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SOIL MANAGEMENT

Rice Yield and Nitrogen Utilization Efficiency under Alternative Straw Management Practices

Alison J. Eagle, Jeffrey A. Bird, William R. Horwath, Bruce A. Linquist, Sylvie M. Brouder, James E. Hill, and Chris van Kessel*

ABSTRACT

Nitrogen fertility is an important component of rice (*Oryza sativa* L.) cultivation systems, especially where air and soil quality issues have prompted a search for alternatives to rice straw burning. This study examined the effects of different rice straw management practices and winter flooding on yield, N uptake, and N use efficiency. The experiment, established on two sites in California, was initiated in 1993 on a Sodic Endoaquert near Maxwell and in 1994 on a Xeric Duraquert near Biggs. Main plot treatments were winter flooding and no winter flooding, and four straw management practices—straw burned, incorporated, rolled, and baled/removed—were subplot treatments. Zero N fertilizer microplots were established yearly in each plot. At currently recommended N fertilization levels, where other nutrients were sufficient, grain yield was unaffected by alternative straw management or winter flooding. However, in the third year after experiment initiation, the grain yield in zero N fertilizer plots was greater where straw was retained, i.e., incorporated and rolled. In Years 3 through 5 at Maxwell, straw retention increased N uptake by rice by an average of 19 kg N ha^{-1} where no N fertilizer was applied and by 12 kg N ha^{-1} at recommended rate of N fertilizer application. Winter flooding further increased crop N uptake when straw was retained. The additional available soil N from straw led to increased N uptake without corresponding increased grain yield, which decreased N use efficiency and necessitates the re-evaluation of N fertilizer application rates.

Crop residue management and its impact on soil organic matter and nutrient cycling are increasing in importance with the current renewed focus on agricultural sustainability. The traditional method of rice straw disposal in many parts of the world is burning (Becker et al., 1994; Miura and Kanno, 1997) and advantages to this method include disease and pest control, and labor and energy savings (Ponnamperuma, 1984). However, air quality concerns have resulted in banning or dramatic reductions of straw burning in parts of Europe (Ocio et al., 1991) and in California, making the search for alternatives essential.

While there is concern about increased greenhouse gas production (e.g., CH_4) when straw is returned to the soil (Bronson et al., 1997; Bossio et al., 1999), burning rice straw releases amounts of both CH_4 and NO_2 comparable to that from decomposing straw (Miura and Kanno, 1997). By increasing soil organic carbon (SOC) levels, incorporation of rice straw may reduce the release of greenhouse gases, including CO_2, until SOC reaches a maximum level. Intentional winter (fallow season) flooding is utilized in California to aid decomposition of rice straw in the field and in the process restore historical winter wetland habitat for migrating waterfowl (Elphick and Oring, 1998).

Nitrogen fertility in the rice cropping system is likely to be affected by alternative management practices that change straw retention practices and aerobic/anaerobic characteristics. Nitrogen is the most yield-limiting nutrient in rice cropping systems worldwide (Mikkelsen, 1987; Cassman et al., 1996a) and because of many opportunities for losses, especially in the alternating wet/dry cycles of rice systems, it is also the most difficult nutrient to manage (Mikkelsen, 1987; Buresh et al., 1989).

Incorporation of wheat (*Triticum aestivum* L.) and rice residue initially had negative yield effects on rice in a number of studies (Rao and Mikkelsen, 1976; Azam et al., 1991; Verma and Bhagat, 1992), with N immobilization one of the main causes (Rao and Mikkelsen, 1976). Yield depression following straw incorporation has been mitigated by adding mineral N (Azam et al., 1991) and the effects of N immobilization have been minimized when straw was allowed to decompose before seeding took place (Rao and Mikkelsen, 1976; Adachi et al., 1997). Plant-available N, yield, and N uptake have all been positively affected by straw incorporation in the long term (Verma and Bhagat, 1992; Cassman et al., 1996a; Kundu and Ladha, 1999).

Since one-third of total rice plant N is in the straw, some N fertilizer requirements may be replaced by returning straw to the field (Ponnamperuma, 1984; Cassman et al., 1998). Wheat–rice rotations in India have successfully reduced fertilizer N application by 29 to 40 kg N ha^{-1} when using straw as a replacement for fertilizer N (Mahapatra et al., 1991; Singh, 1995). Incorporation of straw has been followed by increases in microbial biomass and N mineralization (Bacon, 1990; Singh, 1995) and greater SOC and total N levels (Cassman et al., 1996a). Therefore, straw incorporation has potential for significant residual effects on soil nutrient supply.

A.J. Eagle, J.E. Hill, and C. van Kessel, Dep. of Agronomy and Range Science, Univ. of California, Davis, CA 95616; J.A. Bird, and W.R. Horwath, Land, Air and Water Resources, Univ. of California, Davis, CA 95616; B.A. Linquist, Int. Rice Research Inst., Lao-IRRI Project, Vientiane, Laos; and S.M. Brouder, Dep. of Agronomy, Purdue Univ., West Lafayette, IN 47907-1150. Received 10 Jan. 2000. *Corresponding author (cvankessel@ucdavis.edu).

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Abbreviations: NUE, nitrogen use efficiency; PNUE, physiological nitrogen use efficiency; SOC, soil organic carbon.

The effects of winter (fallow season) flooding on N dynamics in a temperate rice system have not been studied extensively. Nitrogen requirements of microorganisms that decompose organic matter in flooded soils are lower than for decomposers in aerated soils (Broadbent, 1979). This results in lower net N immobilization in flooded soils than in aerobic, well-drained soils (Williams et al., 1968; Mikkelsen, 1987). Increased levels of soil organic C and N were found in a tropical rice system kept flooded most of the year compared to a rice–maize rotation that contained a long aerobic phase (Witt et al., 1998). However, this did not contribute to increased soil N supply for the first two rice crops, and long-term effects are generally unknown.

