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Winter Straw and Water Management Effects on Soil Nitrogen Dynamics in California Rice Systems

Bruce A. Linquist,* Sylvie M. Brouder, and James E. Hill

ABSTRACT

This study examines the effects of straw management and winter flooding on soil N dynamics and crop N uptake in California rice (*Oryza sativa* L.) systems. Experiments were established in two locations in northern California with main plot treatments being winter flooding or no flooding; and four straw management practices (burn, remove, incorporate, and roll) as subplot treatments. Fertilizer was applied to the plots at the recommended levels for each site, but within each plot a zero N microplot was established. Total straw inputs before winter flooding averaged 7000 kg ha^{-1} for the incorporate and roll treatments, 4200 kg ha^{-1} for the remove, and 1600 kg ha^{-1} for the burn treatment (straw N ranged from 11 to 66 kg ha^{-1}). Before flooding the field for planting, there was 9% less straw in winter flooded plots compared to nonflooded plots. Straw incorporation resulted in more rapid straw decomposition compared to other treatments where the straw was not incorporated. Furthermore, potentially mineralizable N and soil extractable N was higher in the winter flooded treatments and where rice straw was retained. Crop response varied between sites but our results suggest that N fertilizer recommendations could potentially be reduced by 20 kg ha^{-1} if straw is incorporated and winter flooded.

In California and the southern USA, various environmental and economic factors are resulting in a change in the way rice straw has historically been managed. California legislation to phase down rice straw burning to 25% of total acreage has required major changes in straw management. Furthermore, in California, and more recently the southern USA (Anders et al., 2005), the rice industry and conservation groups have embraced the concept of winter flooding to provide substitute wetlands for waterfowl. The effect of these alternative winter straw management practices under flooded or nonflooded winter conditions on straw decomposition and N cycling are not known.

Large amounts of straw in the field before spring field operations is a potential concern as it can interfere with field operations and may immobilize N. Three avenues of straw disposal are possible: burning, removal for off-site use, and in-field decomposition. Removing straw by burning or for off-farm use alleviates these concerns, but burning is only available on a limited area and there is a limited market for rice straw, therefore, in-field decomposition is the only viable alternative for many farmers. Moisture, aeration, and temperature are principle soil factors determining the rate of organic residue decomposition. Below a certain critical moisture level biological processes are arrested, while at high moisture levels anaerobic conditions result. Decomposition under anaerobic conditions is thought to be slower than under aerobic conditions (Tate, 1979). In a lab study, Pal and Broadbent (1975) reported that 14% more straw C was lost from soil at 60% water holding capacity compared to 150% water holding capacity after 4 mo incubation. Similar results were found by Clark and Gilmore (1983). However, there are few field studies comparing aerobic vs. anaerobic decomposition. In one such study, Neue and Scharpenseel (1987) using ^{14}C labeled rice straw found no difference in straw decomposition in submerged vs. aerobic soils. Low temperatures retard organic residue decomposition (Sain and Broadbent, 1977; Pal and Broadbent, 1975) but temperature has much smaller influence on decomposition rates in saturated than unsaturated soil (Clark and Gilmore, 1983).

The potential for N immobilization under flooded soil conditions is thought to be less than in aerobic soils (Arharya, 1935a, 1935b; Broadbent and Nakashima, 1970). However, in pot and field studies, N immobilization has resulted in N deficiencies in rice (Bacon et al., 1989; Becker et al., 1994; Huang and Broadbent, 1989; Rao and Mikkelsen, 1976). Broadbent and Nakashima (1970) found significant N immobilization regardless of the N concentration of the straw residue in a lab study. Based on results from field studies, Williams et al. (1968) reported that a straw N concentration of 0.54% N was the critical level of straw N determining whether or not N immobilization would affect yield response in single growing seasons. However, it is also important to consider when straw is incorporated in relation to when rice is planted. Williams et al. (1968) incorporated straw immediately before sowing. Rao and Mikkelsen (1976) found that incubating straw in soils for 15 to 30 d decreased N immobilization. In a field study, Bacon et al. (1989) also found that incorporating straw residue in the fall increased N availability from the straw and soil resulting in increased rice yields compared to when the straw was incorporated shortly before harvest in the spring.

Two experimental sites were established in California to examine the long-term effects of straw management and winter flooding on rice production. Experiments were initiated in 1993 (Colusa County) and 1994 (Butte County) and continued through 1999. A number of reports have been published from these experiments which focus on the effects of straw and winter flood management practices on: microbial populations (Bossio and Scow, 1995), methane emissions (Fitzgerald

B. Linquist and J. Hill, Dep. of Plant Sciences, Univ. of California, Davis, CA 95616; and S. Brouder, Dep. of Agronomy, Purdue Univ., West Lafayette, IN 47907-1105. Received 21 Dec. 2005. *Corresponding author (balinquist@ucdavis.edu).

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Abbreviations: ExN, soil extractable nitrogen; F, flooded; PMN, potentially mineralizable nitrogen; NF, nonflooded.

et al., 2000), yield and fertilizer use efficiency (Eagle et al. (2000, 2001), N immobilization (Bird et al., 2001), and N dynamics in the humic fractions (Bird et al., 2002, 2003). The purpose of this paper is to report on research studying the effects of winter water and straw management on seasonal soil N dynamics. This research was conducted at both sites during the 1995 winter and 1996 growing season.

MATERIALS AND METHODS

Site Description and Management

Experiments began in the fall of 1993 at a 28 ha site in Colusa County (Maxwell) and in the fall of 1994 at a 10 ha site in Butte County (Biggs). The soil at the Maxwell site was a Willows clay (Sodic Endoaquert) and at the Biggs site was a Neerdobe (Xeric Duraquert). Soil characteristics of each site are given in Table 1.

The experimental design at each site was a split-plot design with four replications. Winter flooding (F) and nonflooding (NF) were main plots and straw treatments (burn, incorporate, roll, and bale/remove) were subplots. Plot size was 0.87 ha at Maxwell and 0.31 ha at Biggs. Each of the 32 plots was separated by a levee and had its own inlet and outlet. Straw and flood treatments were imposed immediately following rice harvest in the fall. All straw treatments were completed before flooding except the F roll.

