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Immobilization of Fertilizer Nitrogen in Rice: Effects of Straw Management Practices

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ABSTRACT

A recent transition in rice straw management, from open-field burning to soil incorporation in combination with winter-fallow flooding, has led to uncertainty in evaluating long-term N fertility. A 2-yr field study of ^{15}N-labeled fertilizer and crop residue was initiated in the fourth year of a rice straw management trial to examine the impacts of winter flooding and straw management on N fertilizer immobilization and crop uptake. After six seasons of residue incorporation and winter flooding, no effect on total soil C or N was observed. During the fifth and sixth year of the field study, microbial biomass C and N were greater for straw incorporation than for straw burned. Microbial biomass contained a sizable portion of soil-recovered ^{15}N fertilizer after the first (23%) and second (10%) crop season of the ^{15}N study. The half-life of the ^{15}N in the biomass ranged from 0.55 to 0.87 yr. One year after ^{15}N-fertilizer application, greater recovery of ^{15}N in the soil from straw incorporation versus burning (22.2 versus 18.7%) resulted in a slight increase in residual fertilizer N recovery in grain in the second growing season of the ^{15}N study. Increased soil ^{15}N recovery 1 yr after fertilizer application in the straw incorporation treatment, however, was offset by higher grain recovery of ^{15}N in the burned treatment during the first growing season. Hence, the net result of these competing soil and plant sinks for fertilizer N led to similar ^{15}N losses after 2 yr (50.3 ± 2.2%) under burned and incorporated straw. The cumulative effects of straw incorporation resulted in greater net N mineralization, an increase in microbial biomass N, and greater recovery of ^{15}N in soil one year after application. Clearly, an active, labile N pool was formed when straw was incorporated that led to a reduction in fertilizer N dependency for rice.

IMMOBILIZATION of fertilizer and crop residue N in soil is one of the most critical aspects affecting long-term fertility in rice (*Oryza sativa* L.). The most important source of plant-available N for rice is soil organic N, representing 50 to 80% of total N assimilated by the crop (Broadbent, 1979; Mikkelsen, 1987). The relatively low fertilizer N use-efficiency in lowland rice systems compared with upland crops (40–60% recovery of applied N) has been attributed to higher losses due to denitrification and volatilization, and a greater degree of immobilization in soil (Broadbent and Nakashima, 1970; Craswell et al., 1985; Vlek and Byrnes, 1986). The mechanisms controlling immobilization of fertilizer and soil N in crop residue and their impact on long-term soil fertility are not well understood, especially in flooded rice soils. A better knowledge of the biological controls on N immobilization would enable improved utilization of N from fertilizers and crop residues.

Recently, grain producers in North America and Europe have been required to adopt alternative straw management practices, because burning has raised air pollution concerns (Ocio et al., 1991; Eagle et al., 2000). In California, soil incorporation of crop residues during the fall and shallow flooding of fields during the winter-fallow period has replaced open-field burning. These changes in straw management have prompted a reexamination of N immobization–mineralization dynamics and their effect on N fertility in rice soils. In California, rice straw production is 8 to 10 Mg ha^{-1}, and it contains 50 to 70 kg N ha^{-1} (Brandon et al., 1995). The traditional practice of burning eliminates 70 to 80% of the C and N held in the straw, crown, and roots (Hill et al., 1999). Most of the straw C and N left after burning remains in the form of noncombusted root, crown, and stubble. Consequently, the change from burning to straw incorporation and winter flooding will likely alter the cycling of C and N in soil.

Although many studies have reported the fate of added ^{15}N-labeled fertilizer N in lowland rice agroecosystems, most investigations were limited to the measurement of total fertilizer N in the plant and recovery in the soil (Patnaik and Broadbent, 1967; Patrick and Reddy, 1976; Clement et al., 1995). Few investigations have directly examined the pathways of N immobilization into the microbial biomass (Paul and Juma, 1981). We determined the effects of alternative rice straw management practices on the dynamics of N immobilization of applied fertilizer and crop residue N. ^{15}N stable isotope methodology was used to follow the turnover of added fertilizer and crop residue N in the inorganic, microbial, and total soil and plant N pools. A 2-yr study of ^{15}N fertilizer and crop residues was initiated in a 4-yr-old rice straw management experiment. Our main objective was to assess the effects of straw incorporation and winter flooding on crop N availability, microbial N use-efficiency, and the stabilization of added fertilizer-N and crop residue N in the soil. These parameters are critical to develop straw management practices that lead to an optimization of long-term N supply in flooded soils.

MATERIALS AND METHODS

Field Site

In fall 1993, winter-flood and straw management treatments were established at a 28-ha field site located on a commercial rice farm in the northern Sacramento Valley, near Maxwell, CA (USA). The soil is classified as a fine, smectitic, superactive, thermic, Sodic, Endoaquert (Willows clay). The field experiment is a split-plot design with four replications. Winter flood management (flooded vs. unflooded) is the main-plot

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Abbreviations: SMB-N, soil microbial biomass N; SMB-C, soil microbial biomass C; SOM, soil organic matter; WF, winter flooded; NF nonwinter flooded.

treatment and straw management (incorporated vs. burned) is the split-plot treatment. The four treatments are (i) burned straw and winter flooded, (ii) burned straw and nonwinter flooded, (iii) incorporated straw and winter flooded, (iv) incorporated straw and nonwinter flooded. Each of the individual plots measured 0.75 ha.

Straw management practices were implemented following grain harvest in late October 1993. The harvester-combine chopped the rice residue at a height of 7 to 12 cm above the soil surface. The rice straw remaining after harvest averaged 9.5 Mg ha^{-1}. The straw was incorporated by swathing, forage chopping, and stubble disking to a 12-cm depth. The straw was burned by ignition of dry straw with a torch. After the straw was burned, the unburned roots, crown and stubble were left undisturbed. Winter flooding to a depth of 15 cm occurs after fall tillage in November and the fields are drained in early March prior to field preparation. Traditionally, rice soils in California had only undergone submergence during the growing season and remained fallow during the rainy winter months. Unless fields are winter flooded, precipitation during the winter months results in frequent wet and dry periods. Spring tillage operations for all treatments included chisel plowing, disking, and rolling prior to flooding to 15 cm during the growing season (May–September). Fertilizer N was applied prior to aerial seeding as aqua ammonia at rates of 167 and 146 kg N ha^{-1} in 1997 and 1998, respectively. Triple-super phosphate was applied at a rate of 32 kg P ha^{-1} in both 1997 and 1998. The fields were maintained with commercial equipment and conventional weed, disease, and insect control management practices.

^{15}N Fertilizer Study

We used ^{15}N to examine the dynamics of fertilizer over a 2-yr period (May 1997–1999). Microplots (4 by 3 m) were established in each main plot prior to the fourth growing season of the field study (May 1997). Enriched urea fertilizer (9.99% ^{15}N-atom excess) was uniformly applied to the microplots at a rate of 20 kg N ha^{-1} prior to seeding in 1997. The total amount of excess ^{15}N added was 2 kg N ha^{-1}. To reduce losses of applied N during the few days prior to flooding, N-Serve 24-E [nitrapyrin: 2-chloro-6-(trichloromethyl) pyridine; Dow-Elanco, Indianapolis, IN] was applied with the N fertilizer at a rate of 0.4 L ha^{-1}. Immediately following ^{15}N application, the microplots were tilled to a depth of 12 cm. To reduce lateral flow and dilution of the applied fertilizer N, metal barriers were placed around the plot exterior to a depth of 30 cm. Additional unlabelled urea-N fertilizer was applied to the ^{15}N-microplots at a rate of 167 and 146 kg N ha^{-1} prior to planting in May 1997 and 1998, respectively.