Because of the high potential for losses, N use efficiency in rice tends to be low in comparison with other major crops (Keeney and Sahrawat, 1986). Reduction of N losses would increase both soil and fertilizer N use efficiency and reduce environmental costs associated with denitrification and leaching of NO_3 (George et al., 1993). Cessation of straw burning would also reduce N losses, since most of the straw N is lost in the burning process (Ponnamperuma, 1984). Additionally, straw incorporation may immobilize mineral N, which would otherwise be volatilized or denitrified (Broadbent and Tusneem, 1971).

Comparisons between different straw management systems in rice and their impacts on N fertility have been largely limited to tropical climates. Incorporation and burning of straw have had mixed impacts on both yield and N uptake in previous California studies (Williams et al., 1957, 1968, 1972). These studies utilized cultivation practices different from those in current use, or used rice cultivars no longer in commercial use. Therefore, further information is needed on the effects of alternative straw management using current rice cultivation practices. Winter flooding has only recently become common practice in California, so the impact of long-term winter flooding on nutrient cycling and rice production is also unknown. A multidisciplinary, long-term study on two sites was initiated to examine the effects of straw management practices and winter flooding. The objective of this portion of the study was to look at the impacts of these practices on rice yield, N uptake, and N use efficiency.

MATERIALS AND METHODS

Field Sites

Two field sites were established on different rice-growing soils in the Central Valley of California, a Sodic Endoaquert (Maxwell) and a Xeric Duraquert (Biggs). The site near Maxwell, Colusa County, consisted of 28 ha on a commercial rice farm and was established in the fall of 1993. The Biggs site, 10 ha at the California Rice Research Station near Biggs, Butte County, was established in the fall of 1994. The soils were analyzed for selected physical and chemical characteristics before initiation of the experiment (Table 1).

Treatments were laid out in a split plot, randomized complete block design replicated four times. Main plot treatments were winter flooding and no winter flooding. Split plot treatments were four straw management practices: burn, incorporate, roll, and bale/remove. Individual plot size was 42 by 180 m at Maxwell and 15 by 142 m at Biggs.

Fields were flooded during the summer growing season, then drained before harvest. Following harvest the straw treatments imposed were: (i) straw burned; (ii) straw chopped, then incorporated using a chisel plow and/or disc; (iii) straw rolled, crushed, and flattened into the soil surface using a heavy roller; and (iv) straw windrowed, then baled and removed. All treatments were accomplished after harvest in the fall and all received spring tillage. With the exception of the rolled treatment that was flooded before rolling, winter flooded treatments were flooded 10 to 15 cm following the fall straw operations.

The winter flooded treatments were drained in late March to allow time for drying before spring tillage. Spring operations included tillage, seedbed preparation, and fertilizer application, all using field-scale equipment and methods utilized by local producers. All fertilizer application occurred before seeding. Fertilizer N and P application rates are summarized in Table 2. Nitrogen rates depended on preseason available soil N, resulting in the changes over the years. Potassium fertilizer was not applied at either site. Following fertilizer application the fields were flooded within a few days and rice

Table 1. Soil characteristics at Maxwell and Biggs at the initiation of the experiment.

	Maxwell	Biggs
Classification	**Willows clay: fine smectitic, superactive, thermic Sodic Endoaquert. Sodic >15SAR at depth to 1 m**	**Neerdobe clay: fine mixed, superactive, thermic Xeric Duraquert. Duripan variable: Neerdobe-Esquon complex at site**
Physical characteristics†		
Soil texture, g kg^{-1}		
Sand	**50**	**170**
Clay	**510**	**350**
Chemical characteristics		
pH	**6.6**	**4.7**
CEC, cmol$_c$ kg^{-1}	**42**	**30**
Total C, g kg^{-1}	**19.5**	**12.3**
Total N, g kg^{-1}	**1.7**	**1.0**
Extractable P–Olsen, mg kg^{-1}	**11.3**	**11.1**
Exchangeable K, mg kg^{-1}	**305**	**72**
S, mg kg^{-1}	**159**	**63**
Ca, mg kg^{-1}	**128**	**96**
Mg, mg kg^{-1}	**102**	**49**
Na, mg kg^{-1}	**234**	**21**
Electrical conductivity, S m^{-1}	**0.14**	**0.04**
Sodium adsorption ratio (SAR)	**7.8**	**<1.0**

† Soil characteristics represent the 0- to 15-cm depth increment.

variety M202 was seeded aerially at both sites. All operations utilized commercial equipment and conventional weed and pest control strategies.

During each growing season, microplots that received no fertilizer N were established within each main plot, placed in a different location each year. Phosphorus was added to the zero N plots at rates equivalent to the N fertilized plots.

Yield

At maturity, plants in quadrats of 0.5 to 1 m^2 area in the zero N and the main plots were cut at 1 to 2 cm above the soil surface, separated into grain and straw components, dried to constant mass at 60°C, and weighed. Grain yield was corrected to 140 g kg^{-1} water content. For comparison, yield measurements were also obtained with a small plot combine harvester on a strip (7.6 by 30.5 m) in the middle of the main plots.

Nitrogen Uptake and Nitrogen Use Efficiency

Dried straw samples were coarse ground using a Wiley mill, and then both grain and straw were ground into a fine powder with a rolling ball mill and analyzed for total N by combustion on a CNS analyzer. Nitrogen uptake was calculated from the yield measurements and total N in the plant parts.