Specific fall field operations varied at each site. At Maxwell, straw in the incorporated plots was swathed, foraged chopped and spread, then chisel plowed and/or stubble disked. In the NF roll treatment, straw was rolled using a V-groove roller. Straw in the F roll treatment was cage-rolled into the soil following flooding. In the straw removal plots the straw was cut at about 15 cm above the soil level then swathed, baled, and removed. At Biggs, straw in the incorporated plots was chopped with a flail ground chopper and incorporated by chiseling, followed by disking. A cage roller was used in the rolled treatments for both the F and NF treatments. In the straw removal treatment, the straw was cut at 15 cm and then baled and removed.

In the fall of 1995, F treatments were flooded on 1 November (Maxwell) and 12 November (Biggs) and drained on 1 Mar. 1996 (Maxwell) and 23 Feb. 1996 (Biggs). Water levels in the F treatments were maintained between 5 and 15 cm deep.

Table 1. Characteristics of the soil (0–15 cm) from each experimental site.

Parameter	Maxwell	Biggs
Classification	Willows clay: fine, smectitic, superactive, thermic Sodic Endoaquert. Sodic > 15SAR at depth to 1 m	Neerdobe clay; fine, mixed Xeric Duraquert. Duripan variable: Neerdobe-Esquon complex at site
Clay, %	51	35
Sand, %	5	17
pH	6.6	4.7
CEC, meq 100 g^{-1}	42	30
Total N, %	0.17	0.10
Total C, %	1.95	1.23
P, ppm bicarbonate	11.3	11.1
Exchangeable K, mg kg^{-1}	305	72
S, mg kg^{-1}	159	63
Ca, meq L^{-1}	1.6	1.2
Mg, meq L^{-1}	2.1	1.0
EC, mmhos cm^{-1}	1.4	0.4
SAR	7.8	<1.0
Na, meq L^{-1}	10.2	0.9

Spring field operations began in April and were the same for all treatments. At Maxwell, 121 kg N ha^{-1} (aqua NH_4^+) was injected on 3 May and an additional 23 kg N ha^{-1} (18–46–0) was surface applied then rolled in with a V-groove roller on 4 May. At Biggs, 138 kg N ha^{-1} of $(NH_4)_2SO_4$ and 30 kg N ha^{-1} as 18–46–0 was applied aerially on 11 May then harrowed into the soil surface. In each plot microplots which received no N fertilizer (−N) were established to more accurately access the fate of straw N. At Maxwell these plots were 4.9 by 6.0 m and at Biggs they were 3 by 3 m. Phosphate (triple superphosphate) was applied to the −N plots at the same rate as the rest of the field. All plots were flooded on 5 May (Maxwell) and 16 May (Biggs). Rice (var. 'M-202') was planted on 7 May at Maxwell and 19 May at Biggs. Fields remained flooded until approximately 1 mo before harvest when fields were drained.

Straw Inputs and Litter Bag Studies

Straw biomass and N inputs were determined for each treatment before winter flooding. In the incorporate and roll treatments, straw biomass was determined by cutting all plants at ground level within two 0.5 m^2 quadrats at physiological maturity of the 1995 season rice. Plant samples were then partitioned into grain and straw. In the burn and bale/remove treatments, all straw within three 0.3 m^2 quadrats was collected after burning (ash was not collected) or straw removal. These samples were dried to constant moisture at 65°C for dry weight determination then ground and analyzed for N using a Carlo Erba 1500 NCS analyzer (Milan, Italy).

To provide an estimate of rice straw decomposition during the winter, nylon litter bags (1.6 mm mesh, 21.0 by 15.5 cm) were filled with rice straw from the corresponding field treatment. The amount of straw used to fill the bags corresponded to the amount of straw remaining in each treatment. Bags were placed in the field after all fall straw management treatments had been completed. Litter bags were placed in or on the soil to mimic field straw conditions. Litter bags in the incorporated treatment were buried at an angle in the soil so that the bag was between 1 and 10 cm below the soil surface. In the other treatments bags were placed on the soil surface. The bags were removed before the start of spring land preparation, washed free of soil, dried to constant moisture at 65°C and weighed.

Soil and Plant Sampling and Analysis

Soil sampling for extractable N (ExN) began in March 1996 at both sites, before draining the F treatments, and continued at 2 to 6 wk intervals through the season. During the growing season, soil samples were taken from both the main field (+N) and −N microplots. From each plot, 6 to 8 soil cores (0–15 cm) were taken and combined in zip-lock plastic bags and stored in a cooler until being moved to a cold room. Soil N was extracted with 2 *M* KCl no more than 48 h after sampling. Extractable NH_4^+ and NO_3^- was measured using diffusion-conductivity analyzer (Carlson, 1978).

Potentially mineralizable N (PMN) was determined on soils sampled (0–15cm) just before planting and following the final harvest using a 7 d anaerobic incubation (1:5 soil/solution ratio) at 40°C (Keeney and Bremner, 1966). Soils were stored in a cooler and incubations were initiated no more than 48 h after sampling.

Plants from both the main field (+N) and −N microplots were harvested four times during the growing season at: mid-tillering, panicle initiation, flowering, and physiological maturity. For the first three sample dates plants were sampled from two quadrats for a total sample area of 0.45 m^2. At harvest, plants were

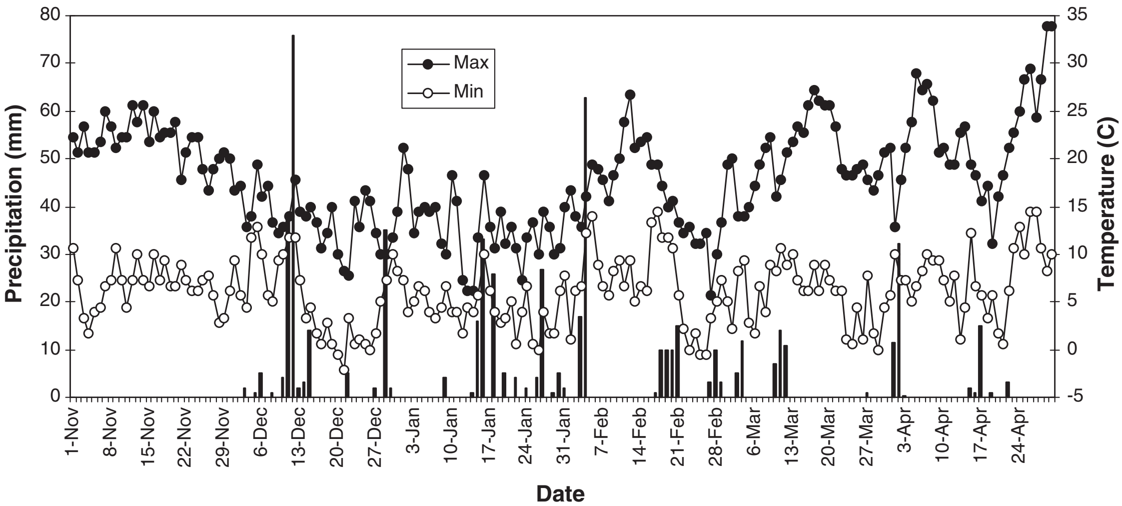

Fig. 1. Precipitation and maximum and minimum temperatures during the 1995–1996 winter and spring.

sampled from two larger quadrats for a total sample area of 1.0 m^2. The plants were cut at soil level and oven-dried at 65°C for yield determination. For the final harvest the plants were partitioned into straw and grain fractions before oven-drying. All samples were then ground and analyzed for N content.