In 1997 and 1998, straw incorporation in the ^{15}N microplots was achieved using a small-scale chopper and tiller that simulated field-scale operations; it conserved the integrity of the microplots. All other agronomic operations applied to the microplots, including annual spring tillage and fertilizer applications, utilized commercial, field-scale equipment.

Instead of burning ^{15}N-labeled straw after the first growing season of the ^{15}N study (1997), the labeled surface straw from the burned plots (straw cut 7–12 cm above the soil surface) was replaced with equivalent amounts of unlabeled rice straw from the adjacent area. The labeled roots, crowns, and stubble along with the unlabeled surface straw in the designated burned plots were then burned. The labeled straw removed from the burned ^{15}N microplots was used for an accompanying study examining the fate of straw N described below. In 1998, labeled surface straw in the burned plots was not removed and was burned.

^{15}N Straw Residue Study

We applied ^{15}N-labeled straw to new microplots to examine the fate of rice straw N. Following harvest in October 1997, the ^{15}N-labeled rice straw from the burned treatment microplots was transferred onto new ^{15}N microplots (4 by 3 m) located in the winter-flooded and unflooded incorporated plots. The labeled surface straw and unlabelled stubble, crowns and roots were incorporated as described for the labeled N fertilizer microplots. The labeled straw applied contained 51.1 kg N ha^{-1}, 3615 kg C ha^{-1}, and had a mean ^{15}N atom excess of 0.434%. The total amount of excess ^{15}N added was 0.221 ± 0.005 kg ^{15}N ha^{-1}. Agronomic operations for the new straw residue microplots were similar as described earlier for the straw management study. The labeled ^{15}N straw was followed for 1 yr . Recovery of the added ^{15}N straw in the different soil N pools was related to the total amount of ^{15}N applied straw N.

Soil Characterization

Prior to the initiation of the field study, selected physical and chemical soil properties were determined. Values were determined on soil sub-samples from a combined soil sample representing the multiple cores from the 0- to 15-cm depth (Table 1). Soil was extracted for exchangeable K, Ca, and Mg with 0.5 *M* NH_4COOH (Knudsen et al., 1982; Lanyon and Hearld, 1982) and subsequently quantified by atomic absorption/emission spectrometry. Plant-available P (Olsen P) was determined by the sodium bicarbonate method (Olsen and Sommers, 1982). Soil pH and electrical conductivity (EC) were measured as a saturated soil paste (Richards, 1954). Soil cation exchange capacity (CEC) was determined by barium acetate saturation and calcium replacement (Janitzski, 1986). Soil particle size distribution was measured in soil suspension by the hydrometer method (Gee and Bauder, 1979). Total soil C and N were measured with a CHN gas analyzer (Nelson et al., 1982). Soil chemical data listed in Table 1 are expressed as concentrations, as soil bulk density was not measured in 1993.

Soil samples (15 cm) were collected from the microplots with an intact core sampler (5-cm diam) that allowed for bulk density determinations. During 1997 to 1999, three soil cores per microplot were collected every 2 to 4 mo and analyzed separately for soil C and N. Soil cores were stored field-moist at 4°C in capped, butyrate plastic tubes and subsampled within 7 d for extractable inorganic N and microbial biomass C and N. Large visible pieces of crop residue (>2 mm) were removed from the soil prior to analyses. For the determination of total soil N and C, the remaining soil was air-dried to a constant weight at 40°C; it was then ground with a ball-mill to pass a 250-μm sieve. In May 1999, soil cores (5-cm diam.) to 90 cm were collected from each microplot for the determination of total soil C, N, and ^{15}N. These deep soil cores were separated into three depth increments (15–30, 30–60, and 60–90 cm) to follow the movement of the labeled N fertilizer through the profile at the end of the 2-yr ^{15}N study. Soil clods were excavated from the face of 1-m deep pits at each of the three lower depth intervals (15–30, 30–60, and 60–90 cm) for bulk density determination by the saran resin-coated clod method (Brasher et al., 1966).

Microbial biomass C and N were determined by a modified version of the chloroform-fumigation incubation method (10-d chloroform period on saturated soil, Horwath and Paul, 1994). Soil microbial biomass C (SMB-C) was calculated without use of the control and adjusted by a K_C value of 0.41 (Voroney and Paul 1984; Horwath et al., 1996). Soil microbial biomass N (SMB-N) was calculated after subtracting the initial extractable soil NH_4^+. SMB-N values were adjusted by a K_N value of

Table 1. Selected soil chemical and physical properties at the study site. Soil samples and values expressed are unadjusted for soil bulk density (October 1993).

Soil property 0- to 15-cm depth											
pH	EC	C	N	Olsen - P	Exchangeable-K	Mg	Ca	CEC	sand	silt	clay
	dS m^{-1}	g kg^{-1}		mg kg^{-1}		cmol kg^{-1}			g kg^{-1}		
6.6	1.4	19.5	1.65	11.3	305	0.21	0.16	42	50	440	510

0.57 (Jenkinson, 1988). Carbon dioxide concentrations evolved at the end of the 10-d incubation of the microbial biomass samples were measured with an infrared gas analyzer.

Field moist soil subsamples were extracted with 2 *M* KCl for exchangeable inorganic N (5:1 extractant:dry soil ratio). Inorganic N was quantified colorimetrically with an automated N analyzer (LACHAT, Mequin, WI) (Keeney and Nelson, 1982). Gravimetric water content was determined by drying soil subsamples at 105°C for 24 h. Total soil C and N were measured as previously described. For ^{15}N analysis, inorganic N and microbial biomass extracts were diffused onto Whatman DF/A filter paper by the teflon filter-pack method on the basis of Stark and Hart (1996). The ^{15}N content of total soil N, extractable inorganic NO_3^- and NH_4^+ and microbial biomass N was determined on a Europa Scientific Integra Mass Spectrometer (PDZ Europa Ltd., Crewe, UK). Soil C and N determinations are expressed on a volumetric basis for data gathered from 1997 to 1999. All soil determinations are expressed on a dry soil basis.

Plant Analyses

In 1997 and 1998, rice plant samples were collected from the ^{15}N-microplots by cutting plants just above the soil surface in two 0.25-m^2 quadrats. Grain and straw dry matter were determined after drying samples until constant weight at 60°C and separating into grain and straw biomass. Dried straw subsamples were ground using a Wiley mill fit with a 2-mm screen; grain and straw subsamples were ball milled to pass a 250-μm sieve. Total C, N, and ^{15}N content were determined as previously described. All plant determinations are expressed on a dry-matter basis.

Statistical Analysis

Main effects of winter flooding and straw management were tested by a general linear model (GLM) designed for the split-plot design. The winter flooding × replicate mean square error (3 df) was used as the error term in the GLM for the winter flooded versus the no winter flood treatments (1 df). The replicate × winter flood × straw management mean square error (6 df) was used as the error term in the GLM for the burned versus incorporated straw treatment (1 df) and the winter flood × straw management interaction (1 df). All data are expressed as least squares means with standard errors of indicated treatments. *F* statistics and *P* values are indicated in text and tables for all GLM procedures. A significance level of $P < 0.05$ was set a priori as the α-level; and *P* values were specified between 0.05 and 0.20 in tables and text to facilitate data interpretation. *P* values greater than 0.20 are indicated simply as NS (nonsignificant) in the tables. Adjusted Bonferroni t-tests were performed between soil inorganic N and microbial biomass N data to compare ^{15}N atom excess values on specific sample dates. The kinetic parameters of S_o (initial substrate concentration) and *k* (decay rate) for microbial biomass fertilizer recovery were derived by fitting the recovery of ^{15}N fertilizer as SMB-^{15}N to a single exponential model (Eq. [1]).

$$\mathrm{SMB} - {}^{15}\mathrm{N}\ (\mathrm{S_t}) = S_o \times e^{-\mathrm{kt}} \qquad [1]$$

Time is expressed in years. Kinetic parameters were derived for each plot ($N = 16$) by the Non-linear procedure in SYSTAT version 7.0 (1997, SPSS Inc., Chicago, IL). Parameters from each plot were then used to test main effects by GLM procedures described previously. Means and standard errors of S_o and *k* for each treatment ($N = 4$) are presented. All statistical tests were performed using SYSTAT version 7.0.