Soil mineral N content (NO_3 and NH_4) was measured from cores taken at the 0- to 15-cm depth increment both before seeding and at harvest. Nitrogen available to the crop is equal to the sum of the soil mineral N at the end of the season and the N accumulated in the zero N plants, minus mineral N from the beginning of the season. Since most of the mineral N in the spring was in the form of NO_3, and thus lost by denitrification following flooding (Buresh et al., 1989), and soil mineral N measured in the fall was minimal (data not shown), the available soil N over the season was based on the N uptake in the zero N plants.

Physiological N use efficiency (PNUE) (Singh et al., 1998), also called N utilization efficiency (Sowers et al., 1994; Fiez et al., 1995) or N use efficiency for grain production (Borrell et al., 1998), is equal to grain yield per unit total N uptake. PNUE was calculated as follows:

$$\text{PNUE} = \text{Grain dry mass (kg ha}^{-1}\text{)}/\text{Total aboveground plant N uptake (kg ha}^{-1}\text{)}$$

On the other hand, N use efficiency (NUE) (Sowers et al., 1994; Fiez et al., 1995) is equal to the grain yield per unit available N and includes both a physiological and soil N supply component. NUE was calculated using the following equation:

$$\text{NUE} = \text{Grain dry mass (kg ha}^{-1}\text{)/Total N supply (kg ha}^{-1}\text{)}$$

where N supply = N uptake in zero N treatment (kg ha^{-1}) + N fertilizer applied (kg ha^{-1}).

Statistical Analysis

Analysis of variance (ANOVA) was performed using the PROC GLM procedure in SAS (SAS Inst., 1989). The flood by block error was used as the error term in the ANOVA for the winter flooding vs. no winter flooding treatments. Contrast statements were used to compare treatment means and sets of treatment means when the ANOVA indicated treatment effects. When there was a significant straw × flood interaction the effect of winter flooding within the straw management treatments was analyzed using a contrast statement. To account for differences between years, a repeated measures model was used with time as the repeated variable. A Duncan's multiple range test was used to contrast means when winter-flooded treatments were pooled together for the NUE data. To assess compatibility of large plot harvest data with quadrat harvest data, the ANOVAs for the data sets were compared.

Table 2. Fertilizer N application rates used at Biggs and Maxwell for the duration of the straw management study.

	Fertilizer N			
Year	Source	Rate	Total N applied	Total P applied
		kg ha^{-1}		
	Biggs			
1995	Urea†	103	139	45
	Ammonium phosphate sulfate	36		
1996	Ammonium sulfate	138	168	77
	Diammonium phosphate	30		
1997	Urea	155	185	77
	Diammonium phosphate	30		
1998	Urea	129	141	57
	Monoammonium phosphate	12		
	Maxwell			
1994	Aqua ammonium	152	182	74
	Diammonium phosphate	29		
1995	Aqua ammonium	155	183	72
	Diammonium phosphate	28		
1996	Aqua ammonium	149	174	64
	Diammonium phosphate	25		
1997	Aqua ammonium	138	168	74
	Diammonium phosphate	29		
1998	Aqua ammonium	118	146	72
	Diammonium phosphate	28		

† All fertilizer was applied preplant.

RESULTS

Yield

Unless otherwise noted, plant parameters such as yield and N uptake refer to N-fertilized rice. Treatment effects calculated using grain yields from large plot combine measurements were not significantly different from those calculated from the yield quadrats. Therefore, the quadrat yield data was used for all the following analyses. Grain yields at Maxwell averaged 10.2, 10.6, 11.8, 13.1, and 10.8 Mg ha^{-1} in 1994 through 1998 and were not significantly affected by either winter flooding or straw treatment. Similarly at Biggs, winter flooding had no significant effect on grain yield. However, a straw treatment effect was significant in the first year and during 4 yr with the repeated time analysis. This was caused by lower yields in the bale/remove treatment when contrasted with the other treatments (Table 3). Straw yield was significantly increased when straw was retained (incorporate or roll) at both Maxwell and Biggs ($P < 0.01$, data not shown).

Straw management affected grain yield in zero N fertilizer plots at Maxwell in Years 3 through 5 (Table 4). The straw effect was mainly due to the greater yields in the straw retained treatments (incorporate and roll) compared with the straw removed treatments (burn and bale/remove). A significant straw × flood interaction in 1996 and 1997 indicated that the effect of winter flooding on zero N fertilizer yield depended on straw treatment. Poor yields and high variability due to weather patterns in 1998 resulted in no significant interaction, although the trend was still observable. Average zero fertilizer N grain yield was significantly increased by winter flooding in 1996 through 1998 (repeated time ANOVA) when straw was incorporated (27% increase

Table 3. Rice grain yield as affected by winter flooding and straw management at Biggs.

Treatment	Grain yield 1995	1996	1997	1998	All years
	Mg ha^{-1}				
Winter flood					
Burn	8.9	10.1	10.6	8.6	
Incorporate	9.3	9.7	10.1	8.3	
Roll	8.1	10.1	10.0	8.8	
Bale/remove	7.0	9.6	9.7	8.1	
No winter flood					
Burn	9.7	9.7	10.5	8.8	
Incorporate	9.5	9.2	9.8	7.9	
Roll	9.9	9.7	10.0	7.5	
Bale/remove	8.9	9.3	8.8	6.8	
	Analysis of variance				
Source of variation					
Straw	*	NS	NS	NS	**
Winter flood	NS†	NS	NS	NS	NS
Straw × winter flood	NS	NS	NS	NS	NS
Contrasts					
Bale/remove vs. others	**	NS	*	*	***

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NS, not significant.

Table 4. Rice grain yield (no N fertilizer) as affected by winter flooding and straw management at Maxwell.