Statistical analysis for each plant or soil sampling date was analyzed using a split-plot design with winter flood treatments as main plots and straw treatment as subplots.

RESULTS

Precipitation and Temperature

Weather data was taken from a site situated between the experimental sites. Average maximum and minimum temperature during the winter flood treatment period was 16 and 5.7°C, respectively. The first rainfall of the 1995–1996 winter season occurred on 3 December (Fig. 1). Total rainfall during the winter flooded period was 462 mm.

Straw Biomass and Nitrogen Inputs

In the incorporate and roll treatments, where all the straw remained in the field following harvest, average straw biomass was 6933 and 7102 kg ha^{-1} at the Maxwell and Biggs sites, respectively (Table 2). Straw removal reduced the amount of straw by approximately 38% at both sites while burning reduced the amount of straw by 73% at the Maxwell site and 80% at the Biggs site. Straw N concentration was similar across straw treatments at each site, averaging 0.89%N at Maxwell and 0.74%N at Biggs. Total straw N remaining in the field following the implementation of straw treatments ranged from 19 to 65 kg N ha^{-1} at Maxwell and 10 to 55 kg N ha^{-1} at Biggs (Table 2). At both sites, straw burning resulted in 40 to 46 kg ha^{-1} less N inputs from straw compared to the treatments where straw was retained in the field.

Table 2. Straw biomass and N following treatment implementation in the fall of 1995.

Straw treatment	Straw biomass	Straw N
	kg ha^{-1}	
	Maxwell	
Burn	1858 c†	19
Remove	4254 b	36
Incorp	7447 a	65
Roll	6419 a	59
	Biggs	
Burn	1419 c	10
Remove	4471 b	31
Incorp	7283 a	55
Roll	6920 a	50

† Different letters beside each treatment mean indicates a significant difference ($P = 0.05$) from other means within each site.

Straw Decomposition

The amount of straw and straw N remaining in the field just before planting the 1996 crop was estimated based on straw loss from litter bags. Averaged across sites and straw management treatments, 49% of the straw remained in the F plots compared to 58% in the NF plots (Table 3).

Table 3. Residue straw before planting in 1996. Estimates are based on litter bag data.

Main plot	Subplot	Maxwell: Straw remaining in litter bag	Maxwell: Total straw†	Biggs: Straw remaining in litter bag	Biggs: Total straw*
		%	kg ha^{-1}	%	kg ha^{-1}
Flood	burn	59 a‡	1096	53 ab	752
	remove	44 b	1872	57 a	2518
	incorp	31 b	2309	48 b	3496
	roll	45 b	2889	52 ab	3598
	mean	*45*		*53*	
Nonflood	burn	52 a	966	77 a	1091
	remove	59 a	2510	62 b	2772
	incorp	36 b	2681	53 c	3860
	roll	59 a	3787	65 b	4498
	mean	*52*		*64*	
ANOVA					
Flood		**		*	
Straw		**		**	
Flood × straw		*		*	

* Significance at $P = 0.05$.
** Significance at $P = 0.01$.
† Calculated by multiplying the percent in the litter bag by the initial straw biomass (Table 2).
‡ Different letters beside each subplot treatment mean indicates a significant difference ($P = 0.05$) from other means within the same main plot treatment.

Comparison of the individual straw treatments indicates that incorporating the straw resulted in the highest amount of straw decomposition. Following the winter flood, only 42% of the straw remained in the incorporated treatment compared to an average of 57% for the rest of the treatments. A significant straw by winter flood treatment interaction at both sites is due to slow straw decomposition in the NF roll and remove treatments compared to the F treatment.

Soil Nitrogen

Before the spring drain, soil extractable N (ExN) levels at Maxwell and Biggs were similar (Fig. 2). Due to the relatively saturated conditions in the NF plots most of the N (>95%) was in the NH_4^+ form. In the F treatments, ExN averaged 9.3 mg kg^{-1} compared to 3.1 mg kg^{-1} in the NF treatments. At both sites ExN in the burn and remove treatments was the lowest, averaging 4.6 and 5.5 mg kg^{-1}, respectively. The incorporate and roll treatments had the highest ExN levels, averaging 6.5 and 7.9 mg kg^{-1}, respectively, across both sites.

During the spring dry down, following the drain of the F treatments, most of the ExN nitrified. During this period, ExN at Maxwell increased by 3.4 mg kg^{-1} while at Biggs ExN declined relative to the predrain conditions. Before flooding all plots for planting, NH_4^+ at both sites