RESULTS

Total Soil C and N

After six seasons of straw management, neither straw incorporation nor winter flooding significantly affected total soil C and N contents in the top 15-cm soil depth: 25.9 ± 0.4 Mg C ha^{-1} and 2.07 ± 0.03 Mg N ha^{-1} (averages across treatments). Total soil C and N in the 15- to 90-cm profile also were similar among treatments: 70.1 Mg C ha^{-1} and 6.63 Mg N ha^{-1} (averages across treatments).

Total fertilizer ^{15}N recovery in the 0- to 15-cm soil depth was similar among treatments during the first growing season of the ^{15}N fertilizer study and averaged 29% at crop maturity in August 1997 (Fig. 1). Following rice harvest in 1997, soil recovery of applied fertilizer ^{15}N increased in all plots 14 d after straw incorporation and burning. In May 1998, fertilizer ^{15}N recovery in the soil after the winter fallow period was greater when straw was incorporated compared with the amount of ^{15}N recovered with straw burned ($F = 5.68$; $P = 0.054$). From that applied in May 1997, the amount of residual ^{15}N fertilizer recovered in the soil averaged 14.9% after the 1998 growing season (September) and 14.1% after the second winter fallow season (May 1999). Although more ^{15}N in the soil 0- to 15-cm depth was recovered after 2 yr (May 1999) when straw was incorporated, this difference was not statistically significant ($F = 1.99$; $P = 0.208$). Winter flooding did not affect total ^{15}N recovery in the top 15-cm of the soil during the 2-yr ^{15}N-study period.

Two years after application, fertilizer N loss from the soil (0- to 90-cm depth)-plant system was not significantly different among treatments and averaged 50.3 ± 2.23% across treatments (Table 2). Averaged across treatments, recovery of fertilizer ^{15}N in grain was 25.6% in 1997 and 2.1% in 1998 (Table 2; Eagle, 2000). In 1997, significantly less fertilizer N was recovered in grain in incorporated treatments than in burned treatments ($F = 26.5$; $P = 0.014$). However, in 1998, grain recovery of residual fertilizer N was slightly higher when straw was incorporated ($F = 4.5$; $P = 0.078$). Total soil recovery of fertilizer N to 90 cm, measured 2 yr after application (May 1999), was not significantly different among treatments (Table 2). Below 15 cm, the recovery of soil ^{15}N was higher when fields were not winter flooded

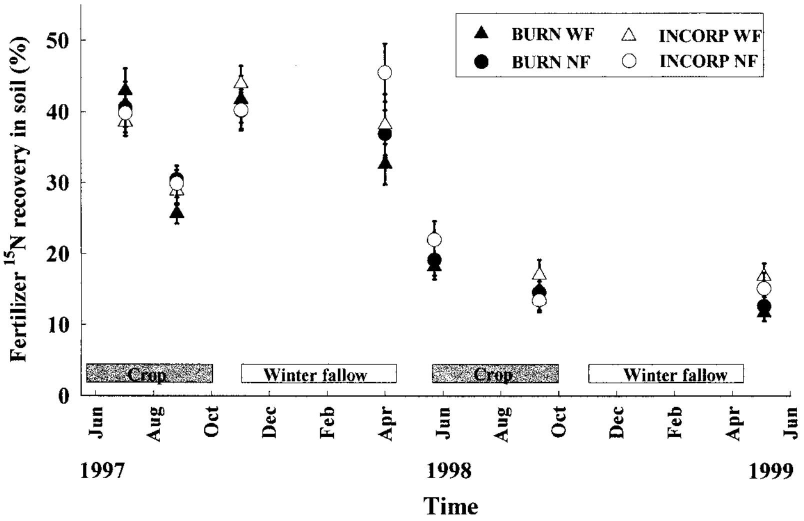

Fig. 1. Percent soil ^{15}N fertilizer recovery over a two year period (1997–1999) in the 0- to 15-cm soil depth when straw was incorporated or burned and the fields were winter-flooded (WF) or nonwinter flooded (NF). Two kg ^{15}N ha^{-1} was added prior to planting in May, 1997. All treatments were flooded during the cropping season while only the winter flooded treatments were flooded during the winter fallow period. Least-squares means, standard errors (N = 12).

(40% of 0–90 cm) than when winter flooded (20% of 0–90 cm) (F = 7.0; P = 0.078, Table 2). After 2 yr (May 1999), these differences in total soil ^{15}N recovery between fields that were winter flooded or not were mainly due to the recovery of ^{15}N in the 15- to 30-cm depth. Recovery of ^{15}N in the soil was similar among treatments in the 30- to 60- and 60- to 90-cm depths and averaged 3.2% of applied fertilizer ^{15}N for the 30- to 90-cm depth.

The ^{15}N-labeled rice straw applied in October 1997 contained 51.1 kg N ha^{-1}, which corresponded to 11.0% of applied fertilizer ^{15}N. Recovery of straw-^{15}N in the soil (0–15 cm) was 39% during spring dry-down period (April 1998) and declined to 19.9% just prior to planting in May 1998. Recovery of straw ^{15}N in the soil was not affected by winter flooding. The amount of straw ^{15}N recovered prior to planting (May 1998) in the straw-only microplots (0.043 ± 0.004 kg ha^{-1}) represented 62% of the difference observed between incorporated and burned ^{15}N fertilizer microplots (i.e., incorporated plots sequestered 0.069 kg ha^{-1} more ^{15}N than burned in May 1998).

Soil Extractable Inorganic N

Inorganic N (NO_3^- and NH_4^+) during the 2-yr ^{15}N study was relatively low and ranged from 25.4 to 1.5 kg N ha^{-1} (Fig. 2). Ammonium was the dominant inorganic N form extracted during flooded periods. Nitrate was present at amounts greater than 0.2 kg N ha^{-1} during the seasonal dry periods in the fall (November), spring (May) and winter (nonwinter flooded) and was the dominate form of inorganic N only at preplanting (May 1998 and 1999). Highest inorganic N values were observed during mid-season in July 1997 and prior to planting in May 1998 and 1999. Compared with nonwinter-flooded conditions, inorganic N contents increased under winter

Table 2. Total soil and plant ^{15}N-fertilizer recovery as affected by incorporated or burned straw, winter flooding and nonwinter flooding fields after two years (May 1999). Prior to planting in May 1997, 2 kg ^{15}N ha^{-1} was added. Least-squares means, standard errors (N = 4) except soil 0- to 15-cm depth (N = 12).

