Assessing the Necessity of Surface-Applied Preplant Nitrogen Fertilizer in Rice Systems

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ABSTRACT

California rice (*Oryza sativa* L.) growers typically use two forms of preplant N fertilizer: aqua NH_3 applied 7 to 10 cm below the soil surface (subsurface N) and surface-applied N. The rational for applying about 25% of the total N rate to the surface is to provide a readily available N source for young rice seedlings; however no research has been done to verify this. On-farm field studies were conducted over a 3-yr period (12 site-years) with the specific objectives of determining when rice begins to use subsurface N and to compare the efficiency of surface and subsurface applied N. Rice seedlings began accumulating subsurface N within 2 wk after sowing at some sites. When a portion of the N rate was applied to the surface, early season plant biomass and N uptake was higher than when all of the fertilizer-N was applied subsurface. In contrast, grain yields were higher when all of the N fertilizer was applied subsurface. Averaged across all sites, the fertilizer-N recovery efficiency of surface-applied N was 38% compared to 53% when only subsurface N was applied. As aqua NH_3 is less expensive than NH_4^+ based fertilizers and the application of surface N requires an additional field operation, there is no justification to recommend the practice of applying surface N fertilizer in these rice systems. Instead, all of the preplant N should be applied subsurface as aqua NH_3.

RICE IS GROWN on approximately 200,000 ha in California with grain yield averaging close to 9.0 Mg ha^{-1}. The total amount of fertilizer N applied averages 165 kg ha^{-1} (Hartley and van Kessel, 2003). Most N fertilizer is applied before planting in two forms: 70 to 80% is applied as aqua-NH_3 injected 7 to 10 cm below the soil surface and 20 to 30% to the soil surface in a fertilizer blend which may contain P and K. Some farmers also apply a mid-season top-dress N application at an average rate of 30 kg N ha^{-1}.

The rational behind applying preplant surface N is that the N is available for early season uptake until the root system develops sufficiently to access subsurface applied N. These recommendations were developed when rice residues were routinely burned. However, as a response to increased environmental legislation, most rice residue in California is incorporated in the fall and fields are flooded during the winter to accelerate residue decomposition. The N concentration of rice straw is 0.51 to 0.71% (Dobermann and Fairhurst, 2000). In California, modern varieties typically produce 8 to 9 Mg ha^{-1} and thus contain approximately 50 kg N ha^{-1}. Straw N has been shown to increase early season soil N availability and reduce the fertilizer requirement by up to 25 kg N ha^{-1} (Eagle et al., 2000; Linquist et al., 2006). With increasing fuel and fertilizer costs, eliminating the surface-N fertilizer application can reduce field operations and reduce fertilizer costs as aqua NH_3 is generally a more cost effective form of N. Thus, the necessity of applying surface-N fertilizer to guarantee sufficient soil available N for rice seedlings should be re-assessed.

Surface applied N is taken up less efficiently and is more susceptible to losses than N applied below the soil surface (Mikkelsen and Finfrock, 1957; Broadbent and Mikkelsen, 1968; Obcema et al., 1984). Mikkelsen and Finfrock (1957) showed that the mean oxidation–reduction potential in the surface 0.5 cm remained in an oxidative state following flooding while soil at the 5 cm depth showed reduced conditions 5 d after flooding. Nitrification of surface N can therefore lead to losses in these flooded systems. As there is limited plant demand for N during the first 2 wk following planting, soil NO_3 can be leached into the reduced soil layers where it is susceptible to denitrification (Buresh and De Datta, 1991). On the other hand, N placed below the soil surface is better protected from such losses as this subsurface layer becomes reduced relatively quickly (Broadbent and Mikkelsen, 1968; Schnier et al., 1990; Kundu and Ladha, 1999). In all these studies N fertilizer placed 5 to 10 cm below the soil surface substantially increased N use efficiency and grain yields.

The overall objective of the study was to determine if the use of surface-applied NH_4^+ fertilizer is justified in rice systems. In a series of replicated on-farm studies located across the Sacramento Valley the following specific objectives were addressed to assess: (i) when rice seedlings begin to use subsurface applied aqua NH_3, (ii) the effect of N placement on early season

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Abbreviations: DAS, days after sowing; NRE, nitrogen recovery efficiency.

Table 1. Crop management details for each of the study sites and the timing of the three early season planting sampling dates (DAS-days after seeding). This table does not include the preplant surface N rate used by each grower as this was not applied to the experimental area.

Site designation (Location-year)	Cropping system	Previous years straw management (when done in yr of study) and years of practice	Variety	Planting date	Time of early season plant samples (DAS)	Aqua-NH_3 rate	Top-dress N	Early season water management
						kg ha^{-1}		
Arbuckle-05	4 yr rice; 1 yr tomato	Straw incorporated (spring) 2 yr	M202	1 May	22, 30, 37	112	0	Drained (3–5 d)†
Sheridan-05‡	Continuous rice	Straw incorporated (fall) 10 yr	M202	6 May	26, 31, 38	148	24	Drained (3 wk)
Princeton-05	Continuous rice	Straw incorporated (fall) 3 yr	M205	11 May	22, 29, 35	159	0	Flooded
Gridley-05	Continuous rice	Straw incorporated (fall) 10 yr	M206	26 May	21, 27, 35	107	0	Flooded
Richvale-05	Continuous rice	Straw incorporated (fall) 15 yr	M202	3 June	20, 26, 33	118	0	Flooded
Arbuckle-I-06	4 yr rice; 1 yr tomato	Straw incorporated (spring)	M206	12 May	19, 26, 33	101	0	Drained (3–5 d)
Arbuckle-B-06§	4 yr rice; 1 yr tomato	Straw burn (fall) 1 yr	M206	13 May	20, 27, 33	101	0	Drained (3–5 d)
Sheridan-06‡	Continuous rice	Straw incorporated (fall) 11 yr	M202	23 May	14, 23, 35	126	47	Drained (3 wk)
Richvale-06	Continuous rice	Straw incorporated (fall) 15 yr	M206	2 June	17, 27, 34	112	0	Drained (1 wk)
Arbuckle-I-07	4 yr rice; 1 yr tomato	Straw incorporated (spring)	M202	27 April	14, 21, 38	101	0	Drained (3–5 d)
Arbuckle-B-07§	4 yr rice; 1 yr tomato	Straw burn (fall) 2 yr	M206	28 April	13, 20, 39	108	0	Drained (3–5 d)
Biggs-07	Continuous rice	Straw incorporated (fall) 15 yr	M206	24 April	14, 21, 36	140	0	Flooded

† The number in parentheses refers to the period of drain.

‡ The experimental site was in the same field in 2005 and 2006 but in a different location within that field.

§ The experimental site was in the same field in 2006 and 2007 but in a different location within that field.

biomass, grain yields and N uptake, and (iii) the efficiency of surface-applied NH_4^+ and subsurface applied aqua NH_3.