Treatment	Grain yield 1994	1995	1996	1997	1998	All years
	Mg ha^{-1}					
Winter flood						
Burn	4.1	7.1	5.9	5.8	3.1	
Incorporate	3.9	5.8	8.4	8.8	5.3	
Roll	4.1	6.1	7.7	7.5	5.4	
Bale/remove	4.0	6.9	5.8	5.5	3.4	
No winter flood						
Burn	4.4	6.2	5.8	6.5	3.5	
Incorporate	4.2	6.8	6.6	6.8	4.3	
Roll	4.0	4.9	5.8	6.9	4.7	
Bale/remove	3.4	6.8	5.3	5.7	3.6	
	Analysis of variance					
Source of variation						
Straw	NS†	NS	***	***	***	**
Winter flood	NS	NS	NS	NS	NS	NS
Straw × winter flood	NS	NS	***	**	NS	NS
Contrasts						
Retain vs. remove‡	NS	NS	***	***	***	***
Flood in incorporate§	NS	NS	*	***	NS	NS
Flood in roll	NS	NS	**	NS	NS	NS

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† NS, not significant.
‡ Retain = incorporate and roll, Remove = burn and bale/remove.
§ Contrast statements were used to assess effects of flooding in the incorporated and rolled treatments.

over no winter flooding, $P < 0.001$) or rolled (19% increase, $P = 0.05$). However, there was no effect on zero N fertilizer grain yield when straw was removed. The interaction between straw treatment and winter flooding in zero N fertilizer straw yield at Maxwell was more pronounced than for grain yield in 1996 through 1998 (data not shown). Winter flooding increased average zero N straw yield over no winter flooding by 26 and 22% in the incorporated and rolled treatments, respectively.

Zero N fertilizer grain yields at Biggs averaged 6.8, 6.8, 8.5, and 6.2 Mg ha^{-1} in the years 1995 through 1998, respectively, significantly higher than the zero N yields at Maxwell (Table 4). High variability at Biggs, as indicated by a significant block effect for grain yield ($P < 0.001$), straw yield ($P < 0.01$) contributed to the lack of significant treatment effects. Planing and leveling of the field before the establishment of the experiment were likely causes of the variability, since this process resulted in greater amounts of topsoil on one end of the field than on the other.

Yield response to N fertilizer application was stronger at Maxwell than at Biggs. Fertilizer N application increased yields at Biggs on average by 30% more than zero N fertilizer yields. At Maxwell, however, application of fertilizer N resulted in an average yield increase of 105%. After 5 yr of straw management at Maxwell, increased zero fertilizer N yield due to straw retention resulted in lower yield responses to added fertilizer N (Fig. 1).

Nitrogen Uptake and Nitrogen Use Efficiency

Total plant N uptake in the N fertilized plots was greater in the straw-retained plots at Maxwell (Table 5). In Years 3 through 5, when straw retention began to significantly increase N uptake, the average increase in N uptake was 12 kg ha^{-1}. Of the total increase in N uptake, 67% was in the straw (data not shown). Winter flooding had no significant effect. There were no significant treatment effects on N uptake at the Biggs site (data not shown).

Plant N uptake in the zero fertilizer N plots at Maxwell closely mirrored grain yield, showing year-by-year variation and straw management effects, but no effect of winter flooding (Table 6). However, a significant straw × flood interaction appeared in Year 3 and 4 (Table 6) and in the repeated measures analysis for Year 3 through 5 (data not shown). Winter flooding significantly increased N uptake in the zero N fertilizer plots where straw was retained, but not where it was

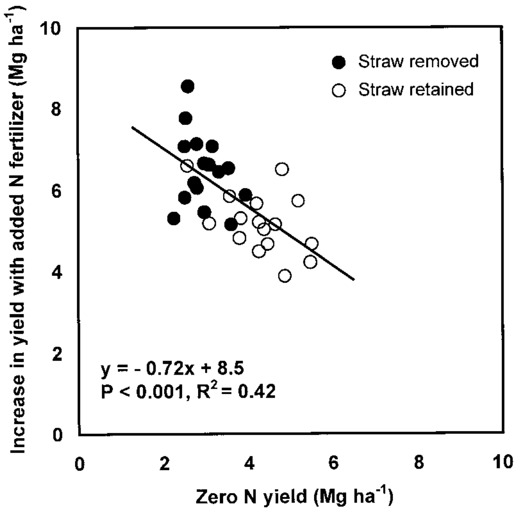

Fig. 1. Rice grain yield in N-unfertilized microplots compared to the yield response to fertilizer N addition at Maxwell after 5 yr of alternative straw management practices. Data points include four straw treatments and winter flooding vs. no winter flooding. Each point represents one experimental plot.

Table 5. Total rice plant N uptake as affected by winter flooding and straw management at Maxwell.

Treatment	Plant N 1994	1995	1996	1997	1998	All years
	kg ha^{-1}					
Winter flood						
Burn	162	179	203	176	141	
Incorporate	155	195	218	194	174	
Roll	129	181	212	189	158	
Bale/remove	160	154	198	173	160	
No winter flood						
Burn	175	196	187	189	147	
Incorporate	176	193	212	191	160	
Roll	156	151	195	182	159	
Bale/remove	154	181	203	185	143	
	Analysis of variance					
Source of variation						
Straw	NS‡	NS	*	NS	*	**
Winter flood	NS	NS	NS	NS	NS	NS
Straw × winter flood	NS	NS	NS	NS	NS	NS
Contrasts						
Retain vs. remove†	NS	NS	*	NS	**	NS

* Significant at the 0.05 level.
** Significant at the 0.01 level.
† Retain = incorporate and roll, Remove = burn and bale/remove.
‡ NS, not significant.

Table 7. Physiological N use efficiency (PNUE) as affected by winter flooding and straw management at Maxwell.