	Fertilizer ^{15}N recovery			
N pools	Burn Winter flooded	Burn Nonwinter flooded	Incorporated Winter flooded	Incorporated Nonwinter flooded
	%			
	Soil			
Soil pre-plant 1999				
0- to 15-cm depth	11.8 (1.7)	12.7 (2.2)	16.9 (2.2)	15.2 (2.4)
15- to 30-cm depth	1.6 (1.5)	8.0 (1.9)	1.5 (0.2)	7.3 (3.4)
30- to 60-cm depth	0.7 (0.2)	2.4 (1.2)	1.9 (0.5)	2.5 (1.0)
60- to 90-cm depth	1.1 (0.3)	1.5 (0.3)	1.5 (0.4)	1.2 (0.1)
Total soil (0–90 cm)	15.2 (1.1)	24.6 (5.0)	21.8 (2.1)	26.2 (2.6)
	Grain			
Grain 1997–1998				
Grain 1997	26.7 (1.6)	28.4 (1.3)	26.2 (1.9)	21.2 (1.6)
Grain 1998	1.7 (0.4)	1.9 (0.3)	2.9 (0.6)	2.0 (0.3)
Total 1997 and 1998	28.4 (1.5)	30.3 (1.5)	29.1 (1.8)	23.2 (1.8)
	Loss			
Total loss 1997–1999	56.4 (2.8)	45.1 (6.4)	49.1 (2.6)	50.6 (4.3)

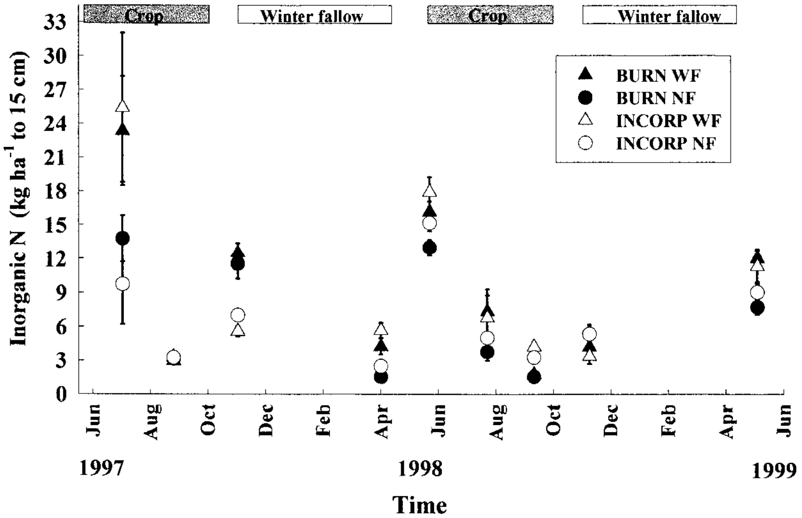

Fig. 2. Extractable inorganic N (NO_3^- and NH_4^+) over a two year period (1997–1999) in the 0- to 15-cm soil depth when straw was incorporated or burned and the fields were winter-flooded (WF) or nonwinter flooded (NF). All treatments were flooded during the cropping season while only the winter flooded treatments were flooded during the winter fallow period. Least-squares means, standard errors (*N* = 12).

flooded conditions when straw was burned and incorporated (Fig. 2). Increases in inorganic N due to winter flooding occurred prior to the growing season (May) in both years of the fertilizer study compared with nonwinter flooded (Table 3). Additionally, winter flooding led to significantly higher inorganic N levels during mid-season (July 1997) and prior to the winter fallow in November 1998. Two weeks after straw incorporation in November 1997, inorganic N in incorporated plots was less than the inorganic N content in the soil when burned. In November 1998, both burned and incorporated treatments had low inorganic N contents. Slightly greater inorganic N was present in the top 15 cm of soils in incorporated plots versus burned prior to planting (May 1998) and during the growing season in September 1998 (Fig. 2).

Initial ^{15}N enrichment of NH_4^+, measured at mid-season of 1997, was similar among treatments: 0.378 ± 0.031% ^{15}N atom excess. In July 1997, more ^{15}N was recovered as inorganic N under winter-flooded conditions (3.8% of applied ^{15}N) than under nonwinter-flooded conditions (2.1% of applied ^{15}N). The majority of recovered fertilizer ^{15}N in the soil 60 d. after application of ^{15}N fertilizer was in the organic form (89.9%). Four months following the straw incorporation in year one of the fertilizer study (April 1998), ^{15}N enrichment of inorganic N in all treatments was similar and declined during the following growing season (Fig. 3). Winter flooding increased the recovery of ^{15}N fertilizer in the inorganic N pool in May 1998 with 1.1% in incorporated treatments and 0.8% in burned ($F = 230.0$; $P < 0.001$). With the exception of September 1998, straw incorporation had little effect on fertilizer ^{15}N in the inorganic N pool during cropping. At the end of the 1998 growing season (September 1998), less than 1% of the ^{15}N recovered in the soil was in the inorganic N pool; 2 yr after ^{15}N application (May 1999), 2.2% of the ^{15}N fertilizer recovered was inorganic N in the top 15 cm of soil.

Microbial Biomass C and N

A consistently larger SMB-N pool was observed when straw was incorporated than when burned; this effect persisted throughout the period of the ^{15}N study (August 1997–May 1999) (Fig. 4a–b and 5; $P < 0.05$). However, no difference was found in SMB-N content between burned and incorporated treatments during mid-season in July 1997. The SMB-C was always significantly greater when straw was incorporated than when burned during the ^{15}N study ($P < 0.05$). The C:N ratio of the microbial biomass, averaged across treatments, ranged from a low of 4.8 ± 0.2 during mid-season (July 1998) to 7.7 ± 0.2 at preplant in May 1999 (Fig. 4c). No consistent seasonal fluctuations in the SMB-N, C or C:N ratio were observed over the 1997 to 1999 sampling period. With one exception for mid-season in July 1997, winter flooding had no effect on SMB-N or SMB-C.

The ^{15}N recovery in the SMB-N was greatest approxi-

Table 3. Significance of winter flooding and straw incorporation on soil inorganic N, 1997–1999 (0- to 15-cm depth).

		Inorganic N (NH_4^+ and NO_3^-)								
Effect	**F statistic/ P value**	**1 July**	**25 August**	**4 November**	**1 April**	**22 May**	**23 July**	**11 September**	**11 November**	**3 May**
Straw (S)	**F**	**<0.1**	**0.2**	**37.1**	**3.3**	**6.9**	**1.5**	**61.2**	**0.3**	**0.1**
	P	**NS**	**NS**	**<0.001**	**0.121**	**0.039**	**NS**	**<0.01**	**NS**	**NS**
Winter flood (WF)	**F**	**12.7**	**<0.1**	**1.6**	**9.9**	**9.3**	**1.0**	**3.7**	**29.8**	**24.3**
	P	**0.038**	**NS**	**NS**	**0.052**	**0.055**	**NS**	**0.148**	**0.012**	**0.001**
WF × S	**F**	**0.3**	**<0.1**	**1.6**	**0.2**	**<0.1**	**1.5**	**0.1**	**0.3**	**1.2**
	P	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**