MATERIALS AND METHODS

Research was conducted over a 3-yr period on representative rice fields around the Sacramento Valley where the majority of rice is grown in California (Fig. 1). The studies were conducted in six areas of the valley, denoted by the names of the nearest town: Arbuckle, Biggs, Gridley, Princeton, Richvale, and Sheridan. Within each of these areas, studies were performed in different fields during the 3-yr period except at the Sheridan-05/-06 and Aurbuckle-B sites where the studies were performed over 2 yr in the same field but at different locations within the field (Table 1). In total, the data set is comprised of 12 site-year field studies. Soils in Biggs, Gridley, and Richvale had a similar classification and chemical and physical properties (Table 2). Most soils had high clay contents (37–63%), typical of rice soils in California; however, the Sheridan soils contained only 20% clay. All soils were acidic, with pH ranging from 5.1 to 6.7 and organic matter contents ranged from 1.59 to 3.86%. Average monthly temperatures were collected from a centrally located California Irrigation Management Information System (CIMIS) weather station in Colusa, CA (Fig. 2).

At all sites, fields were flooded after aqua-NH_3 and surface fertilizers were applied followed by aerial seeding presoaked seeds of medium grain rice varieties with medium growth duration (Table 1). Sites differed in terms of crop rotation, residue management, planting date, N management and early season water management. With the exception of Arbuckle, rice had been grown every year for at least the previous 15 yr. At Arbuckle, rice was rotated with tomato (*Lycopersicon esculentum* Mill.), with tomato being grown every 4 yr. In general, rice residue was incorporated in the fall followed by winter flooding which is the common practice. The exception was the Arbuckle-B site where residue was burned in 2006 and 2007. In 2007, residue at Arbuckle-I was not incorporated and flooded in the fall but left on the surface and the residue remained largely undecomposed when spring tillage operations began.

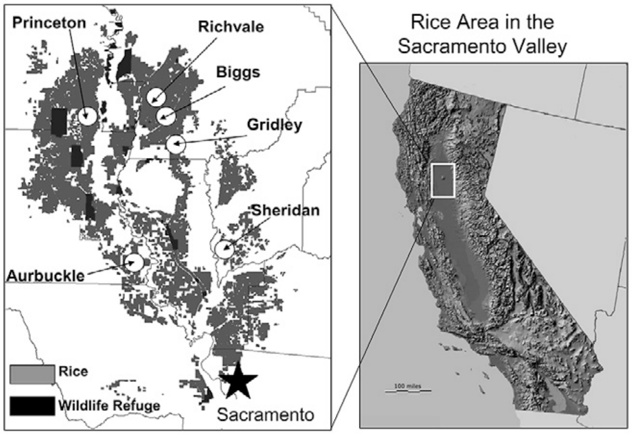

Fig. 1. Map of California highlighting the research sites within the Sacramento Valley where the majority of California rice is grown.

Table 2. Soil descriptions and selected properties of the 12 experimental sites located across the Sacramento Valley.

Site and year	Soil	pH	Total N	Organic matter	Olsen P	Exchange-able K	Sand	Silt	Clay
			%		mg kg^{-1}		%		
Arbuckle-05	Clear Lake fine, smectitic, thermic Xeric Endoaquerts	6.3	0.16	2.53	3.9	190	10	36	54
Sheridan-05	San Joaquin fine, mixed, active, thermic Abruptic Durixeralfs	5.2	0.10	1.89	18.5	97	41	39	20
Princeton-05	Willows fine, smectitic, thermic Sodic Endoaquerts	5.5	0.20	3.86	4.7	144	10	53	37
Gridley-05	Lofgren very fine, smectitic, thermic Xeric Epiaquerts	5.7	0.17	2.31	4.1	151	19	28	53
Richvale-05	Lofgren very fine, smectitic, thermic Xeric Epiaquerts	5.2	0.16	2.24	9.4	190	20	30	50
Arbuckle-I-06	Clear Lake fine, smectitic, thermic Xeric Endoaquerts	6.4	0.18	2.37	6.6	177	9	35	56
Arbuckle-B-06	Clear Lake fine, smectitic, thermic Xeric Endoaquerts	6.4	0.15	2.37	14.2	183	10	35	55
Sheridan-06	San Joaquin fine, mixed, active, thermic Abruptic Durixeralfs	5.1	0.09	1.59	14.6	83	43	37	20
Richvale-06	Lofgren very fine, smectitic, thermic Xeric Epiaquerts	6.4	0.14	1.74	5.9	155	18	29	53
Arbuckle-I-07	Clear Lake fine, smectitic, thermic Xeric Endoaquerts	6.7	0.16	2.33	10.8	na	5	41	54
Arbuckle-B-07	Clear Lake fine, smectitic, thermic Xeric Endoaquerts	6.6	0.18	2.60	9.2	na	8	39	53
Biggs-07	Lofgren very fine, smectitic, thermic Xeric Epiaquerts	5.3	0.17	2.40	2.2	na	12	25	63

The rate of aqua-NH_3 used by each grower ranged from 101 to 159 kg N ha^{-1} (Table 1). Fertilizer N was top-dressed at Sheridan in 2005 and 2006. Early season water management differed between experimental sites. At some sites, fields remained continuously flooded from planting until a few weeks before harvest, while other fields were drained early in the season. At Arbuckle the fields were drained a few days after planting for 3 to 5 d to allow the seedling to anchor into the soil followed by reflooding. To facilitate herbicide applications at Sheridan in 2005 and 2006 and Richvale in 2006, fields were drained about 2 wk after planting and remained drained for 1 wk at Richvale and 3 wk at Sheridan.

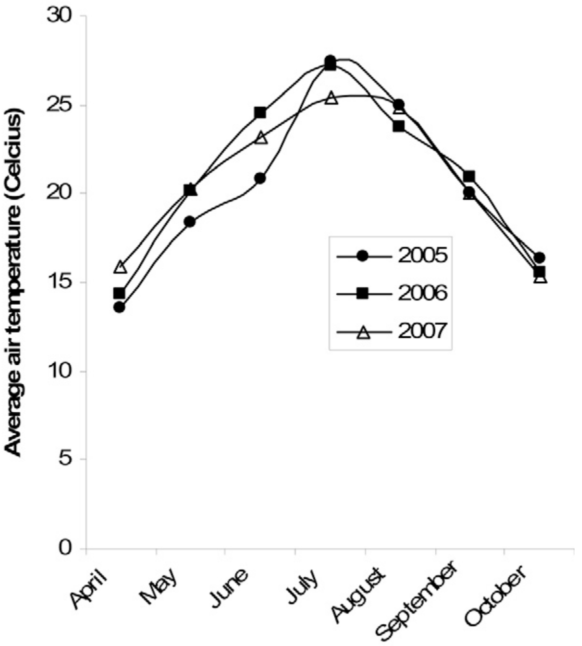

Fig. 2. Average monthly temperature during the 2005 through 2007 rice growing seasons. Data are collected from the Colusa CIMIS weather station.

