3 (25-cm-tall) in the winter without rice to 49,000 cm^3 (95 cm tall) in the summer with rice. Semipermanent sample rings, of the same diameter, were pushed 1–2 cm into the soil surface to act as supports for the chambers and minimize disturbance. These were removed twice annually to allow for spring and autumn tillage and replaced in approximately the same locations. Gas samples were collected in 10-mL syringes, stored away from direct Sun, and analyzed within 24 hours. Syringe needles were sealed by piercing rubber stoppers. Four samples per chamber were collected at 0-, 5-, 10-, and 20-min intervals. Syringes containing a known standard (10 ppm CH_4) were periodically included to adjust for potential gas loss from the syringes and were handled using the same protocols and procedures used for the sampling syringes. The 20-min sampling period fell within the linear portion of the methane mixing ratio curve. Chamber temperature was measured to correct gas concentration in flux calculations.

In the summer, samples were collected from two chambers per plot, one enclosing rice plants ("vegetated") and the other open water ("nonvegetated"). In the winter the two chambers were placed in each plot either over bare soil or open water depending on water treatment (F or NF). There were neither rice plants nor weeds in any plots in the winter. During 1994–1995, measurements were taken approximately monthly. During 1995–1996, sampling occurred every 2 weeks, except during spring and summer postdrain periods when sampling occurred weekly. Methane was analyzed on an SRI gas chromatograph fitted with a Haysep D column and a flame ionization detector (FID) detector. Two standards were employed, 2.5 ppm and 25 ppm methane, to calibrate the gas chromatograph.

Soil moisture was estimated gravimetrically (dried to 105°C and weighed) during the winter in the NF treatments and during the two postdrain periods in spring and summer. All plants and roots within the sampling rings were harvested, dried, counted, and weighed at the end of each summer. Soil under the sampling rings was excavated and inspected for root encroachment from adjacent plants but little or none was found. Sampling rings were kept weed free. Plants near the methane sampling areas were collected periodically using three 0.3 m^2 quadrants for measurement of biomass, height, and plant and tiller number. Plot yield, aboveground biomass, and residual straw were collected from the plots as part of an ongoing agronomic study (unpublished data). Winter plots were weed-free, and summer plots were treated using conventional herbicides to reduce weeds. Diurnal changes in methane fluxes did not add statistically significant amounts of methane to daily, seasonal, or annual emissions and did not change the patterns between treatments [*Bossio et al.*, 1999].

Soil temperatures were measured at 10 cm depth near each chamber when gas samples were collected. Seasonal mean soil temperatures are presented in Table 3. Spring temperatures were distinct from winter and summer, so they are presented separately. There were no statistical differences between water or straw treatments, so these were pooled.

Soil reduction-oxidation potential (redox) was measured periodically under flooded and nonflooded conditions with platinum tipped probes and a calomel reference electrode. Redox values were corrected to the H_2 standard and adjusted for soil temperature. The platinum tip of each probe was placed 10 cm below the soil surface for 6–24 hours before reading. Three probes were placed in each plot.

Flux calculations were computed using the equation $f = (V/A)(\Delta C/\Delta T)$ [*Rolston, 1986*], where f is the CH_4 flux, V is the chamber volume, A is the chamber cross-sectional area, ΔC is the change in gas concentration, and ΔT is the sampling time. The ideal gas law ($PV = nRT$, where P is pressure, V is volume, n is the number of moles, R is the gas constant, and T is the temperature) was used to solve for C, since concentration is dependent on temperature, pressure, and volume of gas [*Livingston and Hutchinson*, 1995]. Linear regressions were fit with the mixing ratio as the dependent variable and time as the independent variable. Flux regressions less than $r^2 = 0.90$ were excluded from calculations except for the very low fluxes near the limit of detection used to estimate methane fluxes in the B treatments. Cumulative seasonal (winter and summer) and annual fluxes were calculated by integrating the daily rates between dates (area under curve). Methane emissions and other data sets were statistically analyzed using analysis of variance to test for treatment mean and interaction differences at $\alpha = 0.05$.