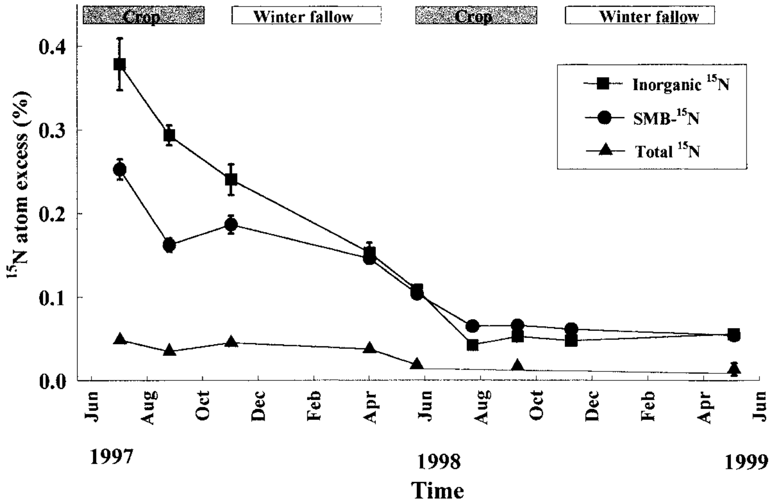

Fig. 3. ^{15}N atom excess values (%) of soil inorganic N (NO_3^- and NH_4^+), soil microbial N and total soil N, 1997 to 1999 (0- to 15-cm depth). Least-squares means, standard errors ($N = 48$, average of all treatments). Zero ^{15}N atom excess (%) represent natural abundance measured in adjacent main plots. All treatments were flooded during the cropping season while only the winter flooded treatments were flooded during the winter fallow period.

mately 60 d after fertilizer application (July 1997) and declined during the remainder of the 2-yr fertilizer study (Fig. 5). During the first growing season after ^{15}N-fertilizer application (July–September 1997), the ^{15}N enrichment of the SMB-N was initially lower than the inorganic N pool (Fig. 3). By April 1998, both the SMB-N and inorganic N pools had similar ^{15}N atom excess values. Following ^{14}N-fertilizer application in the spring 1998 (May), the ^{15}N-atom excess of the SMB-N was greater than the ^{15}N-atom excess of extractable inorganic N pool in July 1998 at mid-season ($t = 5.98$; $P < 0.001$) and in November 1998 ($t = 4.86$; $P < 0.001$). Two years after ^{15}N-fertilizer application (May 1999), both SMB-N and inorganic N had similar ^{15}N-atom excess values.

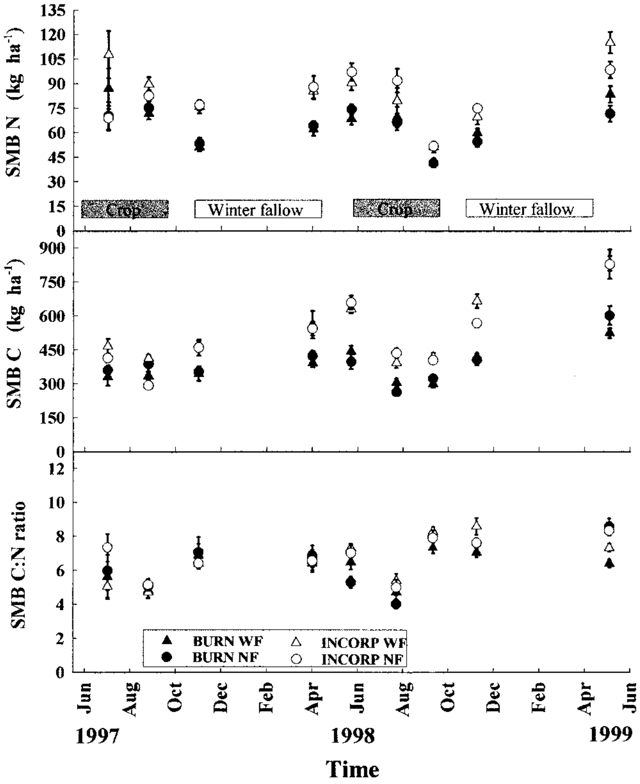

Fig. 4. Effects of winter flooding (WF), nonwinter flooding (NF) and straw incorporation on soil microbial biomass N (top), C (center) and C:N ratio (bottom) in the 0- to 15-cm depth, 1997 to 1999. All treatments were flooded during the cropping season while only the winter flooded treatments were flooded during the winter fallow period. Least-squares means, standard errors ($N = 12$)

Over the 2-yr ^{15}N-fertilizer study, no significant differences were detected among straw management treatments for the ^{15}N-atom excess values of the SMB-N (data not shown). In July 1997, 22.8% of the N in the microbial biomass was from the N fertilizer. At this stage, winter flooding led to an increase in the recovery of fertilizer-N in the SMB-N as compared with nonwinter flooding: 12.1 ± 1.3% and 8.5 ± 0.6%, respectively ($F = 9.4$; $P = 0.054$). Initial amounts of ^{15}N immobilization were similar when straw was incorporated or burned in July and August 1997. In fall (November 1997) and spring (May 1998), the recovery of SMB-^{15}N was greater when straw was incorporated than when burned (fall: $F = 4.0$; $P = 0.093$; spring: $F = 12.0$; $P = 0.013$). Four months after ^{15}N-fertilizer application (September 1997), about one-quarter of the ^{15}N remaining in the soil was immobilized in the SMB-N. Averaged across treatments, the percentage of ^{15}N-fertilizer in the soil that was present in the SMB-N decreased to 10% in September 1998 and became 18.8% 2 yr after ^{15}N fertilizer application (Table 4). Overall, during the second growing season of the ^{15}N-fertilizer study (1998) the amount of ^{15}N in the microbial biomass was not affected by straw management.

To estimate the initial ^{15}N concentrations (S_o) in the SMB-N, and the decay rates (k) for each of the four treatments, the amounts of SMB-^{15}N over the 2-yr period (1997 to 1999) were fit to a single exponential decay function: SMB-^{15}N $= S_o \times e^{-kt}$ (Table 5). When fields were winter-flooded, a slightly greater predicted value

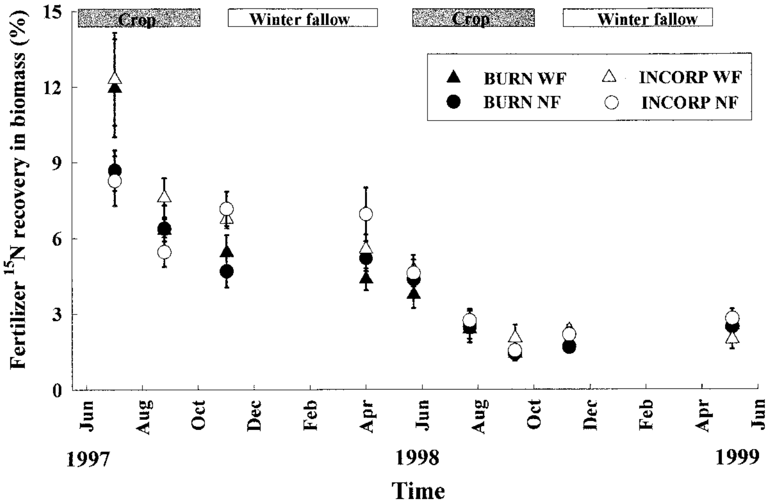

Fig. 5. Percent soil microbial immobilized ^{15}N fertilizer recovery over a two year period (1997–1999) in the 0- to 15-cm soil depth when straw was incorporated or burned and the fields were winter-flooded (WF) or nonwinter flooded (NF). Two kg ^{15}N ha^{-1} was added prior to planting in May, 1997. All treatments were flooded during the cropping season while only the winter flooded treatments were flooded during the winter fallow period. Least-squares means, standard errors ($N = 12$).

for S_o in the SMB-^{15}N was found than when not winter-flooded ($F = 6.8$:$P = 0.079$). A faster turnover rate and half-life of SMB-^{15}N ($F = 5.7$: $P = 0.097$) was observed in winter-flooded fields. Incorporating or burning straw led to similar half-lives of SMB-^{15}N (0.55–0.87 yr).