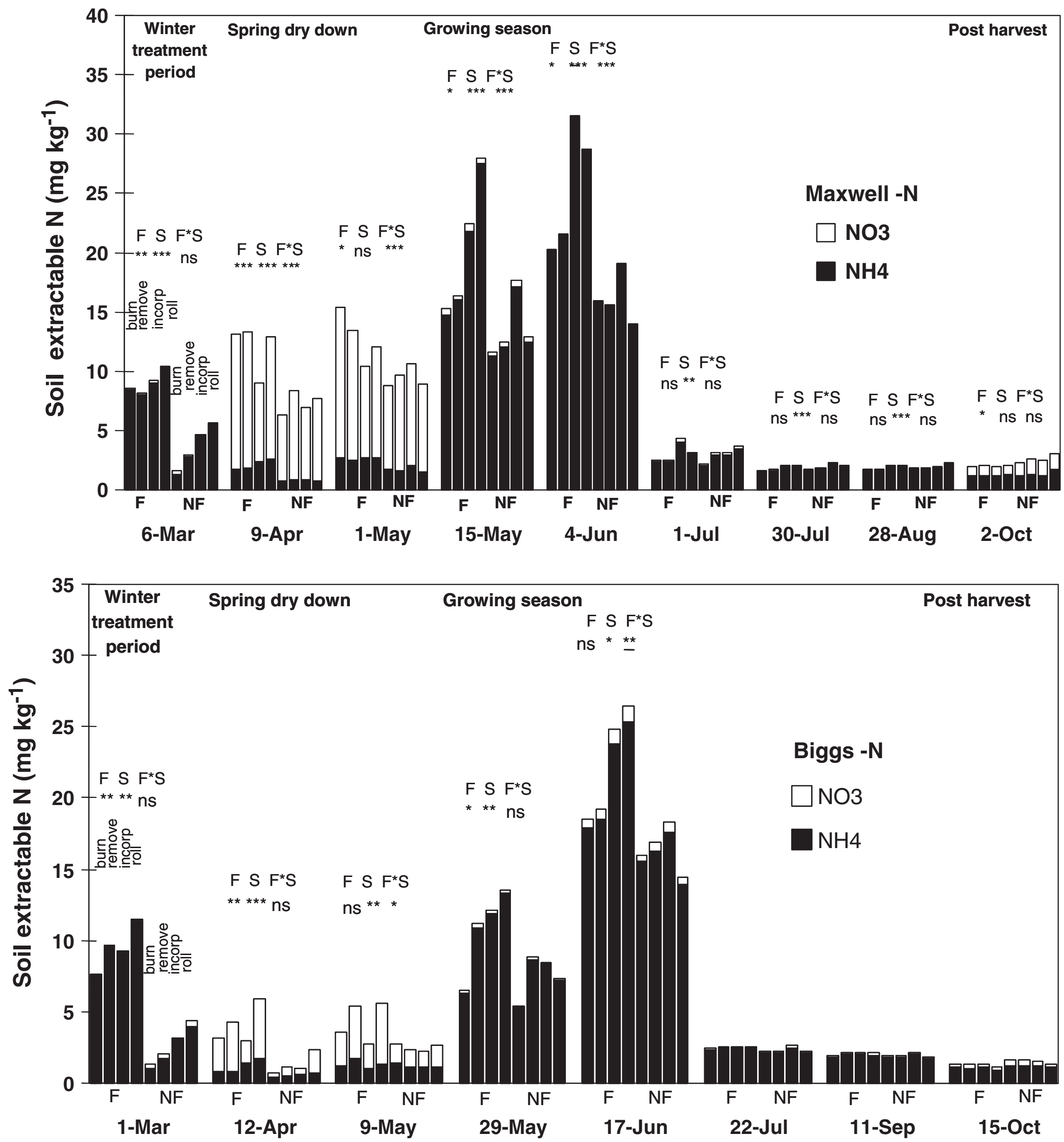

Fig. 2. Soil extractable N (ExN) as affected by winter flood (F) or no flooding (NF) and winter straw management in the −N microplots. Sample times were before draining the winter flood treatments, during the spring dry down period, and during the growing season in the −N plots for both Maxwell and Biggs sites. All plots were flooded at Maxwell on 5 May and at Biggs on 16 May in preparation for planting. Above each sample time, where differences are significant, the analysis of variance (ANOVA) results are presented for the effect of winter flood (F) the effect of straw management (S) and the interaction (F × S). *, **, and * represent a significance level of 0.05, 0.01, and 0.001, respectively.**

was similar (between 1 and 3 mg kg^{-1}), however NO_3^- at Maxwell was much higher. Greater ExN levels at Maxwell relative to Biggs was most likely resulted from the higher potential for denitrifcation at Biggs due to poor drainage, in conjunction with heavy rainfall in early April (Fig. 1). At both sites, ExN in the F treatments remained greater than in the NF treatments but differences between straw treatments were inconsistent.

The PMN before planting was greater at Maxwell than at Biggs (Table 4). Winter flooding resulted in higher PMN values at both sites but this was only significant at the Maxwell site. In general, PMN was higher in the incorporate and roll treatments, with the exception of the NF roll which had the lowest PMN of the treatments in which all straw was retained in the field.

During the first 5 wk following sowing, ExN in the −N plots averaged 6.4 mg kg^{-1} higher in the F treatments at both sites and was primarily in the NH_4^+ form (Fig. 2). Soil extractable N was generally positively related to the amount of straw incorporated at planting, with the exception of the NF roll treatment which had lower levels of ExN (similar to low PMN). At both sites, but more pronounced at Biggs, ExN increased by about 5 to 10 mg kg^{-1} between the first and second sampling dates, indicating that N mineralization was more rapid than N uptake and loss early in the growing season. ExN at both sites declined to <5 mg kg^{-1} between 1 and 2 mo after sowing, where it remained for the rest of the growing season. Small differences in ExN persisted at the Maxwell site through the growing season and were related to winter straw management. Extractable N in the burn and remove treatments was less than in the incorporate and roll treatments. At the last sample date, taken after harvest, ExN in the NF treatments was higher than in the F treatments at Maxwell, in contrast to ExN levels at the beginning of the growing season.

In the treatments which received fertilizer N, soil ExN values were about 40 mg kg^{-1} greater at Maxwell than at Biggs at the beginning of the season (Fig. 3) despite 24 kg N ha^{-1} more N fertilizer applied at Biggs. Treatment differences in ExN were not measurable at the first sample date, approximately 10 to 13 d after flooding in preparation for planting rice. One month after planting however, ExN at the Biggs site was significantly greater in the F treatments than in the NF treatments. At the Biggs site ExN was greater by about 20 mg kg^{-1} at the second sample date than in the first, similar to results seen in the −N plots at Biggs. Between 1 and 2 mo following planting ExN levels at both sites declined by more than 85%. Later in the season, ExN was higher in the incorporate and roll treatments at Maxwell. Following harvest, ExN was not significantly affected by either winter straw or flood management.

Following crop harvest, PMN was greater at Biggs than at Maxwell (Table 5), in contrast to PMN values before planting (Table 4). In the −N plots, PMN tended to be higher than in the +N plots at both sites. There was no significant effect of winter flooding at either site. Effects of winter straw management were significant but varied between sites. At the Maxwell site, PMN was highest in the incorporate and roll treatments which received the most straw.

Table 4. Potentially mineralizable N just before the 1996 planting.