3. Results

3.1. Methane Fluxes and Seasonal Emissions

Winter fallow fluxes were similar to summer fluxes in the FI and FR treatments within each year (Figure 1a). Strong peaks were present in FI and FR treatments in January and February in both years. Cumulative emissions for the winter were comparable to or greater than summer vegetated plots for these treatments (Table 4). Daily fluxes ranged from 48 to 149 mg CH^4 m^{-2} d^{-1} for the FI and FR treatments in the winter and from 50 to 153 mg CH_4 m^{-2} d^{-1}

Table 3. Mean Seasonal Soil Temperatures at 10 cm Depth[a]

Season	Mean Temperature, °C	Dates
Winter 1994	12.1 (3.4)	December 15, 1994 to February 27, 1995
Spring 1995	16.6 (1.8)	March 20 to April 26, 1995
Summer 1995	21.7 (2.7)	May 31 to September 27, 1995
Winter 1995	11.6 (2.5)	November 13, 1995, to March 2, 1996
Spring 1996	14.1 (2.2)	March 6 to April 24, 1996
Summer 1996	20.8 (3.7)	May 22 to September 27, 1996

[a] Values for all water and straw treatments were pooled. Numbers in parentheses are standard deviations. The range of dates that each mean represents is also indicated.

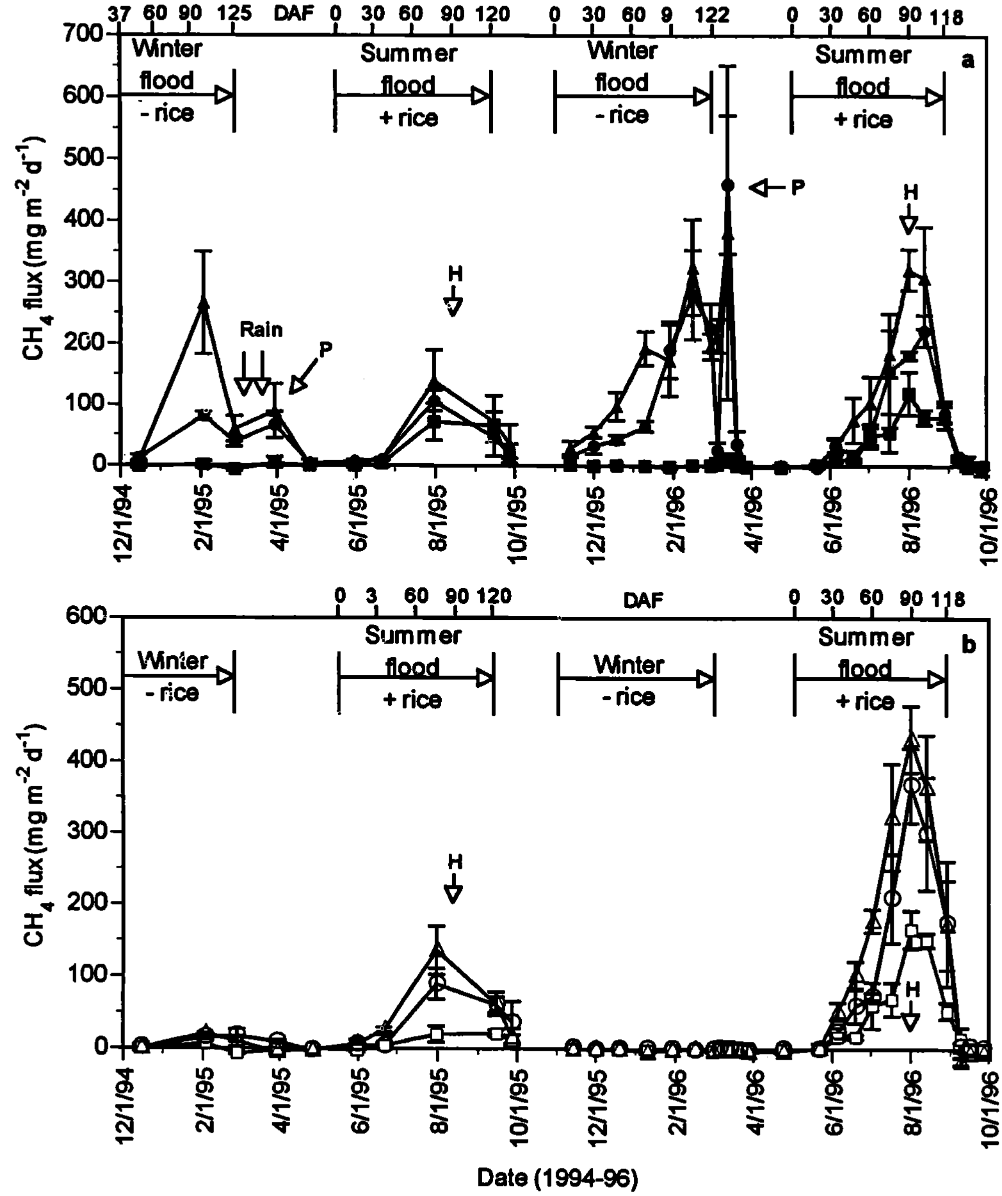

Figure 1. (a, b) Methane fluxes from winter flooded straw treatments for winter fallow and summer crop seasons for 2-year period. Rice was present in the summer (+ rice) and absent in the winter (−rice). Numbers at the top are days after flooding (DAF). The "H" indicates 50% heading date. The "P" indicates postdrain peaks. Error bars are the standard error of the treatment means. Solid squares indicate FB; solid circles indicate FI; solid triangles indicate FR; open squares indicate NFB; open circles indicate NFI; and open triangles indicate NFR.