Nitrogen Fertilizer Treatments

In 2005, on-farm field studies were conducted at five sites and N fertilizer treatment plots were established in a randomized complete block design, replicated five times. Four N fertilizer treatments were evaluated at each site and consisted of subsurface and surface applications (Table 3). Subsurface

Table 3. Fertilizer treatments and rates used in the on-farm field study. The grower rate (GR) refers to the amount of aqua NH_3 each grower applied as a subsurface N application and ranged from 101 to 159 kg N ha kg N ha^{-11} (see Table 1). Thus a subsurface N rate of "SubGR+34" is the grower rate plus 34 kg N ha^{-1}.

Year	Treatment code	Subsurface	Surface
		kg N ha^{-1}	
2005	Sub0/Sur0†	0	0
	Sub0/Sur30	0	30
	SubGR/Sur0†	Grower rate	0
	SubGR/Sur30	Grower rate	30
2006 and 2007	Sub0/Sur0†‡	0	0
	Sub0/Sur30	0	30
	Sub0/Sur60‡	0	60
	SubGR-34/Sur0	Grower rate- 34	0
	SubGR-34/Sur30	Grower rate- 34	30
	SubGR-34/Sur60	Grower rate- 34	60
	SubGR/Sur0	Grower rate	0
	SubGR/Sur30	Grower rate	30
	SubGR/Sur60	Grower rate	60
	SubGR+34/Sur0†	Grower rate + 34	0
	SubGR+34/Sur30	Grower rate + 34	30
	SubGR+34/Sur60	Grower rate + 34	60
	SubGR+68/Sur0‡	Grower rate + 68	0
	SubGR+68/Sur30	Grower rate + 68	30
	SubGR-68/Sur60	Grower rate + 68	60

† Indicates the treatments that were sampled during the first two early season sampling events.

‡ Indicates treatments where early season soil samples were taken in 2007.

(Sub) N was applied as aqua NH_3 by each grower to a depth of 7 to 10 cm and at a grower-determined rate (GR), which ranged between 107 and 159 kg ha^{-1} (Table 1). Surface (Sur) N was applied by hand as $(NH_4)_2SO_4$ at a rate of 30 kg ha^{-1}. The four N treatments were: (1) no N (Sub0/Sur0) and served as the zero N control treatment, (2) surface N only (Sub0/Sur30), (3) subsurface N only (SubGR/Sur0), and (4) subsurface N and surface N (SubGR/Sur30). The amount of N applied in SubGR/Sur30 was equal to the sum of N-fertilizer applied as surface N only and subsurface N only treatments. Plot sizes ranged from 40 to 60 m in length and 6 to 10 m in width depending on the width of the grower's equipment. All treatments received P (50 kg ha^{-1}) and K (50 kg ha^{-1}) to ensure that these nutrients did not limit plant growth. At all sites the subsurface N fertilizer was applied within 5 d of flooding the field for planting and the surface N was applied within 2 d of flooding the field.

In 2006 and 2007, on-farm field studies were conducted at seven sites and N fertilizer treatments were established in a randomized complete block design, laid out as a split-plot design and replicated three times. The main plot treatments consisted of subsurface applications of aqua NH_3 applied at five N rates: (1) no subsurface N (Sub0), (2) 34 kg N ha^{-1} less than the grower rate (SubGR-34), (3) grower rate (SubGR), (4) 34 kg N ha^{-1} in addition to the grower rate (SubGR+34), and (5) 68 kg N ha^{-1} in addition to the GR (SubGR+68). As in 2005, aqua NH_3 rates were determined by the grower and ranged between 101 and 140 kg N ha^{-1} over all site years (Table 1). Subsurface N was applied to a depth of 7 to 10 cm by the growers using their own equipment. The subplot treatments consisted of three rates of surface applied $(NH_4)_2SO_4$: 0, 30, and 60 kg ha^{-1} (Sur0, Sur30, and Sur60, respectively). See Table 3 for a full description of the N treatments and codes. The size of the surface N rate subplots was 4.6 × 3.3 m (15.2 m^2). All plots received P (40 kg ha^{-1}) and K (50 kg ha^{-1}) to ensure that these nutrients did not limit crop growth. The timing of fertilizer N applications in relation to flooding the field was similar to 2005 with the exception of Arbuckle I-2007. At this site, rainfall following the aqua NH_3 application delayed the surface N application and flooding for planting by 10 d.

Plant Sampling

Young rice seedlings were sampled three times early in the season. The first two samples were taken from the zero N control (Sub0/Sur0) in all years and from the SubGR/Sur0 treatment in 2005 and SubGR+34/Sur0 treatment in 2006 and 2007. The first sample was taken between 20 and 26 d after sowing (DAS) in 2005, and 14 and 20 DAS in 2006, and 13 and 14 DAS in 2007 (Table 1). The second sample was taken between 20 and 31 DAS from the same plots. A third sample was taken between 33 and 39 DAS from all plots in all years of the study. For each sampling event 20 to 40 rice seedlings were collected along a transect in each plot. Seedlings were counted, roots separated from the aboveground biomass and the entire sample dried to determine biomass. At the first sampling, plant density was measured in 10 30 by 30 cm areas within the experimental area and early season biomass was converted to an area basis using the average plant density. At harvest, the entire aboveground portion of the plants were harvested from a 0.6 m^2 area. Samples were dried and separated into grain and residue fractions for determination of total biomass yield and grain yield (presented at 14% moisture). For all sites and years, early season and final harvest grain and residue samples were oven dried, ground, and analyzed for N. Yields are presented on a 14% moisture basis.

N recovery efficiency (NRE, %) was calculated as:

$$\text{NRE} = ((\text{N uptake in "+N" treatment} - \text{N uptake in control})/\text{N applied}) \times 100,$$

where N uptake is equal to total N in the aboveground plant biomass.

Soil Sampling

Soils were collected from the top 15 cm from all sites before planting and fertilizer-N application. Soils were analyzed for pH (saturated paste, U.S Salinity Laboratory Staff, 1954), total N (AOAC International,1997), soil organic matter (Nelson and Sommers, 1982), available P (Olsen and Sommers, 1982), available K (Thomas, 1982), and soil texture (Sheldrick and Wang, 1993).

To determine fertilizer N movement within the soil profile, soil samples were taken in 2007 from the control (Sub0/Sur0), only surface N applied (Sub0/Sur60) and only subsurface N applied (SubGR+68/Sur0) treatments approximately 2 wk after sowing. Soil samples were collected from 0 to 5 cm and 5 to 15 cm soil depths. Soils were stored in a cooler or cold room and were extracted for N within 48 h of sampling. The amount of mineral N in the soil was determined by extracting N with 2 mol L^{-1} KCl and determining NH_4 (Forster, 1995) and NO_3 concentrations in solution (Doane and Horwath, 2003).