DISCUSSION

Soil C and N Cycling

SOM dynamics over a relatively short period of time are difficult to measure as changes in total soil C and N due to large background amounts of stable organic matter already present (Gregorich, 1994). Similar results are seen in our study. To assess these effects better, researchers have suggested focusing on smaller and more active, labile C and N organic matter pools that are important in nutrient cycling (Haynes, 2000). Repeated straw incorporation resulted in an increase in SMB-N and greater fertilizer ^{15}N immobilization during the first year following fertilizer application. This additional ^{15}N fertilizer was retained in the soil when straw was incorporated and utilized by the subsequent crop.

In this study, straw incorporation increased plant available soil N supply compared with straw burning after the straw was incorporated for 3 yr (Eagle et al., 2000). When rice was grown without any additional fertilizer-N in annual trials, grain yield and total N accumulation almost doubled when straw was incorporated. This effect of yield and N uptake was seen annually after the third season of treatments (Eagle et al., 2000). Additionally, in the absence of N fertilizer, winter-flooded treatments with straw retained resulted in greater yields and N uptake than those not winter flooded with straw retained in Years 3 and 4 of the field study. However, no yield effect was seen at optimum N fertilizer levels among all treatments through Year 6 (Eagle et al., 2000).

Studies directly examining the long-term effects of application of straw compared with burning have reported both positive and negative effects on soil N accumulation, plant-N availability, and yields under tropical conditions. Comparing 5 yr of straw incorporation compared with straw burning, a slightly higher soil organic C, greater inorganic N levels and increased wheat and rice yields were observed (Verma and Bhagat, 1992). In contrast, Beri et al. (1995) reported a yield decline during an 11-yr field study when straw was incorporated even though total soil N increased. Beri et al. (1992) attributed this yield reduction to low available N because this decline was reversed after straw incorporation ceased. While the yield constraints in these studies from the tropics are likely different than under the temperate climate found in California, it appears that long-term straw incorporation can play an active role in providing greater amounts of plant-available N.

Inorganic N in winter-flooded soil was higher than in

Table 4. Recovery of fertilizer N in the microbial biomass and inorganic N pools as a percentage of soil immobilized fertilizer N over two years (1997–1999). Least-squared means, standard errors ($N = 48$).

	Recovery of soil immobilized fertilizer	
Sample date	Microbial immobilized ^{15}N	Inorganic ^{15}N
	%	
September 1997	24.5 (1.3)	1.6 (0.1)
May 1998	23.0 (1.7)	4.3 (0.3)
September 1998	9.7 (0.6)	0.6 (0.1)
May 1999	18.8 (1.2)	2.2 (0.1)

Table 5. Initial SMB-^{15}N concentrations (So), decay rates (k), and half-lives of soil microbial biomass ^{15}N over the two-year period calculated using the equation SMB-$^{15}N = S_o \times e^{-kt}$ under alternative straw management practices.

Residue management treatment		Regression parameters		
		S_o	k	$t_{1/2}$
		kg ^{15}N ha^{-1}	yr^{-1}	yr
Burn	Winter flooded	0.238 (0.023)	1.26 (0.182)	0.550
Burn	Nonwinter flooded	0.189 (0.021)	0.96 (0.096)	0.719
Incorporated	Winter flooded	0.273 (0.051)	1.19 (0.195)	0.580
Incorporated	Nonwinter flooded	0.188 (0.021)	0.80 (0.125)	0.871

nonwinter-flooded soil prior to planting, and during the growing season. The large amounts of inorganic N present during July 1997 may be due to the higher N fertilizer rates used in 1997 compared with 1998 when N rates were decrease to more accurately meet crop demand. The increase in inorganic N in winter-flooded plots may occur because of the lower N requirement of anaerobic heterotrophs (Acharya, 1935). While most of the differences in inorganic N due to winter flooding were generally small, they may play an important role in plant N nutrition when inorganic N is limiting. Our results indicate greater available N in the both burned and incorporated winter flooded treatments compared with the respective nonflooded treatments.

Straw incorporation, compared with burning, resulted in lower inorganic N in November 1997, thereby conserving N likely to be lost over the winter fallow period. This straw management effect was not observed in November 1998 when inorganic N amounts were low in all treatments. No effect of straw incorporation on inorganic N in November 1998 suggests that N immobilization was occurring in both incorporated and burned straw management treatments. Additionally, straw incorporation increased inorganic N levels in 1998 during the spring and growing season suggesting the release of immobilized N to the crop. The effects of straw incorporation on inorganic N are consistent with other work that showed a brief period of N immobilization followed by a subsequent increase in N mineralization (Rule et al., 1991; Nishio et al., 1993).

Sustained, higher SMB-N and SMB-C were observed after 4 yr of straw incorporation. Changes in the C content of the microbial biomass have been promoted as an early indicator of changes in the soil organic matter status and fertility from long-term in situ straw incorporation studies (Powlson and Jenkinson, 1981). Laboratory investigations using continuous applications of rice straw compared with straw removal, showed temporal increases in SMB-N and SMB-C, which in general, declined over time (Azmal et al., 1997; Devêvre and Horwath, 2000). Continuous applications of crop residues appear to be necessary to sustain higher SMB-N and SMB-C (Sørenson, 1987; Dalal et al., 1990). Long-term incorporation of straw (18 yr) showed greater SMB-N (50 and 46%) and SMB-C (45 and 37%) than when barley straw was burned (Powlson et al., 1987). For these reasons, the greater sustained microbial biomass levels in incorporated plots compared with burned suggest a larger active C and N pool.

^{15}N Fertilizer and Straw Residue Dynamics

The use of ^{15}N-labeled fertilizer during the fourth and fifth year of the field study enabled us to follow the fate of fertilizer N as affected by changes in rice residue management implemented in 1993. As expected, soil microbial biomass and inorganic N pools were the most enriched soil N pools; however, the size of these pools were small illustrating their dynamic nature. At the time of maximum plant N uptake following ^{15}N addition (July 1997), most of the fertilizer N remaining in the soil was organic (90%). In September 1997, grain uptake of fertilizer N was greater in the burned plots than incorporated, whereas total grain-N uptake (fertilizer and native soil N) was similar among treatments (Eagle, 2000). These results suggest that in incorporated plots, there was greater immobilization of fertilizer N by the soil microbial biomass with a concurrent greater mineralization of native soil N. However, our results also show similar amounts of fertilizer N in microbial biomass and inorganic N pools in the incorporated and burned treatments at both sampling times during the first growing season after ^{15}N application. Therefore, the net result is a greater loss of fertilizer N from the incorporated treatments than the burned by the end of the 1997 growing season. This loss was offset by greater fertilizer N retained in the soil after fall straw incorporation in May 1998 in incorporated plots compared with burned.

Straw incorporation resulted in greater total soil recovery (0–15 cm) of fertilizer N prior to planting 1 yr after ^{15}N application (May 1998), and more ^{15}N as available N in September 1998. Similarly, grain uptake of residual fertilizer N in 1998 was slightly greater in incorporated plots than in burned (Table 2; Eagle, 2000). Increased retention of N in the incorporated plots contributed to increased plant-N availability in the second crop cycle of the fertilizer ^{15}N study. Results from the additional microplot study, assessing the contribution of straw-N to immobilization of fertilizer N, suggest that slightly more than half (62%) of the increase in total ^{15}N immobilization in incorporated plots over the burned in May 1998 was due to fall incorporated straw. These results suggest a significant contribution of the unburned straw stubble-N and root-N to soil N immobilization over the winter fallow period in incorporated plots. This may be due to the incorporation of straw in the top 15 cm of the soil compared with the no-till winter fallow in burned plots.