Main plot	Subplot	Potentially mineralizable N	
		Maxwell	Biggs
		mg kg^{-1}	
Flood	burn	8.6 c†	4.9
	remove	10.1 c	6.4
	incorp	14.4 a	6.8
	roll	12.3 b	7.7
	mean	*11.4*	*6.4*
Nonflood	burn	8.0 a	3.4
	remove	8.3 a	3.4
	incorp	8.5 a	6.8
	roll	6.2 b	5.1
	mean	*7.7*	*4.7*
ANOVA			
Flood		*	NS
Straw		*	NS
F × S		*	NS

* Significance at $P = 0.05$.
† Different letters beside each subplot treatment mean indicates a significant difference ($P = 0.05$) from other means within the same main-plot treatment.

Crop Nitrogen

In the −N plots, N uptake patterns differed between the two sites: at Maxwell, most N accumulation occurred before flowering while at Biggs, N accumulation was almost linear through the growing season (Table 6). Nitrogen uptake at both sites and at all four sampling times was greater in the F than in the NF treatments, although this was not always significant. At the Maxwell site, shoot N concentration was higher in the F treatments early in the season suggesting greater early season N uptake due to flooding. However, there was an interaction between flooding and straw management in the first half of the season which can largely be explained by lower shoot N or N uptake in the NF roll treatment; an effect that became smaller as the season progressed. At the end of the season, total N uptake at Maxwell, where straw was retained, averaged 27 (F) and 6 (NF) kg ha^{-1} more than where straw was burned or removed. Shoot N concentration was significantly higher in F treatments at Maxwell for the first two sample times (through tillering); a similar trend was also observed at Biggs. There was an interaction between winter flooding and straw management on shoot N concentration at Biggs at the first sampling date, where the NF roll had lower shoot N concentration.

Early crop N accumulation and shoot N concentration was generally not affected by winter water and straw management in the +N plots (Table 7). Early season N accumulation was initially greater at Biggs but total seasonal crop N uptake at Maxwell averaged 212 compared to 178 kg ha^{-1} at Biggs. Nitrogen uptake during the last three sampling dates was greater in the F than in the NF treatments. While these differences were not significant, it is a similar trend and of a similar magnitude as to what was seen in the −N plots (Table 6). At Maxwell there were significant straw management

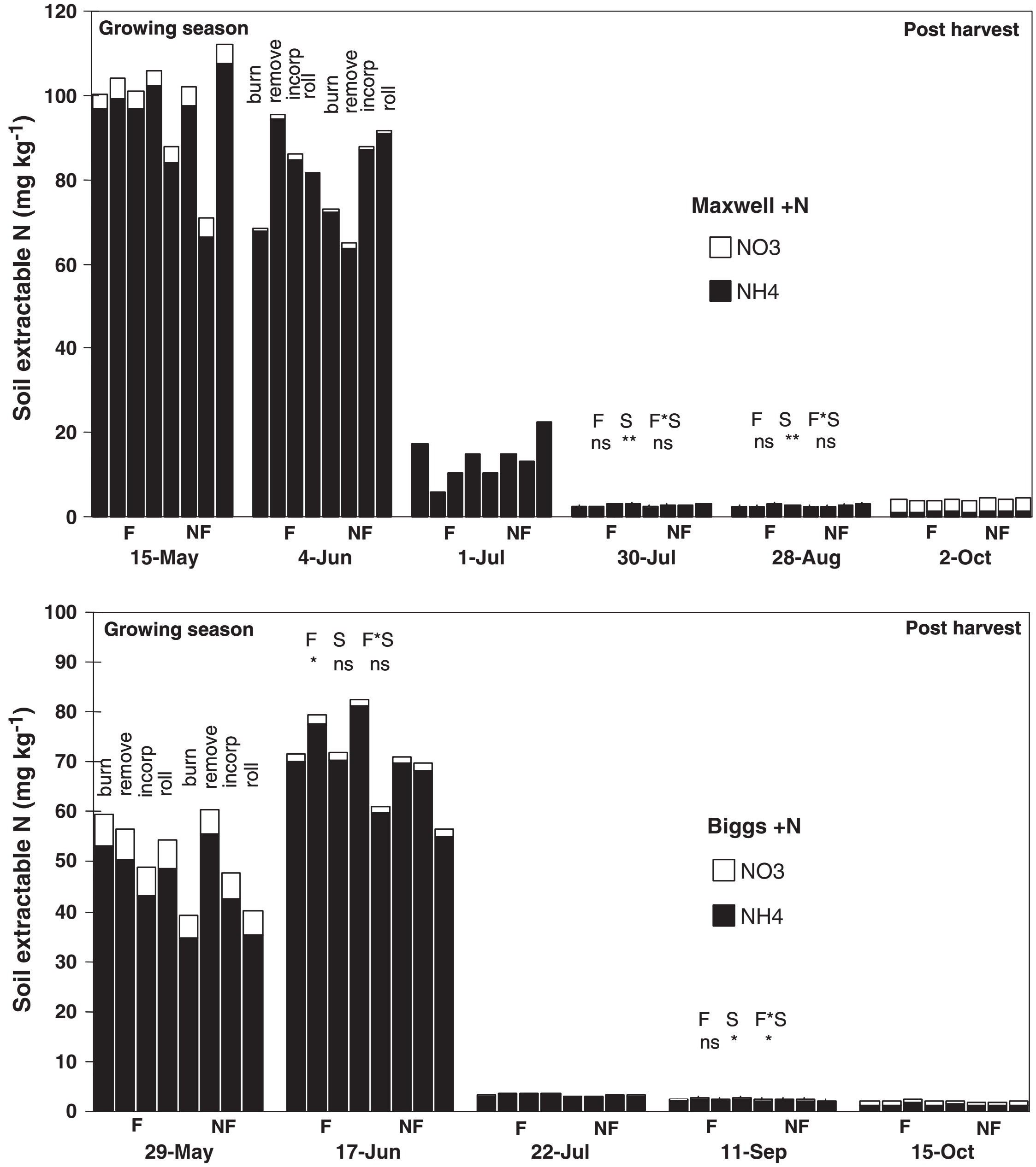

Fig. 3. Soil extractable N (ExN) as affected by winter flood (F) or no flooding (NF) and winter straw management in the main field (+N). Sample times were during the growing season. All plots were flooded at Maxwell on 5 May and at Biggs on 16 May in preparation for planting. Above each sample time, where differences are significant, the analysis of variance (ANOVA) results are presented for the effect of winter flood (F) the effect of straw management (S) and the interaction (F × S). *, **, and * represent a significance level of 0.05, 0.01, and 0.001, respectively.**

effects on crop N accumulation. In the incorporated and roll treatments, seasonal N uptake averaged 20 and 9 kg ha^{-1} greater than the burn, respectively. This differential uptake between the incorporate, roll, and burn treatments is similar to that measured in the nonfertilized plots. No differences in N uptake due to winter straw management were found at Biggs.