Data Analysis

Analysis of variance was conducted on individual site data using a completely randomized block design in 2005 and a split-plot design in 2006 and 2007. Analysis of data across all sites and years considered the regression of rice responses against total fertilizer N rate (total N rate) for each level of surface N rate. A random-coefficient regression was conducted using the PROC MIXED procedure available from SAS (SAS Institute, 1999). The effect of total N rate (slope coefficient) and the corresponding intercept coefficient were modeled as both fixed and random effects. The effect of surface N was modeled as a fixed class factor to determine if responses to total N rate were consistent among surface N levels. The variance estimates (random effect among sites; location by year combinations) for the intercept and total N rate were estimated across sites and levels of surface N. A combination of unstructured and variance component covariance structures were used to estimate variance components for the slope coefficients. The unstructured covariance structure, unlike variance component, additionally estimates a covariance between the intercept and slope coefficients among sites. A combination of model convergence (yes/no) and model fit criterion (AICC: corrected Akaike Information Criterion) was used to determine which covariance structure was better. Regression coefficients and corresponding variance estimates were tested for significance at $P < 0.05$.

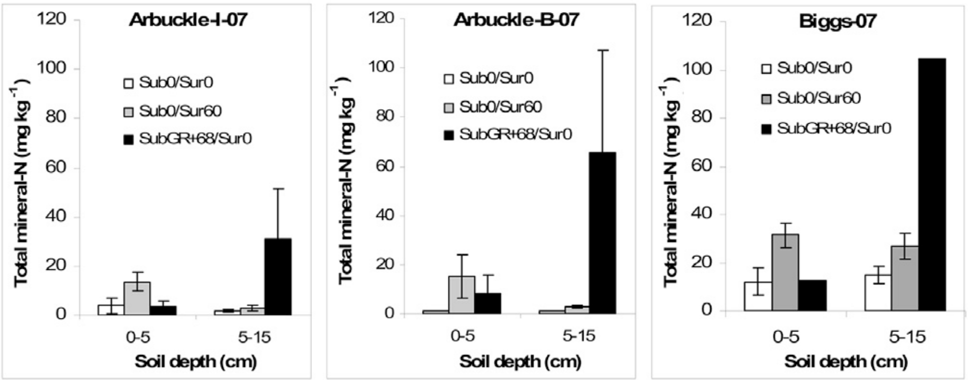

Fig. 3. Soil mineral N in the 0 to 5 cm and 5 to 15 cm soil layers in the control where no N was applied (Sub0/Sur0), where only 60 kg N ha^{-1} was applied to the surface (Sub0/Sur60), and where only subsurface N was injected to a depth of 10 cm at the grower rate plus 68 kg N ha^{-1} (SubGR+68/Sur0). Soil samples were taken approximately 2 wk after sowing. Error bars represent the standard deviation of the three replications and in some cases are too small to detect on the graph.

RESULTS AND DISCUSSION

Early Season Nitrogen Movement in the Soil Profile

In 2007 soil mineral N at 0 to 5 cm and 5 to 15 cm was measured to access vertical fertilizer N movement 2 wk after planting. At all three sites the mineral N content in the 0 to 5 cm layer of the treatment receiving only subsurface N (SubGR+68/Sur0) was similar to the treatment receiving no N (Sub0/Sur0) (Fig. 3), indicating that the fertilizer N had not moved upward in the soil profile. Our results are contrary to those of Obcema et al. (1984) who found N movement in all directions from $(NH_4)_2SO_4$ supergranules placed 5 to 15 cm below the soil surface with the greatest movement being downward followed by lateral and then upward. The reasons for the discrepancy between these studies may be N supergranules result in a much higher localized N concentration thus creating a greater diffusion gradient than when fertilizer N is broadcast or drilled into the soil in rows.

When only surface fertilizer-N (Sub0/Sur60) was applied, the soil mineral N content at the 5 to 15 cm depth was similar to the Sub0/Sur0 treatment at both Arbuckle sites. This suggests that the fertilizer N ($(NH_4)_2SO_4$) remained at the soil surface and did not leach to the lower soil profile. Broadbent et al. (1958) also found that surface applied $(NH_4)_2SO_4$ was initially adsorbed to the surface soil and did not move down the soil profile with the initial wetting event. In contrast, there was evidence of downward movement of surface-applied N at Biggs. It is possible that surface placed fertilizer N moved downward at Biggs because the field was not rolled before the application of surface N fertilizer. Rolling, which is a common practice and is done just before planting, breaks up soil clods and prepares a firm grooved surface for planting. Since the field was not rolled it is possible that the fertilizer granules fell deeper into the soil than what normally would have been the case.

Table 4. Early season above ground N uptake at two sampling times from treatments where no N was applied (Sub0/Sur0) and where only subsurface N was applied (SubGR/Sur0 in 2005 and SubGR+34/Sur0 in 2006 and 2007). Samples were taken between 13 and 31 d after sowing (DAS).

	Sample time and N treatment					
	First sample			Second sample		
Site-year	Sample time (DAS)	No N	Subsurface N only	Sample time (DAS)	No N	Subsurface N only
	N uptake (kg N ha^{-1})					
Arbuckle-05	22	0.7 b†	0.9a	30	2.2 b	3.4 a
Sheridan-05	26	5.6 b	7.2 a	31	10.7 b	18.7 a
Princeton-05	22	3.3 b	5.5 a	29	7.3 b	13.8 a
Gridley-05	21	4.2 b	6.7 a	27	7.8 b	13.0 a
Richvale-05	20	2.3 b	2.8 a	26	5.0 b	8.1 a
Arbuckle-I-06	19	3.6 b	5.5 a	26	9.4 b	25.1 a
Arbuckle-B-06	20	3.7 b	5.5 a	27	8.7 b	21.4 a
Sheridan-06	14	1.4 a	1.5 a	23	12.1 a	13.6 a
Richvale-06	17	4.5 b	5.6 a	27	25.1 b	43.7 a
Arbuckle-I-07	14	0.6 b	1.0 a	21	1.3 b	2.9 a
Arbuckle-B-07	13	0.5 a	0.6 a	20	1.2 b	2.3 a
Biggs-07	14	0.8 b	0.9 a	21	1.9 b	3.5 a
Mean		2.6	3.6		7.7	14.1

† Within the same sample time and row, means followed by the same letter are not significantly different ($P < 0.05$, Fisher's LSD).

Early Season Nitrogen Uptake and Biomass

Early season plant N uptake was evaluated to determine when the young rice seedlings begin taking up subsurface fertilizer N. In 2005 the first samples were taken between 20 and 26 DAS as it was commonly believed that the rice did not begin taking up subsurface N until about 30 DAS. In 2006 and 2007 the first sampling times were taken earlier (13 and 20 DAS). Plant N uptake at the time of the first early season sample in the Sub0/Sur0 treatment where no N was applied ranged from 0.5 to 5.6 kg N ha^{-1} (Table 4). High N uptake was observed at sites where the sample was taken later after sowing (Sheridan-05) or had late planting dates (Richvale-05, 06) (Table 1). Seeding rice later in the season generally ensures warmer weather (Fig. 2) and faster plant growth.