Treatment	PNUE 1994	1995	1996	1997	1998	All years
	kg grain kg^{-1} total plant N					
Winter flood						
Burn	59	52	54	65	67	
Incorporate	60	53	47	57	58	
Roll	56	52	50	62	59	
Bale/remove	59	56	52	65	63	
No winter flood						
Burn	55	51	56	65	64	
Incorporate	53	48	47	59	58	
Roll	59	58	53	61	59	
Bale/remove	54	48	51	63	61	
	Analysis of variance					
Source of variation						
Straw	NS‡	NS	**	**	***	*
Winter flood	NS	NS	NS	NS	NS	NS
Straw × winter flood	NS	*	NS	NS	NS	NS
Contrasts						
Retain vs. remove†	NS	NS	**	**	***	**

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† Retain = incorporate and roll, Remove = burn and bale/remove.
‡ NS, not significant.

removed. In Years 3 through 5, average N uptake in the zero fertilizer N plots increased due to straw retention by 29 and 9 kg ha^{-1} in winter flooded and nonwinter flooded treatments, respectively. Sixty-eight and 86% of this increase occurred in the grain in winter-flooded and nonwinter-flooded treatments, respectively. Nitrogen uptake at Biggs was significantly greater in straw retained vs. straw removed treatments in Year 4 only ($P < 0.05$, data not shown).

Since the increased N uptake was not associated with a change in grain yield, the additional N uptake led to a lower PNUE in N-fertilized plots (Table 7). At Maxwell in Years 3 through 5, PNUE was on average 4.7 kg lower when straw was retained rather than removed. Both grain and straw N content were significantly greater when straw was retained ($P = 0.001$ and $P = 0.0001$ for grain and straw, respectively in the 3-yr repeated time analysis). In Years 3 through 5, the N content in the grain averaged 12.0 and 11.4 g kg^{-1} when straw was retained and removed, respectively. During the same 3 yr, N content in the straw was 7.0 and 6.4 g kg^{-1} when straw was retained and removed, respectively.

Nitrogen use efficiency in Years 3 through 5 at Maxwell was also significantly lower when straw was retained (Table 8), but there was no winter flooding effect. The same trend was seen in the third and fourth year at Biggs when comparing the burned treatment to the two straw retained treatments. However, the bale/re-

Table 6. Total rice plant N uptake (no N fertilizer applied) as affected by winter flooding and straw management at Maxwell.

Treatment	Plant N 1994	1995	1996	1997	1998	All years
	kg ha^{-1}					
Winter flood						
Burn	55	89	66	67	31	
Incorporate	55	70	96	102	66	
Roll	50	82	88	89	68	
Bale/remove	50	89	65	64	41	
No winter flood						
Burn	59	81	68	76	38	
Incorporate	51	95	76	79	57	
Roll	53	64	69	84	54	
Bale/remove	44	91	65	70	52	
	Analysis of variance					
Source of variation						
Straw	NS§	NS	***	***	***	**
Winter flood	NS	NS	NS	NS	NS	NS
Straw × winter flood	NS	NS	**	***	NS	NS
Contrasts						
Retain vs. remove†	NS	NS	***	***	***	***
Flood in incorporate‡	NS	NS	*	***	NS	NS
Flood in roll	NS	NS	**	NS	NS	*

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† Retain = incorporate and roll, Remove = burn and bale/remove.
‡ Contrast statements were used to assess effects of flooding in the incorporated and rolled treatments.
§ NS, not significant.

Table 8. Nitrogen use efficiency (NUE) as affected by straw management at Maxwell and Biggs.†

	NUE 1994	1995	1996	1997	1998
	kg grain kg^{-1} available N				
		Maxwell			
Burn‡	40a*	36ab	44a	49a	52a
Incorporate	39a	37a	39c	43b	48bc
Roll	41a	35ab	41b	45b	46c
Bale/remove	39a	32b	43ab	49a	50ab
		Biggs			
Burn	–	36a	34a	32a	37a
Incorporate	–	37a	32a	29b	32b
Roll	–	36a	34a	30b	33ab
Bale/remove	–	31b	32a	28b	32b

* Numbers within the same column and site followed by the same letter are not significantly different by Duncan's multiple range test.
† Nitrogen use efficiency calculated as kg grain kg^{-1} available N, where available N is crop N in zero N plots plus fertilizer N applied.
‡ Winter flooded and nonwinter flooded treatments are averaged together, as there were no winter flooding effects.

move treatment at Biggs demonstrated similar efficiency in grain production from available N as the straw retained treatments. Over the course of the experiment, NUE was significantly higher at Maxwell than at Biggs, with an average production of 42 kg grain kg^{-1} available N at Maxwell and an average production of 33 kg grain kg^{-1} available N at Biggs.

DISCUSSION

Yield of Fertilized Rice

At current N fertilizer application levels, there were no significant treatment effects on grain yield, although straw yield was increased due to straw retention. The lack of yield response to the increase in soil N supply following straw incorporation indicated that N fertility was more than sufficient at current N fertilizer application levels.

At Biggs, the significant yield difference due to straw management practices was mainly because of the difference between bale/remove and the other three straw treatments. Both straw removal (burn and bale/remove) treatments resulted in losses from the system. Most of the N and C, 25% of the P, and 20% of the K in the straw are lost during burning of rice straw (Ponnamperuma, 1984). Since most of the K is in the straw, baling/removing resulted in greater losses of K from the system than did burning. The initial extractable K levels at Biggs soil at 72 mg kg^{-1} were considered to be almost deficient, and these levels decreased significantly after baling/removing of the straw compared with the other treatments (Hill et al., 1999). Additionally, more K deficiency symptoms appeared in the plants after baling/removing than in any other straw treatment and addition of K fertilizer significantly increased yields where straw was removed (Hill et al., 1999). Therefore, the lower yields in the bale/remove treatment can be attributed to K deficiency after removal of the straw.