Crop Yields

Rice yields in the −N plots were similar at both sites, averaging 5806 kg ha^{-1} (Table 8). Rice yields were not affected by winter flood treatments but they were significantly higher where the straw was either incorporated or rolled and flooded at Maxwell. Similar trends were not observed at Biggs.

In the N fertilized plots, yields at Maxwell were higher by at least 2300 kg ha^{-1} more than at Biggs (Table 8). There were no significant yield differences at either site due to winter flood or straw management practice.

DISCUSSION

Effects of Winter Flooding and Straw Incorporation on Straw Decomposition

Based on litter bag data, straw decomposition during the winter period was greater in the F than in the NF

Table 5. Potentially mineralizable N at Maxwell and Biggs following the 1996 rice harvest treatments. Mineralizable N values are presented for both the soil which had (+N) and had not (−N) received N fertilizer at planting.

		Potentially mineralizable N			
		Maxwell		Biggs	
Main plot	Subplot	−N	+N	−N	+N
		mg kg^{-1}			
Flood	burn	8.5 b†	9.6 b	17.4	12.6 c
	remove	9.0 b	8.2 b	19.2	16.4 ab
	incorp	15.4 a	12.2 a	23.8	17.8 a
	roll	13.4 a	11.4 a	20.8	14.1 bc
	mean	*11.6*	*10.3*	*20.3*	*15.2*
Nonflood	burn	11.5 b	8.5 b	19.2	16.1 ab
	remove	12.1 b	8.5 b	15.5	15.5 ab
	incorp	12.4 b	11.3 a	17.4	17.3 a
	roll	15.9 a	12.2 a	21.1	14.4 b
	mean	*13.0*	*10.1*	*18.3*	*16.3*
ANOVA					
Flood		NS	NS	NS	NS
Straw		*	**	NS	*
F × S		NS	NS	NS	NS

* Significance at $P = 0.05$.
** Significance at $P = 0.01$.
† Different letters beside each subplot treatment mean indicates a significant difference ($P = 0.05$) from other means within the same main-plot treatment.

treatments. Possible reasons for such results are, first, the F treatments were flooded about a month before the first rainfall in early December (Fig. 1), therefore the start of decomposition in the NF treatments may have been delayed as the straw was dry. Second, the average maximum temperatures during November was 22°C compared to 14°C for the remainder of the winter flooded period. Therefore, higher temperatures combined with moisture (from flooding) may have resulted in greater seasonal decomposition in the winter flooded treatments (Broadbent and Mikkelsen, 1975; Pal and Broadbent, 1975; Sain and Broadbent, 1977).

Incorporating straw under both winter flood and nonflood conditions increased residue decomposition as measured in litter bags. Averaged across sites, 57% of the straw remained in the burn, remove, and roll plots compared with 42% when the straw was incorporated. These results are similar to those found by Sain and Broadbent (1977), although they reported more straw remaining in the early spring (75% straw remaining if the straw was on the surface and 60% straw remaining if it was incorporated). The NF roll treatment had more straw before planting than the other treatments because the straw was rolled when the soil surface was relatively dry and firm resulting in poor straw–soil contact.

Table 6. Nitrogen tissue concentration and total N uptake of rice sampled from −N plots at four sampling dates (1 mo after sowing, tillering, heading, and physiological maturity) for Biggs and Maxwell. At the final harvest the plants were portioned into grain and straw fractions.

Treatment	%N	kg N ha^{-1}	%N	kg N ha^{-1}	%N	kg N ha^{-1}	Straw %N	Grain %N	kg N ha^{-1}
					Maxwell −N				
	11 June		9 July		6 August		19 September		
F-Burn	3.84	14	1.25 a†	43 c	0.73 a	68 b	0.42	0.85	66 b
F-Remove	3.60	15	1.30 a	45 c	0.74 a	68 b	0.43	0.86	65 b
F-Incorp	3.71	15	1.51 b	63 a	0.82 b	94 a	0.44	0.88	96 a
F-Roll	3.68	15	1.47 b	57 ab	0.76 ab	79 ab	0.45	0.88	88 ab
Mean	*3.71*	*15*	*1.38*	*52*	*0.76*	*77*	*0.44*	*0.87*	*79*
NF-Burn	3.47	15	1.21 a	37 ab	0.72 ab	69 a	0.46	0.88	68 ab
NF-Remove	3.44	13	1.29 ab	41 ab	0.70 a	60 a	0.46	0.90	65 b
NF-Incorp	3.48	14	1.32 ab	43 a	0.78 b	70 a	0.51	0.89	76 a
NF-Roll	3.25	9	1.42 b	33 b	0.78 b	64 a	0.49	0.89	69 ab
Mean	*3.41*	*13*	*1.31*	*39*	*0.75*	*66*	*0.48*	*0.89*	*70*
ANOVA									
Flood	*	NS	*	*	NS	NS	*	NS	NS
Straw	NS	NS	*	*	*	*	NS	NS	*
F × S	*	NS	*	*	NS	*	NS	NS	*
					Biggs −N				
	18 June		15 July		12 August		30 September		
F-Burn	2.94 a	19	1.30	56	0.77	70	0.51 b	0.93	87
F-Remove	2.88 ab	23	1.29	57	0.80	75	0.58 a	0.92	97
F-Incorp	2.63 b	17	1.31	51	0.80	72	0.51 b	0.94	90
F-Roll	2.86 ab	19	1.37	57	0.78	68	0.49 b	0.93	95
Mean	*2.83*	*20*	*1.32*	*55*	*0.79*	*71*	*0.52*	*0.93*	*92*
NF-Burn	2.66 ab	17	1.29	49	0.77	69	0.52 a	0.93	90
NF-Remove	2.76 b	19	1.20	47	0.77	66	0.56 a	0.89	86
NF-Incorp	2.56 ab	16	1.27	52	0.77	58	0.56 a	0.89	88
NF-Roll	2.52 a	14	1.19	41	0.72	57	0.52 a	0.91	80
Mean	*2.63*	*16*	*1.24*	*47*	*0.76*	*63*	*0.54*	*0.91*	*86*
ANOVA									
Flood	NS	NS	NS	NS	NS	NS	NS	NS	NS
Straw	*	NS	NS	NS	NS	NS	*	NS	NS
F × S	*	NS	NS	NS	NS	NS	NS	NS	NS

* Significance at $P = 0.05$.
† Different letters beside each subplot treatment mean indicates a significant difference ($P = 0.05$) from other means within the same main-plot treatment.