Table 5. Above ground biomass and N uptake in 2005 at 33 to 38 d after sowing (DAS) and grain yields (14% moisture) and N uptake at harvest in response to preseason fertilizer N placement.

Site	Arbuckle	Sheridan	Princeton	Gridley	Richvale
N treatment	Early season above ground biomass, Mg ha^{-1}				
Early season sample time (DAS)	37	38	35	35	33
No N (Sub0/Sur0)	0.21 c†	0.55 c	0.58 d	0.73 c	0.58 c
Surface only (Sub0/Sur30)	0.38 b	0.68 b	0.84 c	0.96 b	0.87 b
Subsurface N only (SubGR/Sur0)	0.37 b	0.71 b	1.00 b	1.25 a	0.92 b
Surface+subsurface N (SubGR/Sur30)	0.44 a	0.96 a	1.16 a	1.31 a	1.15 a
	Early season N uptake, kg N ha^{-1}				
No N (Sub0/Sur0)	4.2 a	18.2 c	15.0 c	17.4 c	15.1 d
Surface only (Sub0/Sur30)	8.6 c	22.5 c	23.2 b	25.2 b	23.8 c
Subsurface N only (SubGR/Sur0)	9.9 b	31.2 b	41.8 a	46.1 a	30.6 b
Surface+subsurface N (SubGR/Sur30)	12.6 a	43.1 a	47.8 a	46.9 a	40.6 a
	Harvest grain yield, Mg ha^{-1}				
No N (Sub0/Sur0)	3.25 d	3.07 b	3.77 b	4.13 b	6.93 d
Surface only (Sub0/Sur30)	4.56 c	4.03 b	4.55 b	4.72 b	8.30 c
Subsurface N only (SubGR/Sur0)	7.64 b	8.83 a	10.21 a	8.50 a	10.91 b
Surface+subsurface N (SubGR/Sur30)	9.35 a	9.63 a	10.13 a	8.67 a	12.35 a
	Total N uptake at harvest, kg N ha^{-1}				
No N (Sub0/Sur0)	45 d	64 b	67 b	64 b	90 c
Surface only (Sub0/Sur30)	64 c	70 b	81 b	72 b	108 c
Subsurface N only (SubGR/Sur0)	95 b	140 a	183 a	116 a	156 b
Surface+subsurface N (SubGR/Sur30)	119 a	156 a	187 a	123 a	186 a

† Within the same column, means followed by the same letter are not significantly different ($P < 0.05$, Fisher's LSD).

At the first sample event which took place between 13 and 26 DAS, N uptake in 10 of the 12 site-years was significantly higher in the subsurface N only treatment than where no N was applied (Table 4). At these 10 locations N uptake averaged 4.2 kg N ha^{-1} in the subsurface N only treatment compared to 2.9 kg N ha^{-1} where no N was applied. By the third sample event which occurred between 33 and 39 DAS, N uptake was higher at all locations (Tables 5 and 6). At the Sheridan-06 site it took longer than at the other sites for there to be a significant difference in N uptake between the no N and the subsurface N only treatments. At this site water was drained from the field for a period of 3 wk. Drainage began about 10 DAS in both 2005 and 2006 and the field was reflooded after the third sample event (Table 1). This extended period of drainage may have affected early season N uptake. These data indicate that rice can take up subsurface applied N as early as 13 to 14 DAS; in fact at three of the four sites where samples were taken 13 to 14 DAS, N uptake in the subsurface N only treatment was significantly higher than where no N was applied. Since there is no evidence of upward movement of subsurface fertilizer N this early in the season (Fig. 3), roots would need to have grown sufficiently deep to access the subsurface N that was placed 7 to 10 cm below the soil surface. To our knowledge there are no reports that have investigated root depth this early in the season in wet seeded rice systems; however there are studies suggesting that rice plants have the potential to develop root systems rapidly to sufficient depth. Slaton et al. (1990) reported that by 35 d after emergence rice

Table 6. Early season biomass and N uptake in 2006 and 2007 for different levels of subsurface (Sub) and surface (Sur) applied N. The subsurface N rates are all relative to the grower applied rate (GR) so a "SubGR+34" has the grower rate plus 34 kg N ha^{-1}. The actual rates used by each grower can be found in Table 1.

Subsurface N treatment (Sub)		Sub0			SubGR-34			SubGR			SubGR+34			SubGR+68			ANOVA		
Surface N rate (kg ha^{-1}) (Sur)		0	30	60	0	30	60	0	30	60	0	30	60	0	30	60	Sub	Sur	Sub x Sur
Site-year	DAS†	Early season above ground biomass, Mg ha^{-1}																	
Arbuckle-I-06	33	0.79	1.15	1.67	1.51	1.67	2.06	1.29	1.57	1.74	2.07	2.12	2.32	2.16	2.45	2.26	***	***	**
Arbuckle-B-06	33	0.70	1.19	1.58	1.23	1.55	1.55	1.52	1.62	1.89	1.30	1.59	1.81	1.55	1.88	1.90	**	***	*
Sheridan-06	35	1.08	1.26	1.53	1.56	1.55	1.65	1.44	1.66	1.74	1.54	1.66	1.75	1.59	1.79	1.72	*	***	ns
Richvale-06	34	1.88	2.55	3.48	2.98	3.09	2.91	3.37	3.26	3.38	3.04	3.49	3.83	3.61	3.51	3.95	*	***	***
Arbuckle-I-07	38	0.27	0.60	0.86	0.88	0.97	1.37	0.72	0.90	1.12	1.02	1.16	1.35	1.23	1.10	1.40	***	***	ns
Arbuckle-B-07	39	0.62	1.23	1.43	1.30	1.47	1.95	1.51	1.77	2.08	1.65	1.98	2.06	1.78	2.02	2.24	***	***	ns
Biggs-07	36	0.53	0.85	1.09	0.87	1.20	1.31	1.00	1.18	1.41	1.05	1.25	1.37	1.08	1.13	1.35	*	***	ns
		Early season N uptake, kg N ha^{-1}																	
Arbuckle-I-06	33	15	22	42	42	46	55	38	50	60	69	69	84	67	88	83	***	***	ns
Arbuckle-B-06	33	16	28	42	39	51	53	54	57	46	44	57	67	58	68	71	***	***	ns
Sheridan-06	35	38	46	61	64	65	73	62	70	74	58	77	75	69	71	76	**	***	ns
Richvale-06	34	53	86	129	129	139	130	148	141	157	131	156	178	168	161	170	**	***	***
Arbuckle-I-07	38	5	10	17	21	22	34	18	24	33	29	35	42	36	34	44	***	***	ns
Arbuckle-B-07	39	14	27	36	42	46	67	55	62	77	65	77	85	73	84	87	***	***	ns
Biggs-07	36	15	21	28	25	33	41	33	36	44	35	41	46	35	38	43	*	***	ns

* Significant at the 0.05 level of probability.

** Significant at the 0.01 level of probability.

*** Significant at the 0.001 level of probability.

† The number of days after seeding (DAS) when plant samples were taken.