The lack of yield differences between burning and incorporating of straw was also noted at Biggs in studies from the 1940s and 1960s (Williams et al., 1957, 1972). In another study yield was decreased after incorporation of straw where N concentration was <0.54% (Williams et al., 1968). This study resulted in the assumption that when the concentration of N in the straw was higher than 0.54% net N mineralization would occur. Different varieties and production practices as well as the much higher N content of the straw in our study, 0.70 and 0.79% of N in the straw returned to the soil at Maxwell and Biggs, respectively, may make the comparison between these earlier studies and ours difficult. These earlier studies also did not look into the temporal changes in N availability that occur following the incorporation of high C/N ratio straw. These temporal changes are important as in this study we found significant differences between removal and retention of straw only by the third year.

Yield of Unfertilized Rice

An initial negative effect on grain yield following straw incorporation in zero-N fertilizer treatments is common (Azam et al., 1991; Verma and Bhagat, 1992; Kludze and Delaune, 1995). However, such a decline in grain yield was not observed in our study at Maxwell (Table 4) or at Biggs (data not shown). This may be because of the smaller amount of straw added in this study (8 Mg ha^{-1} compared with 11 or 22 Mg ha^{-1} in Kludze and Delaune, 1995) or a higher indigenous soil N supply in the soils of our study due to high clay and organic matter content and lower mean soil temperature. Another potential reason could be differences between the cropping systems; in our study the straw had opportunity to decompose over the fallow winter season, while Verma and Bhagat (1992) and Azam et al. (1991) incorporated wheat straw shortly before planting rice.

The impact of straw management on grain yield where no N fertilizer was applied did not manifest itself until the third year of the study, when straw retention resulted in increased zero-N fertilizer grain yields at Maxwell. All the zero N fertilizer plots had insufficient levels of N, and yield responded to straw retention under these circumstances. Therefore, the main contributor to increased yield is most likely additional soil N following straw retention. By the third year, rice in a long-term rice–wheat rotation study in India and a 3-yr study in Japan also experienced yield increases following straw incorporation (Verma and Bhagat, 1992). A straw-applied treatment surpassed an unfertilized control in both yield and N uptake by the second season in a study from the Philippines (Becker et al., 1994). The magnitude of the beneficial yield effects tends to depend both on timing of straw incorporation due to nutrient release dynamics (Tripathi et al., 1997), and on the amount of straw incorporated (Mahapatra et al., 1991).

As seen in other experiments where N was limiting (Cassman et al., 1996b), yield response to N fertilizer application in 1998 at Maxwell decreased as zero N fertilizer yield increased (Fig. 1). After 5 yr of alternative straw management a separation between straw removal and retention appeared in this relationship, as the increase in soil N supply due to straw retention reduced the yield response to fertilizer N. While straw retention increased zero N fertilizer grain yields, the additional increase in grain yield after fertilizer N application was 6.5 and 5.2 Mg ha^{-1} where straw was removed and retained, respectively. Most of the decrease in fertilizer N response was likely due to the increase in N supply power of the soil following straw retention.

Yield and Winter Flooding

By the third year at Maxwell, winter flooding further increased grain yield when no fertilizer N was applied and the straw was returned to the soil. Again, since yield effects were only observed when N was limiting, winter flooding is surmised to affect the soil N supply during the growing season. Since N uptake is tied to its availability in the soil, winter flooding may improve synchrony of N uptake and N release from incorporated straw.

Winter flooding increased the period in which the soil remains under anaerobic conditions. Continuous rice rotations in southeast Asia have resulted in increased levels of soil organic matter, although an apparent N deficiency in the system led to a decline in rice yield (Cassman et al., 1998). Unlike the situation in southeast Asia, the additional anaerobic period associated with winter flooding in California (up to 5 mo) led to an increase in N mineralization as measured by N uptake in unfertilized rice (Table 6). One main difference between the systems is the significantly greater aerobic period during spring field preparation and autumn harvest in California rice production.

Significant increases in respiration and changes in metabolic diversity due to C inputs and winter flooding were noted after the first year of the straw management treatments in this experiment at Maxwell (Bossio and Scow, 1995). This continued into the second year of treatments, as winter flooding affected relative abundance of fungal versus bacterial populations, characteristic of the differences between aerobic and anaerobic communities (Bossio and Scow, 1998). Adaptations within the microbial community during winter flooding may affect the behavior of that community during the growing season, resulting in potential for different residue decomposition rates and/or timing of that decomposition.

Nitrogen Uptake and Nitrogen Use Efficiency

Retention of straw resulted in increased N uptake in both N fertilizer and zero N fertilizer plots at Maxwell. Similar increases in plant N uptake after straw incorporation have been noted elsewhere (Becker et al., 1994). Where N fertilizer was supplied, higher N uptake as a result of straw retention did not correspond to higher yield. This suggests that the additional N supplied from straw retention was in excess of N needs at current N fertilization rates. Reduction of fertilizer N rates by the difference in N uptake between treatments where straw was removed or retained (16 kg N ha^{-1} in winter flooded treatments) would be unlikely to result in a yield decline.

The increased soil N supply following winter flooding when residue was retained, as evidenced by increased N uptake may be related to microbial community adaptation or changes in decomposition timing. Since decomposition rates decline in anaerobic conditions (Broadbent, 1979), winter flooding may result in lower N mineralization rates during the winter. Losses of N during the fallow season would then be limited since the majority of N mineralization would tend to occur during the aerobic periods and in the warmer growing season.