for the NFI and NFR vegetated plots in the summer. Methane emissions from these treatments during the summer rice-growing season ranged from 39 to 51% of the total annual emissions (Table 4). Thus approximately half of annual emissions occurred during the winter. NF treatments had no or very low winter methane fluxes (Table 4, Figure 1b), although in 1994–1995, NFI and NFR had some emissions due to heavy rains that saturated the soil. In the winter, F plot redox values ranged from −70 to −116 mV, and NF plots ranged from 107 to 222 mV for both years. Flooded redox values were similar in the summer. In the spring, all treatments were soil incorporated and then flooded. Mean winter, spring, and summer soil temperatures were ~12°, 15°, and 21°C, respectively (Table 3). Close contact with the soil, flooding, and higher temperatures caused the summer peaks.

Annual cumulative emissions for nonvegetated and vegetated plots followed the pattern FR > FI > NFR and NFI > FB and NFB

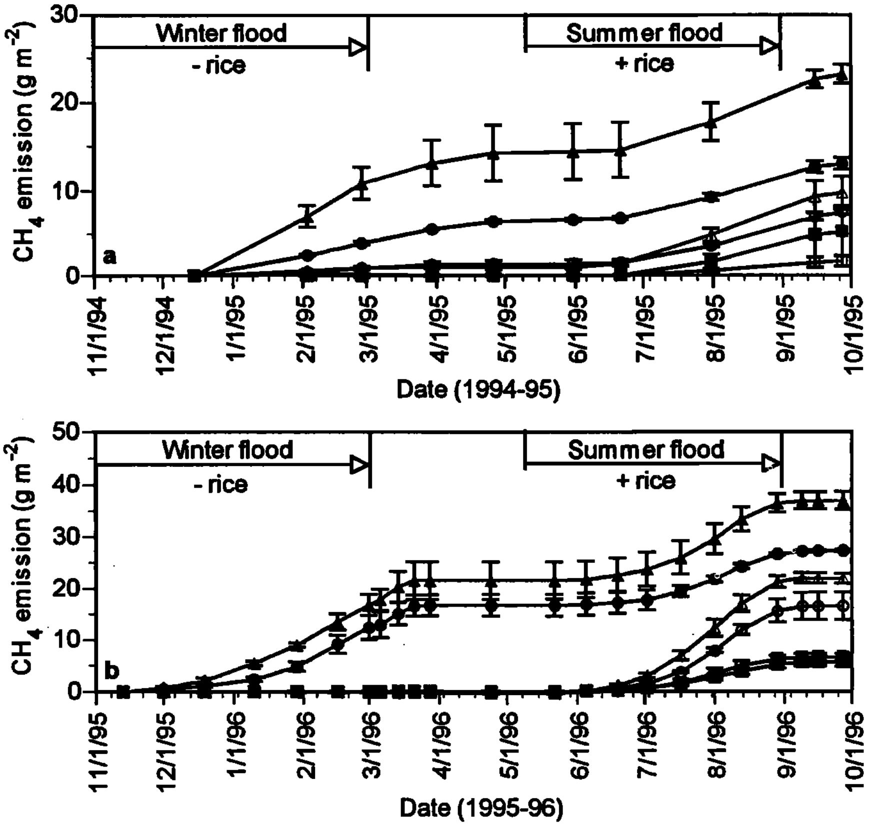

Figure 2. Cumulative methane emissions in (a) 1994–1995 and (b) 1995–1996. Winter was fallow (−rice). Summer was vegetated (+ rice). Error bars are the standard error of the treatment means. Note difference in y axes between Figures 2a and 2b. Solid squares indicate FB; solid circles indicate FI; solid triangles indicate FR; open squares indicate NFB; open circles indicate NFI; and open triangles indicate NFR.