Table 7. Analysis of variance for regression of rice responses vs. total (subsurface plus subsurface) for data collected at eight locations from 2005–2007 (total of 12 location by year combinations).

Effect	Early season N uptake	Early season biomass	Harvest N uptake	Harvest grain yield
	Fixed effects (*P* value)			
Total nitrogen linear (TNL)	<0.001	<0.001	<0.001	<0.001
Surface N (Sur)	0.108	<0.001	0.335	<0.001
TNL × Sur	0.261	0.002	0.531	0.050
Total N quadratic(TNq)	0.006	0.104	0.666	<0.001
TNq × Sur	0.212	0.026	0.368	0.333
	Random effects (variance estimate)†			
Intercept	380	0.259	290	2.69
TNL	0.0135	0.00000402	0.0156	0.0000422
	Random effects (*P* value)			
Intercept	0.012	0.023	0.032	0.011
TNL	0.014	0.033	0.028	0.016

† Covariance between intercept and linear coefficients among sites was fit for early season N uptake (1.39; *P* = 0.088) and N recovery efficiency (–1.04; *P* = 0.141), but is not presented in table.

Table 8. Coefficients and deviations for the regression of rice responses vs. total (subsurface plus subsurface) for data collected at eight locations from 2005–2007 (total of 12 location by year combinations).

Site-year	Parameter/ Surface N rate†	Early season N uptake	Early season biomass	Harvest N uptake	Harvest grain yield
		Estimates			
All sites	Intercept	30.9**‡	1.36**	50.8**	2.59**
	Subsurface only		0.73**		4.29**
	30 kg surface N		0.92**		3.62**
	60 kg surface N		1.36**		2.6*
	Total N rate (TN)	0.2008*	0.0008	0.589**	0.0741**
	Subsurface only		0.0064**		0.0590**
	30 kg surface N		0.0042**		0.0645**
	60 kg surface N		0.0008		0.0741**
	Quadratic (N x N)	–0.000204	0.000003	–0.000175	–0.000159**
	Subsurface only		–0.000013**		
	30 kg surface N		–0.000004		
	60 kg surface N		0.000003		
		Deviations§			
Arbuckle-05	Intercept	–16.5*	–0.56**	–12.6	–1
	TN	–0.165**	–0.0029**	–0.039	–0.0005
Sheridan-05	Intercept	–3.6	–0.26	0.7	–1.28*
	TN	–0.086	–0.0021*	0.012	0.0001
Princeton-05	Intercept	–4.6	–0.16	6.7	–0.64
	TN	–0.043	–0.0013	0.143**	0.0005
Gridley-05	Intercept	–2.2	–0.03	1.6	–0.36
	TN	–0.006	–0.0003	–0.047	–0.0044
Richvale-05	Intercept	–4.8	–0.16	28.5**	2.61**
	TN	–0.072	–0.0012	0.096	–0.0048
Arbuckle-I-06	Intercept	–7.1	0.07	0.1	0.44
	TN	0.115*	0.0029**	0.071	0.0016
Arbuckle-B-06	Intercept	–0.6	0.08	–15.4*	1.47*
	TN	0.027	0.0006	–0.113*	0.0009
Sheridan-06	Intercept	16.6*	0.25	5.5	0.31
	TN	–0.043	–0.0010	0.002	0.0018
Richvale-06	Intercept	54.4**	1.43**	12.2	1.47*
	TN	0.248**	0.0029**	–0.027	–0.0044
Arbuckle-I-07	Intercept	–17.8*	–0.43*	–33.2**	–3.49**
	TN	–0.031	0.0006	–0.292**	–0.0099**
Arbuckle-B-07	Intercept	–5.8	–0.01	–10.7	–0.72
	TN	0.126**	0.0024**	0.057	0.0152**
Biggs-07	Intercept	–8	–0.22	16.7*	1.19*
	TN	–0.069	–0.0006	0.138**	0.0040

† Total N rate (TN) represents the linear slope coefficient and N × N represents the curvi-linear (quadratic) slope coefficient. Estimates are available for each level of surface application where a significant N x surface N and N × N × surface N interactions occurred.

‡ The statistical significance of slope coefficients and deviations are indicated as follows: '*' = 0.05 ≥ *P* value ≥ 0.01; and '**' = *P* value < 0.01. Intercepts were always statistically significant (*P* < 0.01).

§ The deviation from the overall (across all sites) intercept or linear slope coefficient.

roots had grown as deep as 30 cm and that the root length density between the 0 to 10 and 10 to 20 cm soil depths were similar. In another study, Caton et al. (2003) measured rice root growth at 21 DAS and reported total root lengths averaging 6.6 m. These findings, along with our visual observations that individual plant roots were over 10 cm in length at 13 to 14 DAS (data not shown) suggest that roots of rice seedlings are sufficiently long and grow deep enough to access subsurface N fertilizer within 2 wk after seeding.

At the third sampling between 33 and 39 DAS, aboveground plant biomass ranged from a low of 0.20 Mg ha^{-1} to almost 2.0 Mg ha^{-1} and there was a significant response to both surface and subsurface applied N (Tables 5 and 6). A regression analysis across sites and years also indicated a significant early season biomass response to N (Table 7). Analysis of deviations from the overall mean showed significantly different early season biomass intercepts at Arbuckle-05, Richvale-06 and Aurbuckle-I-07 (Table 8) suggesting that biomass yields differed at these sites. The low biomass yields observed for Arbuckle-05 were likely the result of an early planting date (May 1-Table 1) combined with cool temperatures in 2005 (Fig. 2). High biomass yields at Richvale-06 where likely due to a later seeding date (June 2-Table 1) and the warmer temperature during this period (Fig. 2). At the Arbuckle-I-07 overall low biomass yields were likely caused by both immobilization and denitrification of fertilizer N. Rice residues are normally incorporated in the fall followed by winter flooding to encourage decomposition (Linquist et al., 2006); however, at this site the residue was left on the soil surface without flooding and in the spring a large amount of rice straw was present before spring tillage. This residue may have contributed to the immobilization of fertilizer N (Williams et al., 1968; Broadbent and Nakashima, 1970; Rao and Mikkelsen, 1976; Bird et al., 2002). Furthermore, spring rains following the aqua NH_3 application caused flooding and seeding operations to be delayed by 10 d—sufficient time for nitrification of a portion of the aqua NH_3. Lower levels of mineral N 2 wk after flooding in the 5 to 15 cm soil layer at this site also suggest losses or immobilization of aqua NH_3 (Fig. 3).