Table 7. Aboveground biomass and N concentration of rice sampled from +N plots at four sampling dates (1 mo after sowing, tillering, heading, and physiological maturity) for Biggs and Maxwell. At the final harvest the plants were portioned into grain and straw fractions.

Treatment	%N	kg N ha^{-1}	%N	kg N ha^{-1}	%N	kg N ha^{-1}	Straw %N	Grain %N	kg N ha^{-1}
					Maxwell +N				
	11 June		9 July		6 August		19 September		
F-Burn	4.14	18	3.06	183	1.39 b	220	0.71 a†	1.25	212
F-Remove	3.90	19	2.94	174	1.43 b	191	0.77 ab	1.26	206
F-Incorp	4.03	24	3.07	196	1.61 a	229	0.86 c	1.30	226
F-Roll	3.94	23	3.07	185	1.65 a	225	0.82 bc	1.28	220
Mean	*4.00*	*21*	*3.04*	*185*	*1.52*	*216*	*0.79*	*1.27*	*216*
NF-Burn	3.84	24	2.80	175	1.33 a	198	0.69 a	1.20	195
NF-Remove	4.02	22	3.14	184	1.45 a	222	0.76 ab	1.30	213
NF-Incorp	3.85	20	3.07	172	1.43 a	199	0.84 b	1.38	221
NF-Roll	3.90	22	2.76	158	1.44 a	202	0.72 a	1.28	204
Mean	*3.90*	*22*	*2.94*	*172*	*1.41*	*205*	*0.75*	*1.29*	*208*
ANOVA									
Flood	NS	NS	NS	NS	*	NS	NS	NS	NS
Straw	NS	NS	NS	NS	*	NS	*	NS	*
F × S	NS	NS	NS	NS	NS	*	*	NS	NS
					Biggs +N				
	18 June		15 July		12 August		30 September		
F-Burn	4.14 a	33	2.39	150	1.20	163	0.88	1.09	178
F-Remove	4.01 ab	35	2.40	146	1.29	178	0.96	1.18	184
F-Incorp	3.81 b	33	2.34	139	1.22	158	0.93	1.15	189
F-Roll	3.95 ab	28	2.40	143	1.18	154	0.87	1.13	181
Mean	*3.98*	*32*	*2.38*	*145*	*1.22*	*163*	*0.91*	*1.14*	*183*
NF-Burn	4.09 a	34	2.33	140	1.17	153	0.89	1.09	173
NF-Remove	4.09 a	33	2.36	140	1.22	161	0.97	1.13	175
NF-Incorp	3.78 b	30	2.33	139	1.20	159	0.93	1.12	176
NF-Roll	3.96 ab	31	2.09	125	1.13	149	0.85	1.08	171
Mean	*3.98*	*32*	*2.28*	*136*	*1.18*	*156*	*0.91*	*1.11*	*174*
ANOVA									
Flood	NS	NS	NS	NS	NS	NS	NS	NS	NS
Straw	*	NS	NS	NS	NS	NS	NS	NS	NS
F × S	NS	NS	NS	NS	NS	NS	NS	NS	NS

* Significance at $P = 0.05$.
† Different letters beside each subplot treatment mean indicates a significant difference ($P = 0.05$) from other means within the same main-plot treatment.

Availability of Straw Nitrogen as Affected by Flooding

Winter flooding of straw resulted in higher ExN values in the F than in the NF treatments at the end of the winter flood period, during the spring dry down and for the first month after planting (Fig. 2). At the end of the winter flood period most of the ExN in both F and NF was NH_4^+. This is probably because all soils were anaerobic at the time of sampling, with the NF soils being either flooded or saturated due to rain. During the spring dry down most of the N at both sites was nitrified and total extractable N remained greater in the F treatments. Before planting, there was 9% less straw remaining in the F plots (Table 3) confirming that there was greater straw decomposition and hence more straw N mineralization up to this point in the F treatments. At the start of the growing season, all fields were flooded before sowing seed. The first soil sample was taken 10 to 13 d after flooding, by which time most of the soil extractable N was NH_4^+ (Fig. 2). Presumably the NO_3^-, which had accumulated during the spring dry down, was lost due to denitrification when the field was flooded for planting (Broadbent and Tusneem, 1971; Ponnamperuma, 1972). Despite the loss of NO_3^-, total extractable soil N was about 7 mg kg^{-1} higher in the F treatments (averaged across sites, straw treatments, and sample times) during the first month of the growing season. Higher straw N availability at the start of the season as a result of winter flooding is further supported

Table 8. Rice grain yields (dry wt.) for the 1996 growing season.

Main plot	Subplot	Maxwell −N	Maxwell +N	Biggs −N	Biggs +N
		kg ha^{-1}			
Flood	burn	5 213 b†	11 455	5 886	8 835
	remove	5 052 b	10 655	6 336	8 382
	incorp	7 398 a	10 729	6 107	8 477
	roll	6 779 a	10 896	6 639	8 859
	mean	*6 111*	*10 934*	*6 242*	*8 638*
Nonflood	burn	5 060 b	10 795	6 014	8 488
	remove	4 635 b	10 839	5 831	8 132
	incorp	5 797 ab	10 265	5 694	8 076
	roll	5 048 b	10 777	5 397	8 502
	mean	*5 135*	*10 669*	*5 734*	*8 300*
ANOVA					
Flood		NS	NS	NS	NS
Straw		*	NS	NS	NS
F × S		*	NS	NS	NS

* Significance at $P = 0.05$.
† Different letters beside each subplot treatment mean indicates a significant difference ($P = 0.05$) from other means within the same main-plot treatment.

by higher PMN (Table 4) and early season N uptake (Table 6) in the F treatments at Maxwell.