The additional soil N supply following straw retention could be either a direct result of the N added in the straw or from reduced N losses (Mikkelsen, 1987) that reflect changes in microbial dynamics (Bossio and Scow, 1995). Addition of high C residue ties up mineral N within microbial biomass, preventing loss via denitrification or volatilization (Bacon, 1990). Long-term experiments have found greater soil organic matter (Verma and Bhagat, 1992) and microbial biomass C and N (Powlson et al., 1987) following years of residue incorporation, which may result in greater available N pools.

The increased soil N availability that resulted from straw retention translated to lower PNUE, as seen at Maxwell in Table 7. Since PNUE will be maximized at the optimum N supply rate from soil and fertilizer N, the N supply was sufficient or in excess at current fertilizer N application rates.

Nitrogen use efficiency, which has both a physiological and soil N supply component, decreased with the increase in soil N supply (Tables 5 and 8), suggesting that some of the decrease in NUE may have been due to the increased soil N supply. This decrease in NUE after straw retention suggests that N fertilizer rates could be adjusted by the third year of straw incorporation because of the increase in soil N supply. Nitrogen losses due to denitrification and volatilization would then be reduced since these processes tend to occur at greater rates under high mineral N concentrations (Focht, 1979; da Silva and Stutte, 1981).

Rice production at Maxwell was more efficient in N use than at Biggs (Table 8). As detailed in the above discussion on yield, possible explanations for the differences between the sites may be the K deficiency at Biggs, and its lower soil organic matter, clay content, and pH. Lower soil organic matter content may result in reduced N cycling in the system due to decreased microbial activity. The Biggs soil, with lower clay and soil organic matter contents, may also be subjected to greater N losses due to less adsorption of N onto clay particles and organic matter.

When available N was in excess, most of the additional N uptake due to residue retention was partitioned within the straw, resulting in a lower ratio of grain N/straw N (data not shown) and a lower ratio of grain production/total plant N (Table 7). When N was limiting, such as in the zero N fertilized rice plots, the increased N uptake due to straw retention was partitioned within the grain, resulting in higher ratios. Similar effects on harvest index (grain/straw) have been found, with harvest index increasing in N limited conditions after more N was supplied (Adachi et al., 1997). Also, although dependent on cultivar, harvest index generally decreases when additional N is added to rice already at maximum yield (Borrell et al., 1998). Therefore, an optimum level of available N would maximize the harvest index and the utilization of N in grain production.

CONCLUSIONS

The retention of straw in rice fields is a beneficial alternative to burning for straw management. Straw retention resulted in increased soil N supply by year three at Maxwell, as evidenced by greater N uptake. Yield in N-unfertilized rice increased when straw was retained due to the increased N uptake. This increase in soil N supply led to a reduction in N use efficiency in the N-fertilized plots, suggesting that N fertilizer application rates can be reduced when straw is retained. Potassium deficiency at Biggs contributed to a lower N response and the corresponding lack of yield response to straw retention. Thus, the impact of other productivity constraints, such as deficiencies of other nutrients, need to be minimized in order for the N benefit to be fully expressed. Winter flooding further increased the N supply of straw, perhaps due to better timing of N release or to reduction in N losses following microbial community adaptation.

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REFERENCES

Adachi, K., W. Chaitep, and T. Senboku. 1997. Promotive and inhibitory effects of rice straw and cellulose application on rice plant growth in pot and field experiments. Soil Sci. Plant Nutr. 43: 369–386.

Azam, F., A. Lodhi, and M. Ashraf. 1991. Availability of soil and fertilizer nitrogen to wetland rice following wheat straw amendment. Biol. Fertil. Soils 11:97–100.

Bacon, P.E. 1990. Effects of stubble and N fertilization management on N availability and uptake under successive rice (*Oryza sativa* L.) crops. Plant Soil 121:11–19.

Becker, M., J.K. Ladha, and J.C.G. Ottow. 1994. Nitrogen losses and lowland rice yield as affected by residue nitrogen release. Soil Sci. Soc. Am. J. 58:1660–1665.

Borrell, A.K., A.L. Garside, S. Fukai, and D.J. Reid. 1998. Season, nitrogen rate, and plant type affect nitrogen uptake and nitrogen use efficiency in rice. Aust. J. Agric. Res. 49:829–843.

Bossio, D.A., W.R. Horwath, and C. van Kessel. 1999. Methane pool and flux dynamics in a rice field following straw incorporation. Soil Biol. Biochem. 31:1313–1322.

Bossio, D.A., and K.M. Scow. 1995. Impact of carbon and flooding on metabolic diversity of microbial communities in soils. Appl. Environ. Microbiol. 1995:4043–4050.

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

Broadbent, F.E. 1979. Mineralization of organic nitrogen in paddy soils. p. 105–118. *In* Nitrogen and rice. IRRI, Los Baños, Philippines.

Broadbent, F.E., and M.E. Tusneem. 1971. Losses of nitrogen from some flooded soils in tracer experiments. Soil Sci. Soc. Am. Proc. 35:922–926.

Bronson, K.F., H.U. Neue, U. Singh, and E.B. Abao. 1997. Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: I. Residue, nitrogen, and water management. Soil Sci. Soc. Am. J. 61:981–987.

Buresh, R.J., T. Woodhead, K.D. Shepherd, E. Flordelis, and R.C. Cabangon. 1989. Nitrate accumulation and loss in a mungbean/lowland rice cropping system. Soil Sci. Soc. Am. J. 53:477–482.

Cassman, K.G., S.K. De Datta, S.T. Amarante, S.P. Liboon, M.I. Samson, and M.A. Dizon. 1996a. Long-term comparison of the agronomic efficiency and residual benefits of organic and inorganic nitrogen sources for tropical lowland rice. Exp. Agric. 32:427–444.

