Nitrogen Management and Methane Emissions in Direct-Seeded Rice Systems

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ABSTRACT

Rice (*Oryza sativa* L.) establishment systems based on resource-conserving production practices are gaining popularity globally. To investigate the potential for improved N management and mitigation of methane (CH_4) emissions, field experiments were conducted in California on three crop establishment systems: water-seeded (WS) conventional, WS stale seedbed, and drill-seeded (DS) stale seedbed. Fertilizer nitrogen recovery efficiency (NRE) and rice yield as affected by N rate, source, and application timing were evaluated for 2 yr in each system. Methane emissions were monitored over a full annual rice production cycle (growing season plus fallow period). Results indicated that neither split N applications nor ammonium sulfate increased yields or NRE compared with a single application of urea, regardless of system. However, the economic optimum N rate increased by approximately 30 kg N ha^{-1} in WS stale seedbed compared with the conventional system. Since NRE generally remained similar across N treatments that maximized yields, applying the appropriate N rate as a single dose before the permanent flood would satisfy both agronomic and environmental goals of N management within each system. Both WS systems resulted in similar growing season CH_4 emissions. However, the DS system reduced CH_4 emissions by 47% compared with the conventional WS system, possibly due to a decreased period of anaerobic soil conditions. This study highlights the importance of assessing benefits as well as tradeoffs when evaluating opportunities for increasing the sustainability of direct-seeded establishment systems with respect to N management and CH_4 emissions.

It is estimated that global rice productivity will need to increase by 1.2 to 1.5% annually over the next decade to meet growing demand, representing an additional 8 to 10 million Mg yr^{-1} (Seck et al., 2012). However, concerns exist regarding the environmental impacts associated with intensive production practices that support high-yielding rice systems. For example, energy consumption during field operations, including land preparation and tillage activities as well as fertilizer production, can represent a substantial portion of non-renewable energy requirements with respect to the total rice production life cycle (Blengini and Busto, 2009; Xia and Yan, 2011). Moreover, poor fertilizer N management, including excessive N rates (Ju et al., 2009), timing of N applications that are not synchronized with plant demand (Peng et al., 2010), or fertilizer placement practices that may increase the susceptibility for N losses (De Datta, 1987), can negatively impact surrounding ecosystems and freshwater resources (Foley et al., 2011; Robertson and Vitousek, 2009). In addition, methane (CH_4) emissions from rice systems are an important source of global CH_4 emissions (Smith et al., 2007), meaning field-scale management practices ultimately have implications for climate change.

In response to these growing environmental concerns, a number of efforts have been undertaken to develop rice establishment systems that make more efficient use of natural resources and labor while still producing high crop yields (Farooq et al., 2011; Ladha et al., 2009). Among other locations, resource-conserving establishment systems based on reduced tillage, energy, and/or labor inputs are being promoted in the southern United States(Watkins et al., 2004; Griggs et al., 2007), major rice–wheat (*Triticum aestivum* L.) production areas of the Indo-Gangetic Plains in South Asia (Kumar and Ladha, 2011; Ladha et al., 2009), and parts of China (Huang et al., 2012; Xu et al., 2010).

In California, where rice is produced on approximately 200,000 ha annually, stale seedbed rice establishment systems based on minimum tillage practices have been developed to help control herbicide-resistant weeds (Pittelkow et al., 2012). Fields are flush-irrigated before rice seeding to promote weed germination, and emerged weeds are eliminated with a broad spectrum herbicide with no further disturbance to soil to prevent weed seeds from being brought to the soil surface. Although the majority of rice in California is established using water-seeded (WS) methods, drill-seeded (DS) rice systems are also slowly gaining popularity as a weed control method (Hill et al., 2006). By maintaining

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Abbreviations: AS, ammonium sulfate; DS, drill-seeded; EON rate, economic optimum nitrogen rate; GWP, global warming potential; GHG, greenhouse gas; CH_4, methane; NRE, nitrogen recovery efficiency; N_2O, nitrous oxide; WS, water-seeded.

aerobic conditions before the permanent flood, DS systems can help suppress aquatic weed species that dominate WS rice systems (Hill et al., 1994). At present, a limited number of growers have adopted stale seedbed practices despite the potential for WS and DS stale seedbed systems to maintain yields similar to conventional production practices (Pittelkow et al., 2012). However, weed pressures are expected to continue increasing and options for integrated cultural and chemical weed control will likely become more attractive in the future (Hill et al., 2006).