Based on an across site and year ANOVA for the regression of above ground yield response vs. total N applied, for any given level of total N fertilizer applied biomass yields were significantly higher when 60 kg surface N ha^{-1} was applied in combination with subsurface N (Table 7 and Fig. 4). When 30 kg surface N ha^{-1} was applied, response to total N applied was similar or slightly higher than when all N was applied subsurface. We hypothesized that at sites where rice residues were burned the response to surface N would be greater than where residues were incorporated due to lower soil mineral N values early in the season in the burned fields (Linquist et al., 2006); however this was not observed. Higher biomass yields by 33 to 39 DAS where surface N was applied may be due to greater N uptake of surface applied N early in the season. We did not measure N uptake during the first two sampling times in all treatments. However, Obcema et al. (1984) reported that in transplanted rice systems when N was applied at depths of 5 to 15 cm below the soil surface there was a 10 to 30 d lag in N uptake compared to when N was applied on the surface which lead to greater early season biomass when surface N was applied. In our study, by 33 to 39 DAS there were significant differences in N uptake between treatments; however, this was primarily due to differences in total N input (Table 6) and was not significantly affected by whether or not the N was surface or subsurface applied (Table 7).

Fertilizer Placement and Grain Yields

In 2005, grain yield in the zero N control (Sub0/Sur0) ranged from 3.07 Mg ha^{-1} (Sheridan-05) to 6.93 Mg ha^{-1} (Richvale-05) (Table 5). When both surface and subsurface fertilizer-N were applied, yields ranged from 8.67 Mg ha^{-1} (Gridley-05) to 12.35 Mg ha^{-1} (Richvale-05). At two sites (Arbuckle-05 and Richvale-05) there was a significant response to surface applied N when subsurface N had been applied; however, this response to surface applied N may simply be because the subsurface N rate was lower than that required for maximum yields. Similarly, at the other sites the lack of yield response to surface N fertilizer application may be because the subsurface N rate was adequate to obtain maximum yields.

In 2006 and 2007, grain yield in the control (Sub0/Sur0) ranged from 1.6 to 5.9 Mg ha^{-1} across all sites (Table 9). In 2006 maximum yields were approximately 12 Mg ha^{-1} at all sites whereas in 2007 maximum yield ranged from a low of 6.2 Mg ha^{-1} at Arbuckle-I-07 to more than 13 Mg ha^{-1} at the other sites. The likely cause for low yields at the Arbuckle-I-07 site was low N uptake (Table 9) resulting from winter straw

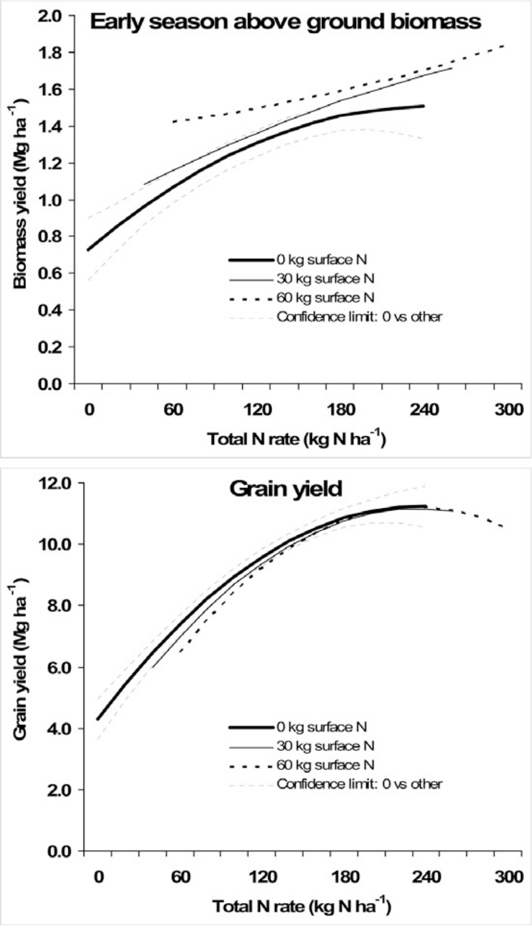

Fig. 4. The effect of N placement on early season above ground biomass and grain yield (14% moisture). Data are the result of a regression analysis using all data from 2005 through 2007. The 95% confidence limit is around the regression line for applying the total N rate as subsurface N. The 30 and 60 kg surface N indicate that 30 or 60 kg N ha^{-1} is applied as part of the total N rate with the remaining N being applied subsurface.

Table 9. Grain yield (adjusted to 14% moisture) and total aboveground N uptake in 2006 and 2007 for different levels of subsurface (Sub) and surface (Sur) applied N. The subsurface N rates are all relative to the grower applied rate (GR) so a "SubGR+34" has the grower rate plus 34 kg N ha^{-1}. The actual rates used by each grower can be found in Table 1.

Subsurface N treatment (Sub)	Sub0			SubGR-34			SubGR			SubGR+34			SubGR+68			ANOVA		
Surface N rate (kg ha^{-1}) (Sur)	0	30	60	0	30	60	0	30	60	0	30	60	0	30	60	Sub	Sur	Sub x Sur
Site-year	Harvest grain yield, Mg ha^{-1}																	
Arbuckle-I-06	4.9	6.2	7.1	8.0	8.8	10.8	9.4	10.0	11.1	10.6	10.8	11.7	11.2	11.9	12.5	***	***	ns
Arbuckle-B-06	5.3	6.5	8.5	8.8	10.2	11.5	10.9	12.0	12.0	12.2	11.7	12.8	12.2	12.3	12.3	***	***	*
Sheridan-06	4.0	6.7	6.8	10.5	11.0	11.7	11.8	11.6	11.5	11.9	12.0	11.8	11.7	11.9	11.7	***	ns	ns
Richvale-06	4.9	5.8	7.4	10.9	11.1	11.0	11.3	11.3	11.7	10.6	11.0	11.7	10.8	11.5	10.8	***	ns	ns
Arbuckle-I-07	1.6	2.1	2.9	2.9	3.6	3.9	4.3	4.5	5.1	4.5	4.8	5.9	5.7	6.0	6.2	***	***	ns
Arbuckle-B-07	3.7	5.5	6.6	7.7	8.4	10.0	10.2	11.7	13.1	11.5	12.9	13.9	13.6	13.7	13.3	***	***	***
Biggs-07	5.9	6.4	7.2	11.4	11.5	12.2	12.2	12.5	13.1	12.6	13.4	13.2	13.4	12.4	13.5	***	**	ns
	Total N uptake at harvest, kg N ha^{-1}																	
Arbuckle-I-06	67	81	93	98	108	141	119	129	149	135	146	167	156	193	206	***	***	ns
Arbuckle-B-06	71	86	106	107	127	153	136	163	170	157	169	202	180	215	224	***	***	ns
Sheridan-06	60	88	89	140	152	162	164	167	183	183	198	207	180	213	216	***	***	ns
Richvale-06	63	72	87	127	136	142	152	156	172	138	153	170	151	168	175	***	***	ns
Arbuckle-I-07	26	30	40	38	46	49	54	54	60	55	56	69	66	70	77	***	***	ns
Arbuckle-B-07	56	70	79	87	93	108	111	126	145	131	152	172	157	173	179	***	***	ns
Biggs-07	83	89	107	159	160	177	174	181	195	210	220	234	201	227	263	***	***	ns

* Significant at the 0.05 level of probability.