The question arises as to the fate of the straw N in the NF treatments since less of it was taken up by the crop. There are two possibilities. First, in the NF treatments, during the winter flood period the soil may have gone through alternating aerobic and anaerobic phases due to rainfall and the generally poor drainage of rice soils. The result of this may have been to mineralize straw N which is converted to NO_3^- and then during the anaerobic phase the NO_3^- is denitrified (Patrick and Wyatt, 1964). Second, at Maxwell ExN is higher in the NF treatments at the end of the growing season (Fig. 2). This suggests that straw mineralization was slower in the NF treatments during the winter and growing season leaving a higher amount of straw to be mineralized at the end of the growing period. While both factors are possible, data from the litter bags (Table 3) show that decomposition was less during the winter in the NF treatments suggesting that in this case the second possibility is more likely. Also, at Maxwell, in the NF–N treatments average percent straw N concentration was lowest at the beginning of the season and higher at the end of the season compared to the F–N treatments (Table 6). This, along with higher extractable soil N values (Fig. 2) suggests that straw decomposition in the NF treatments occurred later than in the F treatments. Bird et al. (2001) reported that lower recovery of ^{15}N from straw in the initial year was balanced by an increase in soil N and crop recovery in the second year, indicating that straw breakdown and N mineralization may take a couple of years.

Availability of Straw Nitrogen as Affected by Straw Management

At the end of the 1995 growing season there was about four times more straw, and hence straw N, in the incorporate and roll treatments than in the burn and about two to three times more straw in the remove treatments than in the burn (Table 2). The relative amounts between straw treatments (averaged across F and NF treatments and sites) were similar before planting the 1996 rice crop (Table 3) but averaged about 50% less than after the 1995 harvest. Assuming that the straw N in the remaining straw is the same across straw management treatments, then there is about 20 kg ha^{-1} more N in the treatments where straw was not removed (incorporate and roll treatments) compared to the burn treatment. Early season ExN was higher in the two treatments where straw was retained than in the burn in both F and NF treatments (NF roll is an exception at both sites and this will be discussed later). This resulted in greater N uptake in the straw incorporated plots at the Maxwell site by an average of 19 kg N ha^{-1}. Increases in N uptake due to straw incorporation have also been noted elsewhere (Becker et al., 1994). Eagle et al. (2000) in an analysis of data from 5 yr at the Maxwell site reported similar findings. Interestingly however, neither in the year of this study nor in the 4-yr analysis of the Biggs site (Eagle et al., 2000) was there increased yields or N uptake due to straw management. Reasons for this are discussed below.

Seasonal Crop Nitrogen Uptake

During the first month of the growing season, ExN increased in the −N plots at both sites and in the +N plots at Biggs (in the Maxwell +N plots soil extractable N decreased slightly) suggesting that N mineralization generally exceeded crop N uptake during the first month. Crop N uptake during the first month was slow in both the −N and +N plots averaging 16 and 27 kg N ha^{-1}, respectively, across treatments and sites during the first month of growth. Following the first month, when the rice reaches mid-tillering, there is rapid growth and high N demand. Between the first and third month the crop accumulated 66% of the total N uptake in the zero N plots and 81% of total N uptake in the +N plots. In fact, in the +N plots at Maxwell, 74% of total N uptake (156 kg N ha^{-1}) was accumulated in the second month after planting (approximately 5.6 kg N ha d^{-1}). This rapid N uptake lowered the ExN in all treatments and sites to <5 mg kg^{-1} by the third sample time during crop growth (Fig. 2 and 3).

Nitrogen Immobilization

Nitrogen immobilization is a concern for growers deciding on various straw management practices. Our data indicate that N immobilization of fertilizer N did not effect crop N uptake. Bird et al. (2001) suggested that in systems that repeatedly incorporate straw, increased immobilization of fertilizer N in the soil has lead to a readily mineralizable N pool to supplement crop N needs. The NF treatments, and particularly the NF roll treatment, would have presented the greatest opportunity for immobilization as it had the most straw remaining at the end of the winter flood period at both sites (Table 3). Also, PMN before planting was lower in the NF roll treatment (Table 4) and crop N uptake from the −N plots 1 mo after sowing tended to be least in the NF roll (Table 6). However, when fertilizer N was applied there was no indication of N immobilization and reduced crop N uptake. Williams et al. (1968) reported that if rice straw N concentration was >0.54% N immobilization would not affect yields (in this case straw was applied immediately before planting). Rice straw N concentrations in this experiment averaged more than 0.74%. Although, there is the potential for N immobilization, winter flooding or incorporation of straw in the fall may have reduced immobilization, making straw N more available for crop growth (Bacon et al., 1989; Rao and Mikkelsen, 1976 and Eagle et al., 2000). Furthermore, others suggest that N fertilizer applications may stimulate straw N mineralization, thereby reducing immobilization (Sain and Broadbent, 1977; Smith and Douglas, 1971; Lueken et al., 1962).

Nitrogen Fertility Recommendations Resulting from Changes in Straw Management

Winter flooding, in combination with straw incorporation, increases early season N availability (Fig. 2). At Maxwell, N uptake was 19 kg N ha^{-1} more where straw was flooded and incorporated compared to when straw was burned. Eagle et al. (2000), based on a 5 yr analysis of the Maxwell site, reported a similar figure and recommended that N rates can be reduced by 25 kg ha^{-1} following a winter where straw was incorporated and flooded. However, crop responses differed between sites, despite similar patterns in soil N availability. At Biggs yields and N uptake were not affected by straw management in the year of this study or any other year (Eagle et al., 2000). Reasons for this are not clear but Eagle et al. (2000) suggested some possible reasons. First, and most likely, the soil had low extractable K (Table 1) and no K fertilizer was applied suggesting that the crop may have been K deficient at the Biggs site. Maximum benefits from improved N fertility will not be realized if the crop is deficient in other nutrients. Second, the lower organic matter and clay contents at the Biggs site (Table 1) may result in less N cycling and make the soil more susceptible to N losses as there would be less adsorption of N. Indeed, while soil extractable N values followed a similar pattern between treatments at both sites, at Biggs the values were lower during the spring dry down and early growing season (Fig. 2). However, these differences may have been due to poor drainage at the Biggs site resulting in greater denitrification losses during the winter and spring (discussed above). It is not possible to determine the effect of soil from this study but further research is required across a wider range of soils in order broaden the domain of these recommendations.

CONCLUSION

Rice straw management practices are changing in California and the southern USA due to various environmental and economic factors. We have shown from this study that altering straw management affects N cycling which can lead to changes in N uptake and N fertility recommendations. In particular, incorporating straw in the fall followed by a winter flood results in the best straw decomposition and increases early season soil N availability. This can lead to increased N uptake and a reduction in the recommended fertilizer N rate. However, as the results of this study suggest, the crop response to these added N inputs may vary depending on the management of other crop nutrients or soil properties.

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