Our results support the active role of the microbial biomass in competing for added fertilizer in flooded rice soils in all rice straw management systems evaluated here. Microbial biomass accumulated 23% of its N with fertilizer N by mid-season (10.2% of added fertilizer). Similar findings were reported from a field study with wheat where microbial biomass accounted for 30% of the N retained in the soil (18.1% of added) at the end of the first growing season (Paul and Juma, 1981). The large amount of N immobilized by the soil microbial biomass in our study may be due to a preference for the dominant form of inorganic N (NH_4^+) by heterotrophic bacteria found in flooded soils and the lower loss potential of NH_4^+ compared with NO_3^- (Jenkinson et al., 1985). In addition, the larger microbial biomass in the straw incorporated plots led to an increase in N immobilization. For these reasons, our study emphasizes the importance of soil microbial biomass in controlling fertilizer N sequestration and subsequent availability in flooded rice soils in California. Overall, the long-term effects of a greater biomass along with a larger organic soil N additions appear positive because greater N immobilization of fertilizer N in the incorporated plots was more than offset by greater remineralization of previously immobilized and native soil N.

The turnover of immobilized fertilizer N in microbial biomass was described by first-order decay model 2 yr following fertilizer application. However, the first-order model poorly accounted for the pulse of ^{15}N entering the microbial biomass as straw-N in the fall. The calculated half-lives of 200 to 300 d for immobilized ^{15}N in the soil microbial biomass are similar to those reported by Paul and Juma (1981). They calculated a half-life of 180 d for N immobilized in the microbial biomass during a laboratory incubation of ^{15}N-labeled soil after one growing season. As expected the rate of turnover of ^{15}N immobilized by the soil microbial biomass was faster than the total loss of ^{15}N from the soil, illustrating the stability of more than 50% of the immobilized ^{15}N in soil organic matter pools.

The turnover of assimilated fertilizer N in crop residues is evident in the large increase in soil ^{15}N enrichment from crop maturity to late fall (November 1997) regardless of treatment. Much of the straw at this time was not decomposed and was present in large pieces ($>$2 mm). Therefore, the most likely sources of this steep increase in recovered fertilizer N in the soil were N released from straw and root turnover. Although not measured directly, turnover of ^{15}N immobilized by algae may have contributed to this steep increase in enrichment in the fall after drainage. Floodwater algae have been found to immobilize up to 40% of ^{15}N-labeled urea applied to greenhouse pots (Vlek et al., 1980).

The total ^{15}N budget 2 yr after ^{15}N fertilizer application shows no significant differences in N losses, and about half of the applied ^{15}N was unaccounted for across all treatments in the plant-soil system. Most studies report ^{15}N recovery and losses at the end of the first cropping season resulting in few examples of losses after one or 2 yr of cropping and fallow (Vlek and Byres, 1986). Our fertilizer ^{15}N loss from the plant-soil (0–15 cm) system after one season (August 1997) averaged 35.8% across treatments. Similar losses were reported for urea (25–30%) in rice (Craswell et al., 1985; Bronson et al., 2000). The two most significant periods of potential N loss from the soil-plant system occur during the spring tillage operation and just after application of the fertilizer. Following the fertilizer application, all treatments were flooded for the growing season. During this initial crop growth period, a rapid and large amount of applied N can be lost the via denitrification and volatilization processes (Vlek and Byrnes, 1986). During the spring, drying, tillage, and higher temperatures increase N mineralization and the conversion of NH_4^+ to NO_3^-, which will subsequently be lost during dry-down and upon subsequent flooding. A higher amount of ^{15}N fertilizer recovered in the subsoil (15- to 90-cm depth) in the nonwinter flooded plots compared with winter-flooded at the end of 2 yr (May 1999), suggests that greater denitrification activity (especially in the 15- to 30-cm depth) may be present in winter-flooded subsoils. This trend observed in the subsoil N loss due to winter flooding, however, was not apparent in the topsoil over the 2-yr period (1997–1999). While the overall loss fertilizer N after 2 yr, considered alone, reveals little information about the effects of straw management practices on fertilizer N utilization, the flux of N through the biomass, inorganic-N, and plant-N pool suggests that a labile pool of available N has been produced with 4 to 6 yr of straw incorporation compared with burned. This soil N pool is released during crop growth and offsets the lower fertilizer- N use efficiency of rice observed in incorporated plots during Year 1.

CONCLUSIONS

The utility of our results in assessing the long-term increase in the supply of soil N to rice must be considered in the context of the effects of many years of fertilizer and straw applications. Our findings suggest that rice systems in California utilizing repeated straw incorporation, benefit through a greater active and available soil N fraction sustained through repeated straw additions. This biological change was evident in the persistently larger SMB-N and SMB-C after 4 yr of straw incorporation compared with the burned straw treatment. Over time, increased immobilization of fertilizer N in the soil, via plant residues and microbial turnover, appears to have built up a pool of readily mineralizable N that has supplemented a portion of crop N needs. Compared with incorporating straw, burning the straw led to an increase in grain N-fertilizer recovery in the year the fertilizer was applied. The lower recovery of fertilizer-N accumulation in the crop in incorporated plots was balanced by an increased N recovery in the soil in the spring of the following year and a small increase in ^{15}N recovery in grain in the second growing season. The net result of these competing soil and plant sinks for added N fertilizer resulted in similar losses of fertilizer N from the plant-soil systems after 2 yr of cropping for all straw management treatments examined. Recovery of fertilizer N in the surface soil (0–15 cm) was slightly greater when straw was incorporated suggesting that many years of straw incorporation may improve N fertility compared with burning. Our results are consistent with yields from unfertilized (0-N) yield trials showing enhanced N uptake after 3 yr of straw incorporation compared with burned (Eagle et al., 2000). These findings suggest that the active, labile N pools increase when straw is incorporated for 4 to 6 yr compared with burning. Consequently, a reduction in the rate of fertilizer N application should be warranted.

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REFERENCES

Acharya, C.N. 1935. Studies on the anaerobic decomposition of plant materials: III. Comparison of the course of decomposition of rice straw under anaerobic, aerobic, and partially aerobic conditions. Biochem J. 29:1116–1120.

Azmal, A.K.M., T. Marumoto, H. Shindo, and M. Nishiyama. 1997.

Changes in microbial biomass after continuous applications of azola and rice straw in soil. Soil Sci. Plant. Nutr. (Tokyo) 43:811–818.

Beri, V., B.S. Sidhu, G.S. Bahl, and A.K. Bhat. 1995. Nitrogen and phosphorous transformations as affected by crop residue management practices and their influences on crop yield. Soil Use Manage. 11:51–54.

Brandon, D.M., S. Brouder, D. Chaney, J.E. Hill, J.M. Payne, S.C. Scardaci, J.F. Williams, and J.E. Wrysinski. 1995. Rice Straw management today and tomorrow. University of California Cooperative Extension Publication, University of California, Davis, CA.

Brasher, B.R., D.P. Franzmeier, V. Valassis, and S.E. Davidson. 1966. Use of saran resin to coat natural clods for bulk density and water retention measurements. Soil Sci. 101:108–110.

Broadbent, F.E., and T. Nakashima. 1970. Nitrogen immobilization in flooded soils. Soil Sci. Soc. Am. Proc. 34:218–221.

Broadbent, F.E. 1979. Mineralization of organic nitrogen in paddy soils. p. 105–117. *In* Nitrogen and rice. International Rice Research Institute (IRRI). Los Baños, Philippines.