** Significant at the 0.01 level of probability.

*** Significant at the 0.001 level of probability.

Table 10. Nitrogen recovery efficiency (%) in 2005 comparing surface (Sur) and subsurface (Sub) N applications. Sur0 and Sur30 indicate no surface N fertilizer and 30 kg N ha^{-1}, respectively. Sub0 and SubGR indicate no subsurface applied fertilizer and subsurface fertilizer applied at the grower rate (GR). The actual rates used by each grower can be found in Table 1.

	N treatment		
Site-year	Sub0/Sur30	SubGR/Sur0	SubGR/Sur30
Arbuckle-05	62	45	52
Sheridan-05	11 b†	44 a	46 a
Princeton-05	48 b	73 a	63 ab
Gridley-05	26 b	48 a	43 ab
Richvale-05	60	56	65
2005 Treatment mean	41	53	54

† Within the same row, means followed by the same letter are not significantly different ($P < 0.05$, Fisher's LSD).

management practices and delayed planting following the application of aqua NH_3 which may have lead to N losses via denitrification or N immobilization, as was discussed earlier.

When equivalent rates of N fertilizer were applied, yields were higher when only subsurface N-fertilizer was applied compared to a combination of surface and subsurface N based on an ANOVA for the regression response across all sites (Table 7; Fig. 4). This is despite the lower biomass yields observed early in the season when the N was all applied as subsurface N (Fig. 4) and differences in cropping history, soils, residue management, crop rotations and early season water management (Table 1). These results confirm findings by others (Mikkelsen and Finfrock, 1957; Broadbent and Mikkelsen, 1968; Obcema et al., 1984) who reported higher rice yields when N fertilizer was incorporated compared to being broadcast on the surface.

Total N uptake at harvest ranged from 26 to 263 kg ha^{-1} and was significantly affected by N treatment (Tables 5 and 9). Differences in N uptake, however, were mostly due to total N input and not due to placement (Table 7). The lack of interaction between subsurface and surface applied N also confirms that N placement did not have a large impact on N uptake (Table 9).

Nitrogen Recovery Efficiency

Nitrogen recovery efficiency (NRE) differed between sites and ranged from as low as 11% to as high as 73% (Tables 10 and 11). The overall low NRE at Arbuckle-I-07 was due to unusual management practices discussed earlier, however the values for the other sites are comparable to the 40 to 62% that others have found in California under on-farm conditions (Eagle et al., 2000) and from on-station research in Asia (Cassman et al., 1993, 1996; Dobermann and Cassman, 1997; Ladha et al., 2005). These authors reported that the NRE observed on-farm were lower and ranged from 30 to 40%. Under rainfed rice conditions in Asia, Linquist et al. (2007) reported NRE values of 13 to 30%. The higher on-farm NRE values found in California relative to Asia, may reflect improved water and fertilizer management practices, a higher yield potential in a Mediterranean climate and the use of more physiological N use efficient rice varieties.

In 2005, the NRE of surface applied N only, averaged across sites, was 41% compared to 53% when all the N was applied as subsurface and differences were significant at three of the five sites (Table 10). In the 2006 and 2007 similar results were found with the NRE of surface applied N only averaging 36% across sites (Sub0- Table 11) compared to 54% when only subsurface N was applied (Sur0- Table 11). While differences were not significant the trends at each site were similar. Mikkelsen and Finfrock (1957) reported that 100% of the drilled fertilizer N was recovered at heading while only 34% was recovered when fertilizer-N was broadcast on the surface. In our study, where both subsurface and surface N was applied, the NRE was 51%- not significantly lower than when only subsurface N was applied (53%). Lower efficiencies of preplant surface applied N is possible due to the high potential for denitrification losses. Mikkelsen and Finfrock (1957) showed that the mean oxidation–reduction potential in the surface 0.5 cm remained in an oxidation state following flooding while soil at the 5 cm depth had reduced conditions 5 d after flooding. Thus, surface applied N can be susceptible to nitrification. Since seedling N demand during this period is low, the NO_3 is not accumulated by the plant and may be leached into the reduced soil layers where it becomes susceptible to denitrification. Subsurface aqua NH_3, on the other hand, is more protected from these losses as the subsoil layer becomes reduced relatively quickly.

CONCLUSIONS

Our research evaluated the necessity of applying surface N in flooded wet seeded rice systems. Early in the season there was no upward movement of subsurface applied fertilizer N in the

Table 11. Nitrogen recovery efficiency (%) in 2006 and 2007. As there was no interaction between surface (Sur) and subsurface (Sub) applied N fertilizer, the means for the surface N include all subsurface N treatments and vice-versa. Sur0, Sur30 and Sur60 indicate no surface N fertilizer, 30 and 60 kg N ha^{-1} applied to the surface, respectively. The subsurface N rates are all relative to the grower applied rate (GR) so a "SubGR+34" has the grower rate plus 34 kg N ha^{-1}. The actual rates used by each grower can be found in Table 1.

	Surface applied N			Subsurface applied N				
Site-year	Sur0	Sur30	Sur60	Sub0	SubGR-34	SubGR	SubGR+34	SubGR+68
Arbuckle-I-06	50	49	53	44	49	50	50	59
Arbuckle-B-06	61	61	63	52	58	65	63	68
Sheridan-06‡	57	52	48	32 b	54 a	55 a	58 a	53 a
Richvale-06	65 a†	53 b	52 b	35 b	69 a	69 a	52 ab	49 ab
Arbuckle-I-07	23	19	22	19	19	23	21	23
Arbuckle-B-07	51	49	48	42 ab	39 b	51 ab	56 a	56 a
Biggs-2007	68 a	53 b	55 b	29	61	59	68	67
Treatment mean	54	48	49	36	50	53	53	54

† Within the same row and N placement method (surface vs. subsurface), means followed by the same letter are not significantly different ($P < 0.05$, Fisher's LSD).

soil profile; however young rice seedlings began accumulating subsurface placed N fertilizer as early as 2 wk after planting at some locations. Applying a portion of the total N rate as surface applied N resulted in higher plant biomass early in the growing season but lower grain yields compared to when the same amount of N fertilizer was applied all subsurface. Subsurface applied N also had higher NRE compared to surface applied fertilizer N. Our results were consistent across varying soils, residue management practices and early season water management practices and indicate that growers could apply all of their preplant N applications subsurface. Applying all the N as subsurface N should be economically attractive to growers as aqua NH_3, the fertilizer used for subsurface applications, is a cheaper source of N fertilizer than the ammonium or urea based fertilizers which growers use for the surface application. Currently, aqua NH_3 is about \$0.66 less per kg of N than ammonium sulfate. If a grower who typically applies 40 kg N ha^{-1} to the surface decides to apply that N as aqua-NH_3, the grower would save over \$26/ha^{-1} in material costs alone. Second, higher yields per unit of fertilizer N applied are possible, and finally, as the application of surface N requires an additional farm operation, eliminating surface applied N fertilizer could further save costs.

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