in all treatments in both years (Table 4 and Figure 2), although NFR > NFI for vegetated plots for both years. FR and FI treatments had the greatest emissions compared to B treatments. The F treatments were flooded for a longer period than NF, and the R and I treatments had 2.5–5.1 times more straw amended in the autumn than B (Table 5). Cumulative differences between methane emissions for FI and FR treatments were established in winter and were maintained all year (Figure 2). In the summer the pattern R > I > B was maintained within each respective water treatment except summer 1995 nonvegetated (Table 4) where NFI > NFR, but the values are not significantly different. Thus straw amendments led to greater methane emissions, and the longer the period of flooding, the greater the emissions. Straw inputs for FR and NFR were greater than FI and NFI, respectively, in spring 1996 (Table 5), and these showed substantially greater summer emissions than summer 1995 when straw inputs for R were less than for I and there were no statistical difference either in straw inputs or summer vegetated emissions.

There were statistically significant differences between straw treatments ($\alpha = 0.05$ F test) for methane emissions in every season (water, straw, and W x S in Table 4). This was caused by differences between the B and the I and R treatments. The winter water treatments had no significant effects on vegetated summer plots in either year. Except for the nonvegetated summer plots of 1995–1996, there were no significant water effects and no interactions (W x S (Table 4)) on summer emissions. Thus winter straw treatments significantly affected summer emissions, but water treatments did not. This was probably due to differences in spring straw additions left from winter decay of autumn inputs (Table 5). Additionally, within any one season, the differences in emissions from FB and NFB treatments were never statistically significant, and there were few statistical differences between the FI and FR or NFI and NFR treatments (denoted by the letters in Table 4). These results were due to high variability in the data, but the consistently higher values for R and I than B treatments and the generally greater emissions for FR and NFR than FI and NFI treatments, respectively, especially in 1995–1996, indicate strong trends in terms of treatment differences.

The winter of 1994–1995 was especially wet compared to 1995–1996. In 1994–1995 the winter NFI and NFR treatments accounted for 18 and 10% of annual emissions, respectively, for these treatments, while during the winter of 1995–1996 the soil may have been a net sink for methane (Table 4).

3.2. Postdrain Fluxes

Postdrain peaks were detected after both winter drains in all F treatments (Figure 1a). They were not observed after the summer drain probably because of infrequent sampling. The 1994–1995

Table 4. Cumulative Seasonal and Annual Emissions of Methane for 1994–1995 and 1995–1996, Vegetated and Nonvegetated Plots (g CH_4 m^{-2})[a]

	Winter	Summer		Annual	
Treatment	Nonvegetated	Nonvegetated	Vegetated	Nonvegetated	Vegetated
			1994–1995		
FB	−0.005 a	0.63 (1.0)[b]a	5.23 (1.0) ab	0.63 a	5.22 ab
FI	6.38 b	2.75 (0.30) b	6.69 (0.51) a	9.13 b	13.07 c
FR	14.26 c	2.82 (0.17) b	8.97 (0.39) a	17.08 c	23.23 d
NFB	0.07 a	0.26 (0.81) a	1.64 (0.96) b	0.32 a	1.71 b
NFI	1.36 a	4.15 (0.75) c	6.15 (0.82) ab	5.51 bd	7.51 a
NFR	0.93 a	3.56 (0.79) bc	8.83 (0.90) a	4.49 ad	9.77 ac
Water	0.05	ns	ns	0.05	ns
Straw	0.01	0.001	0.05	0.001	0.001
W x S	0.01	ns	ns	0.01	0.05
			1995–1996		
FB	0.069 a	0.28 (0.80) a	5.66 (0.99) a	0.35 a	5.73 a
FI	16.76 b	4.14 (0.20) bc	10.59 (0.39) ac	20.89 b	27.34 b
FR	21.54 b	4.17 (0.16) bc	15.40 (0.42) bc	25.71 b	36.94 c
NFB	−0.076 a	2.00 (1.04)[c]ab	6.71 (1.01) a	1.92 ac	6.64 a
NFI	−0.028 a	6.98 (1.00) cd	16.60 (1.00) b	6.96 c	16.57 d
NFR	−0.24 a	7.22 (1.03) d	22.12 (1.01) d	6.98 c	21.89 e
Water	0.05	0.01	ns	0.05	0.05
Straw	0.001	0.01	0.001	0.001	0.001
W x S	0.001	ns	ns	0.01	0.001

[a] Annual nonvegetated emissions equals winter plus nonvegetated summer. Annual vegetated emissions equals winter plus vegetated summer. The numbers in parentheses represent fraction of annual emissions during summers. Different letters within a column represent values significantly different at $\alpha = 0.05$ level (anova, *t* test). An *F* test was performed to test significance of mean water and straw differences and interactions. The *p* value at which each treatment was significant (W, S, W x S) is indicated. The term "ns" means not significant at $\alpha = 0.05$ level.