Bronson, K.F., F. Hussain, E. Pasuquin, and J.K. Ladha. 2000. Use of ^{15}N-labeled soil in measuring nitrogen fertilizer recovery efficiency in transplanted rice. Soil Sci. Soc. Am. J. 64:235–239.

Clement, A., J.K. Ladha, and F.-P. Chalifour. 1995. Crop residue effects on nitrogen mineralization, microbial biomass, and rice yield in submerged soils. Soil Am. Sci. Soc. J. 59:1595–1603.

Craswell, E.T., S.K. De Datta, C.S. Weerarantne, and P.L.G. Vlek. 1985. Fate and efficiency of nitrogen fertilizers applied to wetland rice: I. The Philippines. Fert. Res. 6:49–63.

Dalal, R.C., P.A. Henderson, and J.M. Glasby. 1991. Organic matter and microbial biomass in a vertisol after 20 yr of zero-tillage. Soil Biol. Biochem. 23:435–441.

Devêvre, O.C., and W. R. Horwath. 2000. Decomposition of rice straw and microbial carbon use efficiency under different soil temperatures. Soil Biol. Biochem. 32:1773–1785.

Eagle, A.J., J.A. Bird, W.R. Horwath, B.A. Lindquist, S.M. Brouder, J.A. Hill, and C. van Kessel. 2000. Rice yield and nitrogen efficiency under alternative straw management practices. Agron. J. 92:1096–1103.

Eagle, A.J. 2000. Rice yield and nitrogen dynamics as affected by alternative residue management practices and winter flooding. M.S. Thesis. Univ. of California, Davis, CA.

Gee, G.W., and J.W. Bauder. 1979. Particle size analysis by hydrometer: a simplified method for routine textural analysis and a sensitivity index of measured parameters. Soil Sci. Soc. Am. J. 43:1004–1007.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Montreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367–385.

Haynes, R.J. 2000. Labile organic matter as an indicator of organic mater quality in arable and pastoral soil in New Zealand. Soil Biol. Biochem. 32:211–219.

Hill, J.E., D.M. Brandon, S.M. Brouder, A.U., Eke, T.E. Kraus, M.A. Llagas, B.A. Lindquist, and S.C. Scardaci. 1999. Winter flooding and straw management: Implications for rice production. Agronomy Progress Report 1994–1996. p. 5–25, no. 264. Department of Agronomy and Range Science, University of California, Davis, CA.

Horwath, W.R., and E.A. Paul. 1994. Microbial biomass. p. 753–773. *In* R.W. Weaver, J.S. Angle, and P.J. Bottomley (ed.) Methods of soil analysis. Part 2. Microbiological and biochemical properties. SSSA Book Series no. 5, SSSA Madison, WI.

Horwath, W.R., E.A. Paul, D. Harris, J. Norton, L. Jagger, and K.A. Horton. 1996. Defining a realistic control for the chloroform-fumigation incubation method using microscopic counting and ^{14}C-substrates. Can. J. Soil Sci. 76:459–467.

Janitzski, P. 1986. Cation exchange capacity. p. 34. *In* M.J. Singer (ed.) Field and laboratory procedures used in soil chronosequence studies. U.S. Geological Survey Bulletin 1648.

Jenkinson, D.S., R.H. Fox, and J.H. Rayner. 1985. Interactions between fertilizer nitrogen and soil nitrogen: The so-called priming effect. J. Soil Sci. 36:425–444.

Jenkinson, D.S. 1988. The determination of microbial biomass carbon and nitrogen in soil. p. 368–386. *In* J.R. Wilson (ed.) Advances in Nitrogen Cycling in Agricultural Ecosystems. C.A.B. International, Wallingford, UK.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen: Inorganic forms. p. 643–698. *In* A.L. Page et al. (ed.) Methods of soil analysis: Part 2. 2nd ed., Agron. Monogr. 9. 2nd ed. ASSA and SSSA, Madison, WI.

Knudsen, D., G.A. Peterson, and P.F. Pratt. 1982. Lithium, sodium and potassium. p. 225–237. *In* A.L. Page (ed.) Methods of soil analysis: Part 2, Agron. Monogr. 9. 2nd ed. ASSA and SSSA, Madison, WI.

Lanyon, L.E., and W.R. Heald. 1982. Magnesium, calcium, stronthium, and barium. p. 247–262. *In* A.L. Page (ed.) Methods of soil analysis: Part 2, Agron. Monogr. 9. 2nd ed. ASSA and SSSA, Madison, WI.

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

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon and organic matter. p. 539–594. *In* A.L. Page (ed.) Methods of soil analysis: Part 2, Agron. Monogr. 9, 2nd ed. ASSA and SSSA, Madison, WI.

Nishio, T., H. Sekiya, and K. Kogano. 1993. Estimate of nitrogen cycling in 15N-amended soil during long-term submergence. Soil Biol. Biochem. 25:785–788.

Ocio, J.A., P.C. Brooks, 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.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorous. p. 403–430. *In* A.L. Page (ed.) Methods of soil analysis: Part 2, Agron. Monogr. 9, 2nd ed. ASSA and SSSA, Madison,WI.

Patnaik, S., and F.E. Broadbent. 1967. Utilization of tracer N by rice in relation to time of application. Agron. J. 59:287–288.

Patrick, W.H., and K.R. Reddy. 1976. Fate of fertilizer nitrogen in a flooded rice soil. Soil Sci. Soc. Am. J. 40:678–681.

Paul, E.A., and N.G. Juma. 1981. Mineralization and immobilization of soil nitrogen by microorganism. *In* F.E. Clark and T. Rosswall (ed.) Terrestrial nitrogen cycles. Ecol. Bull. 33:179–195.

Powlson, D.S., and D.S. Jenkinson. 1981. A comparison of the organic matter, biomass, adenosine triphosphate and mineralizable nitrogen contents of ploughed and direct-drilled soils. J. Agric. Sci. (Cambridge) 97:713–721.

Powlson, D.S., P.C. Brooks, 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.

Richards, L.A. (ed.) 1954. Saturated soil paste. Diagnosis and improvement of saline and alkaline soils. Agricultural Handbook 60. USDA, Washington, DC.

Rule, J.S., D.B. Turley, and L.V. Vaidyanathan. 1991. Straw incorporation into soils compared to burning during successive seasons-impact on crop husbandry and soil nitrogen supply. p. 339–354. *In* W.S. Wilson (ed.) Advances in organic matter research - effect of agriculture on the environment. Spec. Publ. 90. Royal Society of Chemistry, Cambridge, UK.

Sørenson, L.H. 1987. Organic matter and microbial biomass in a soil incubated in the field for 20 years with ^{14}C-labelled barley straw. Soil Biol. Biochem. 19:39–42.

Stark, J.M., and S.C. Hart. 1996. Diffusion technique for preparing salt solutions, kjeldahl digests, and persulfate digests for nitrogen-15 analysis. Soil Sci. Soc. Am. J. 60:1846–1855.

SYSTAT. 1997. SYSTAT 7.0 for Windows: Statistics. SPSS Inc., Chicago, IL.

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.

Vlek, P.L.G., J.M. Stumpe, and B.H. Byrnes. 1980. Urease activity and inhibition in flooded soil systems. Fert. Res. 1:191–202.

Vlek, P.L.G., and B.H. Byrnes. 1986. The efficacy and loss of fertilizer N in lowland rice. Fert. Res. 9:131–147.

Voroney, R.P., and E.A. Paul. 1984. Determination of K_C and K_N *in situ* for calibration of the chloroform fumigation incubation method. Soil Biol. Biochem. 16:9–16.