Cassman, K.G., G.C. Gines, M.A. Dizon, M.I. Samson, and J.M. Alcantara. 1996b. Nitrogen-use efficiency in tropical lowland rice systems—contributions from indigenous and applied nitrogen. Field Crops Res. 47:1–12.

Cassman, K.G., S. Peng, D.C. Olk, J.K. Ladha, W. Reichardt, A. Dobermann, and U. Singh. 1998. Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. Field Crops Res. 56:7–39.

da Silva, P.R.F., and C.A. Stutte. 1981. Nitrogen loss in conjunction with transpiration from rice leaves as influenced by growth stage, leaf position, and N supply. Agron. J. 73:38–42.

Elphick, C.S., and L.W. Oring. 1998. Winter management of Californian rice fields for waterbirds. J. Appl. Ecol. 35:95–108.

Fiez, T.E., W.L. Pan, and B.C. Miller. 1995. Nitrogen use efficiency of winter wheat among landscape positions. Soil Sci. Soc. Am. J. 59:1666–1671.

Focht, D.D. 1979. Microbial kinetics of nitrogen losses in flooded soils. p. 105–118. *In* Nitrogen and rice. IRRI, Los Baños, Philippines.

George, T., J.K. Ladha, R.J. Buresh, and D.P. Garrity. 1993. Nitrate dynamics during the aerobic soil phase in lowland rice-based cropping systems. Soil Sci. Soc. Am. J. 57:1526–1532.

Hill, J.E., D.M. Brandon, S.M. Brouder, A.U. Eke, T.E.C. Kraus, M.A. Llagas, B.A. Linquist, and S.C. Scardaci. 1999. Agronomic implications of alternative straw management practices. p. 5–25. *In* Winter flooding and straw management: Implications for rice production 1994–1996. Agron. Progress Rep., Agric. Exp. Stn. & Coop. Ext. Univ. of California, Davis.

Keeney, D.R., and K.L. Sahrawat. 1986. Nitrogen transformations in flooded rice soils. Fert. Res. 9:15–38.

Kludze, H.K., and R.D. Delaune. 1995. Straw application effects on methane and oxygen exchange and growth in rice. Soil Sci. Soc. Am. J. 59:824–830.

Kundu, D.K., and J.K. Ladha. 1999. Sustaining productivity of lowland rice soils: Issues and options related to N availability. Nut. Cyc. Agroecosyst. 53:19–33.

Mahapatra, B.S., G.L. Sharma, and N. Singh. 1991. Integrated management of straw and urea nitrogen in lowland rice under a rice wheat rotation. J. Agric. Sci. 116:217–220.

Mikkelsen, D.S. 1987. Nitrogen budgets in flooded soils used for rice productions. Plant Soil 100:71–97.

Miura, Y., and T. Kanno. 1997. Emissions of trace gases (CO_2, CO, CH_4, and N_2O) resulting from rice straw burning. Soil Sci. Plant Nutr. 43:849–854.

Ocio, J.A., P.C. Brookes, and D.S. Jenkinson. 1991. Field incorporation of straw and its effects on soil microbial biomass and soil inorganic N. Soil Biol. Biochem. 23:171–176.

Ponnamperuma, F.N. 1984. Straw as a source of nutrients for wetland rice. p. 117–136. *In* Organic matter and rice. IRRI, Los Baños, Philippines.

Powlson, D.S., P.C. Brookes, and B.T. Christensen. 1987. Measurement of soil microbial biomass provides an early indication of changes in total soil organic matter due to straw incorporation. Soil Biol. Biochem. 19:159–164.

Rao, D.N., and D.S. Mikkelsen. 1976. Effect of rice straw incorporation on rice plant growth and nutrition. Agron. J. 68:752–755.

SAS Institute. 1989. SAS/STAT user's guide. Version 6. 4th ed. Vol. 2. SAS Inst., Cary, NC.

Singh, H. 1995. Nitrogen mineralization, microbial biomass and crop yield as affected by wheat residue placement and fertilizer in a semi-arid tropical soil with minimum tillage. J. Appl. Ecol. 32:588–595.

Singh, U., J.K. Ladha, E.G. Castillo, G. Punzalan, A. Tirol-Padre, and M. Duqueza. 1998. Genotypic variation in nitrogen use efficiency in medium- and long-duration rice. Field Crops Res. 58:35–53.

Sowers, K.E., W.L. Pan, B.C. Miller, and J.L. Smith. 1994. Nitrogen use efficiency of split nitrogen applications in soft white winter wheat. Agron. J. 86:942–948.

Tripathi, B.P., J.K. Ladha, J. Timsina, and S.R. Pascua. 1997. Nitrogen dynamics and balance in intensified rainfed lowland rice-based cropping systems. Soil Sci. Soc. Am. J. 61:812–821.

Verma, T.S., and R.M. Bhagat. 1992. Impact of rice straw management practices on yield, nitrogen uptake and soil properties in a wheat–rice rotation in northern India. Fert. Res. 33:97–106.

Williams, W.A., D.C. Finfrock, L.L. Davis, and D.S. Mikkelsen. 1957. Green manuring and crop residue management in rice production. Soil Sci. Soc. Am. Proc. 21:412–415.

Williams, W.A., D.S. Mikkelsen, K.E. Mueller, and J.E. Ruckman. 1968. Nitrogen immobilization by rice straw incorporated in lowland rice production. Plant Soil 28:49–60.

Williams, W.A., M.D. Morse, and J.E. Ruckman. 1972. Burning vs. incorporation of rice crop residues. Agron. J. 64:467–468.

Witt, C., K.G. Cassman, J. Ottow, and U. Biker. 1998. Soil microbial biomass and nitrogen supply in an irrigated lowland rice soil as affected by crop rotation and residue management. Biol. Fert. Soils 28:71–80.