[b] Fraction equals summer emissions divided by annual emissions. Fraction winter emissions equal 1.0—summer emissions.

[c] Values greater than 1.0 are due to negative fluxes (CH_4 consumption).

Table 5. Straw Inputs (g m^{-2}) Averaged Across Straw and Water Treatments, 1994–1996[a]

Treatment	Autumn 1994	Spring 1995	Autumn 1995	Spring 1996
FB	155 a	48 a	270 a	107 a
FI	702 b	320 b	762 b	259 b
FR	665 b	262 b	735 b	380 d
NFB	149 a	69 a	239 a	143 ac
NFI	756 b	412 c	604 b	238 bc
NFR	732 b	399 c	668 b	462 d
B	152 a	59 a	254 a	125 a
I	729 b	366 b	683 b	248 b
R	698 b	330 b	708 b	413 c
F	507 a	210 a	589 a	249 a
NF	546 a	293[b]a	483 a	258[c] a

[a] Autumn B treatments represent the amount of straw left after incomplete combustion. Different letters grouped together within a column between horizontal lines represent values significantly different at $\alpha = 0.05$ level (anova, *t* test).

[b] $p = 0.06$.

[c] $p = 0.08$.

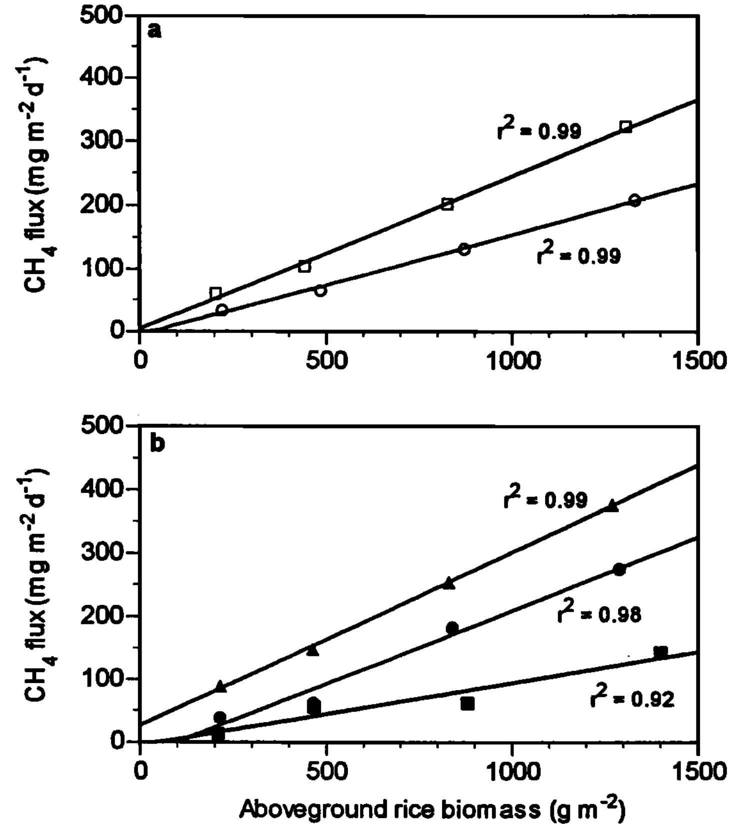

Figure 3. Aboveground biomass versus methane flux during the summer 1996 flooded period. All measurements were taken from vegetated plots. (a) Straw treatments are averaged within each water treatment (open circles indicate F; open squares indicate NF). (b) Water treatments are averaged within each straw treatment (solid squares indicate B; solid circles indicate I; solid triangles indicate R).

peak could represent continued methanogenic activity leading to a delayed postdrain peak due to a longer period of saturated soil conditions because of heavy rains; however, sampling was not frequent enough to determine this conclusively. The peaks on March 14 in the 1996 FB, FI, and FR treatments contributed 0.09, 3.68, and 3.66 g CH_4 m^{-2}, respectively. These peaks represented 17–22% of the winter emission and 10–13% of the annual 1995–1996 emission of methane from the FI and FR treatments, respectively. The postdrain peak for the FB treatment accounted for 26% of annual emissions for that treatment. Soil water potential data (not shown) indicate very wet soil conditions during this postdrain period. No peak was observed after summer drain in 1996 although it was expected. The 1996 summer was very hot and dry, and fluxes were not detected probably because they only occurred for a short period between sampling dates.

3.3. Aboveground Biomass and Plant-Mediated Emissions

Figure 3 shows the relationships between methane flux and aboveground rice biomass (live plants with no weeds) measured periodically until heading during the summer of 1996. The treatments are averaged across water treatments in Figure 3a and across straw treatments in Figure 3b. Individual straw treatments showed the same patterns (e.g., FR > FI > FB) and are not presented. The patterns NF > F and R > I > B were not caused by differences in aboveground biomass, since there were only small differences in biomass between straw treatments. The high-r^2 values indicate a consistent relationship between methane flux and aboveground biomass until heading. After heading, methane fluxes decreased (Figures 1a and 1b), so the relationship did not continue.

Table 6. Fraction of Plant-Mediated Methane Emissions for Summers of 1995 and 1996[a]

Treatment	Summer 1995	Summer 1996
FB	0.93 a	0.93 a
FI	0.58 ab	0.58 b
FR	0.63 ab	0.71 ab
NFB	0.93 a	0.69 ab
NFI	0.33 b	0.55 b
NFR	0.54 b	0.68 ab

[a] Surface emission = 1.0 − fraction listed. Different letters within a column represent values significantly different at $\alpha = 0.05$ level (anova, *t* test). The fraction of plant-mediated summer methane emissions is (vegetated minus nonvegetated emissions) divided by (vegetated summer emissions).

In the summers, flux measurements were made on vegetated and nonvegetated areas within each plot to compare the amount of methane emitted from plants to that from the water surface alone. In the B treatments, 69–93% of summer emissions were transported through the plants (plant mediated), while in the I and R treatments, 33–71% of summer emissions moved through the plants (Table 6). The patterns for the fraction of plant-mediated emissions were B > R > I within each water treatment and F > NF within each straw treatment and were the same for both years. There are statistically significant differences between the B treatments and the NFI and NFR treatments in summer 1995 and between the B and I treatments in 1996. Since the fraction of methane that did not pass through the plant was, by definition, surface emission and this is dominated by ebullition (bubbling of gas through the water column to the atmosphere), ebullitive movement of methane became more dominant in treatments with greater straw amendments.

4. Discussion

4.1. Methane Fluxes and Seasonal Emissions

In both winters the FR treatment had greater fluxes (Figure 1a) and emissions (Figure 2 and Table 4) than FI. FI was expected to have significantly greater emissions due to close contact between the straw and the soil. It is possible this was caused by differences in the physical distribution of unincorporated straw. Straw incorporation depth due to rolling was highly heterogeneous. Straw was matted and protruded above the water and below the soil surface. Thus straw may have enhanced the pathway for ebullition by providing conduits connecting the soil to the surface, similar to the bubble tubes described by *Chanton and Whiting* [1995]. This may have bypassed methane oxidation processes in the oxic soil surface layer. In contrast, FI straw was completely soil incorporated and covered more uniformly by soil and the winter flood. Redox data for this period indicate no significant difference ($\alpha = 0.05$, t test) between the FI and FR treatments (not shown).

The amount of methane emitted during fallow can be a significant portion of annual emissions if soils are saturated and there is a ready supply of organic matter [*Bronson et al.*, 1997]. Winter fallow emissions during 1994–1995 from the NFR and NFI treatments represented 10 and 18%, respectively, of annual totals (Table 4). Even though these treatments were not flooded, heavy rains saturated the soil. During this period the NFB treatment emitted 15–20 times less methane than NFI and NFR, showing the importance of carbon to methane emissions. Just as for postdrain periods, the winter fallow can be a significant source of methane if there are saturated soil conditions and carbon is readily available.

It was expected that F summer methane emissions would be greater than winter F treatments because of cold temperature suppression of biological activity and lack of plants in winter to provide pathways to the atmosphere for methane. The opposite trend observed in the FI and FR treatments (Table 4) suggests that despite lower temperatures, the addition of large amounts of straw just before winter provided ample carbon that allowed methanogens to overcome limitations and thrive. It is also possible that methanotrophs may be more susceptible to cold conditions and were unable to oxidize significant amounts of methane to CO_2. Other data collected indicate that winter CO_2 emissions were similar to summer [*Fitzgerald*, 1998]. Thus relatively high winter CO_2 and CH_4 emissions suggest distinct winter microbial dynamics.

In both years, single summer peaks were observed at about the 50% heading date in F and NF treatments (Figures 1a and 1b). Two [*Holzapfel-Pschorn and Seiler*, 1986; *Lindau et al.*, 1991] or three [*Schütz et al.*, 1989a; *Murase et al.*, 1993] peaks have been reported during the cropping season, although *Cicerone et al.* [1992] and *Seiler et al.* [1984] reported one peak in California and Spain, respectively. *Schütz et al.* [1989a] hypothesized that the early peak is caused by organic matter from the previous season serving as substrate for methanogenesis and the second is due to mineralization of root exudates. Later peaks could be caused by root decay. We may not have seen an early peak possibly because by spring, straw was weathered and carbon may not have been in a readily available form.

The single peak summer flux curves in Figures 1a and 1b closely follow plant growth. *Sass et al.* [1991b] showed that methane emissions are tightly coupled to plant photosynthetic activities. As plants grow and photosynthetic processes increase, more carbohydrates are produced, some of which become available to roots for growth and exudation. As more roots are produced, more exudates are available for methanogenesis. Our data suggest that after heading, this source of food and energy for methanogens decreased, probably due to changes in the plants that cause translocation of carbohydrates to reproductive organs rather than vegetative organs, such as roots.

4.2. Postdrain Fluxes

Postdrain peaks are attributed to the physical release of gases from soil pores following field draining due to soil cracking [*Denier van der Gon et al.*, 1996]. The presence of such peaks was noted from data collected in 1985 by *Cicerone et al.* [1992] but only recently recognized as a significant source of methane emissions. The strong flush of methane ~10 days after the winter drain in March 1996 (Figure 1a) occurred when the soil surface began to show very fine cracks but was still moist. Since this period produced 10–13% of annual emissions, there is a need to anticipate its presence when measuring fluxes. Others have reported that postdrain fluxes (after the summer rice crop) account for 5–20% of cropping season emissions in rice [*Wassmann et al.*, 1994; *Yagi et al.*, 1996; *Denier van der Gon et al.*, 1996]. In a subsequent study at this site, in 1997, methane emissions accounted for 7–12% of summer emissions and were measured within 10 days after summer draining [*Bossio et al.*, 1999]. Thus physical release after soil draining can be a significant source of methane from these systems.

4.3. Plant-Mediated Emissions and Aboveground Biomass

Up to 95% of methane emissions from rice fields pass through the rice plant (plant mediated), while only 5% are emitted through the water surface (ebullition and diffusion) [*Seiler et al.*, 1984; *Schütz et al.*, 1989b]. Surface emissions reported by *Wassmann et al.* [1996], converted here to plant-mediated emissions, showed that 77–85% of emissions were transported through the plants in low organic matter amended treatments but only 38–65% were transported in high organic matter amended treatments, similar to our finding of 33–73% for I and R treatments (Table 6). Since the rate of methane production in the soil should be higher with greater straw amendments and the soil-plant-atmosphere pathway has a given maximum rate of diffusion, any methane produced above this maximum will move through the floodwater via ebullition. Thus treatments with greater straw amendments will have a larger proportion of methane move via ebullition than treatments with less straw, assuming the root and plant transport pathways are similar. This is supported by the significantly lower plant-mediated emissions from NFI and NFR in summer 1995 and the I treatments in summer 1996 compared to B (Table 6).

Differences in aboveground biomass, root biomass, or straw amendments could explain the differences in slopes in Figure 3. However, the NF and F treatments (Figure 4a) and the R and I treatments (Figure 3b) had almost identical aboveground biomass throughout the season. Thus aboveground biomass did not account for methane flux differences between treatments. The NF and R treatments had significantly greater spring 1996 straw inputs (Table 5), higher summer 1996 methane emissions (Table 4), and greater slopes for flux (Figure 3) than the F and I treatments, respectively. Thus it would appear that straw addition in the spring was the controlling factor for the relationship presented in Figure 3. However, the final root biomass under the sampling chambers in the R treatment was 21% greater than I, and NF had 9% greater root biomass than F. Therefore it is possible that differences in emissions were caused by an interaction between root biomass and straw amendments. This is strengthened by the observation that R treatments had greater fractions of plant-mediated methane emissions (Table 6) than I treatments. If treatments such as R, with greater straw amendments, have more ebullition, as stated previously, then plant-mediated emissions for R would be expected to be lower than I in Table 6. Since they are higher and root biomass was greater in R than I, it is possible that greater straw amendments led to increased root biomass which in combination increased methane emissions from R treatments. Whether this is a purely quantitative difference in root and straw biomass or is a qualitative (chemical and structural) difference in the straw, roots or soil microbiology due to treatment effects cannot be determined from this study. *Chanton et al.* [1997] pointed out that root production contributes to methane emissions. It could be that methane flux increases were, in part, the result of increased surface area contact between soil and roots, providing increased transport capacity to the surface.

Methane fluxes per unit aboveground biomass were calculated from the data in Figure 3. These values were compared to *Sass et al.* [1991a] who measured fluxes of 0.172 and 0.132 mg CH_4 d^{-1} g^{-1} aboveground rice biomass at two sites for the first year and 0.417 and 0.260 mg CH_4 d^{-1} g^{-1} at the same sites for a second year. Their first year was equivalent to our NFB, and the second year was equivalent to our NFI treatment in terms of relative amounts of straw amended. Calculated fluxes for the NFB and NFI treatments in this study were 0.178 and 0.301 mg CH_4 d^{-1} g^{-1}, respectively. When the mean of all four of their site years (0.245 mg CH_4 d^{-1} g^{-1}) is compared with the mean from this study (0.240 mg CH_4 d^{-1} g^{-1}), the difference between Sass et al. and our study is ~2%. This suggests that some of the important controlling factors for methane emissions were similar between the two studies. The soils in both studies were heavy clays, straw loading was comparable, and the climate was temperate. Also, it is possible that the rice varieties behaved similarly in terms of rooting dynamics and transport of methane to the atmosphere.

5. Conclusions

Temporal patterns in methane fluxes and emissions from rice fields indicate that the principal factor controlling methane emissions was the interaction of flooding and straw amendments. The presence of either flooding or straw without the other led to low emissions, while straw plus flooding in winter and summer led to high emissions. This is especially obvious when comparing the winter NF treatments from 1994–1995 and 1995–1996. The first year was extremely wet, while the second was relatively dry, resulting in small but significant peaks of methane in 1994–1995 due to saturated soils. There was a statistically significant carry-over effect of winter straw treatment on summer emissions, but winter flooding had no effect. The fact that emissions from winter-flooded plus straw treatments accounted for 50% of annual methane emissions and postdrain periods accounted for up to 18% of annual emissions demonstrates the need to measure fluxes during fallow periods to accurately estimate regional and global methane emissions.

In the Sacramento valley, ~142,000 ha of rice were harvested in 1991 (Rice Project, California rice acreage harvested, 1997, available as http://agronomy.ucdavis.edu/uccerice), before the legislated phasedown of rice straw burning began in 1992. Approximately 90% of this was burned, and 9% was left on the fields over winter, so this was similar to the NFR treatment in this study. Virtually no winter flooding and incorporation was practiced at this time. In 1998, 200,000 ha of rice were harvested with 28% burned, 46% soil incorporated, and 23% winter flooded and incorporated (J. Williams, personal communication, 1999). When the 2-year means of methane emissions for winter and summer for the NFB (equivalent to the conventional practice of burning), NFR, and FI treatments are extrapolated to these regions, 7.35 × 10^3 Mg of methane were emitted in 1992, while 26.3 × 10^3 Mg of methane were emitted in 1998, a 2.6-fold increase. These values are gross estimates only, since no attempt was made to account for soil type differences across the region and other factors affecting methane emission. However, most of the soils on which rice is grown in the Sacramento Valley are similar in terms of clay content (30–50%), much of the region is planted to the same rice variety, and climate and cultural practices are similar.

It is important to note that other gases contribute to the "greenhouse effect," especially CO_2, and it cannot be implied that incorporation of straw in flooded rice systems will lead to vastly greater greenhouse gas loading when compared to burning rice straw. Burning straw releases CO_2 and a small amount of CH_4, [*Jenkins and Turn*, 1994]. Results from *Fitzgerald* [1998] showed that total radiative forcing of CO_2 + CH_4 for the NFB treatment was ~86% of the FI treatment when averaged over the 2-year period. Thus the total radiative effect of CO_2 + CH_4 should be measured when implying the greenhouse gas loading of one management treatment compared to another.

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