An important concern when assessing new establishment systems is maintaining productivity, particularly regarding fertilizer N management. Previous work in California has indicated that fertilizer N requirements differ between stale seedbed and conventional establishment systems (Pittelkow et al., 2012). Reduced tillage or no-tillage practices may cause yield reductions (Bazaya et al., 2009; Gathala et al., 2011; Singh et al., 2011), possibly due to poor germination and crop establishment or the reduced efficiency of applied N fertilizer (Lal, 1986). In addition, accumulation of organic matter near the soil surface can cause immobilization of fertilizer N (Rice and Smith, 1984) and large amounts of surface residue may increase N losses through ammonia volatilization (Griggs et al., 2007). Importantly, a number of studies have documented that rice yields and nitrogen recovery efficiency (NRE) can be improved by selecting the appropriate N rate (Ju et al., 2009), splitting N applications to more precisely match N supply with crop N demand (Peng et al., 2010), or alternating the source of N fertilizer (De Datta, 1987; Mikkelsen, 1987). However, limited research has been conducted on the applicability of these strategies within stale seedbed systems.

In addition to increasing the efficiency of applied N, at question is the degree to which stale seedbed establishment systems may impact indigenous soil N cycling. Although indigenous soil N supply often represents the majority of crop N uptake in a given season and its importance is well known (Cassman et al., 1996), it remains unclear how to effectively manage soil N supply to sustain long-term rice productivity (Kundu and Ladha, 1998). Providing evidence that preseason stale seedbed flood-drain cycles may have consequences for indigenous soil N availability, Pittelkow et al. (2012) observed a reduction in yields under stale seedbed compared with conventional WS practices in plots without N addition. Furthermore, Patrick and Wyatt (1964) reported that total soil N losses increased when soils alternated between aerobic and anaerobic conditions. This is likely a result of nitrification processes occurring when soils dry down followed by denitrification losses when soils are flooded (George et al., 1993; Linquist et al., 2011). In the present study, it was hypothesized that indigenous soil denitrification losses caused by stale seedbed flushes may be contributing to decreased soil N availability, which in turn may increase fertilizer N requirements for stale seedbed as compared with conventional rice production systems.

Differences in early season water management may also impact CH_4 emissions, another key sustainability concern for rice systems. In DS rice systems in California, seeding occurs in non-flooded soils and fields are flush-irrigated for 3 to 4 wk to promote crop establishment (Adviento-Borbe et al., 2013). In contrast, in WS rice systems in California, fields remain continuously flooded before seeding and throughout the growing season (Hill et al., 2006). By reducing the period of soil submergence and avoiding anaerobic conditions during the first portion of the growing season, DS systems may inhibit methanogenesis and reduce seasonal CH_4 emissions. This is supported by results from DS rice in the southern United States, indicating that CH_4 emissions began around 20 d after a flood was established, which itself occurred more than 1 mo after seeding (Rogers et al., 2013). Despite the need for a better understanding of CH_4 mitigation options, particularly in California where climate change policies are beginning to support the development of carbon offset markets and rice growers may be compensated for adopting greenhouse gas (GHG) mitigation practices (CAR, 2011), we are unaware of any direct comparisons between DS and WS rice systems.

In the present study, we evaluated options for improved N management practices and the potential for mitigation of CH_4 emissions in WS and DS stale seedbed rice establishment systems. The objectives were to (i) assess N management strategies for maximizing yield, N uptake, and NRE; (ii) evaluate indigenous soil N dynamics in response to establishment system, and (iii) quantify CH_4 emissions during the growing season and fallow period.

MATERIALS AND METHODS

Site Descriptions

On-station and on-farm field experiments were conducted within the rice-growing region of the Sacramento Valley, CA, during the 2008 and 2009 growing seasons. The on-station experiment was conducted at the California Rice Experiment Station (RES) near Biggs, CA (39°27′31″ N, 121°44′23″ W), to evaluate N management practices for WS and DS stale seedbed rice systems during 2008 and 2009 and CH_4 emissions over a full annual rice cropping cycle (2008 growing season plus 2008/2009 winter fallow). In addition, two on-farm experiments were conducted during the 2009 growing season to investigate N management practices for WS stale seedbed rice establishment systems implemented at a scale common to commercial rice production in this region. On-farm sites were located near Williams, CA (39°9′55″ N, 122°6′54″ W), and Willows, CA (39°33′54″ N, 122°4′27″ W). Soils at the RES, Williams, and Willows sites are classified as an Esquon–Neerdobe complex (fine, smectitic, thermic Xeric Epiaquerts and Duraquerts), Willows silty clay (fine, smectitic, thermic Sodic Endoaquert), and Castro clay (fine, thermic Typic Calciaquoll), respectively.

Selected soil properties for the top 15 cm at each site are presented in Table 1. Five soil cores 3.5 cm in diameter were obtained from each experimental plot before tillage in 2008 and 2009 and composited for analysis by the UC Davis Analytical Laboratory. Soil pH was measured using a saturated paste and pH meter (Richards, 1954). Organic C and total N were measured through combustion on an elemental analyzer following acid fumigation to remove inorganic C (Harris et al., 2001). Particle size was determined using a hydrometer and a settling duration of 40 s for sand and 7 h for silt (Sheldrick and Wang, 1993). Cation exchange capacity (CEC) was measured using the barium displacement method (Rible and Quick, 1960). Olsen P was determined through sodium bicarbonate extraction (Olsen and Sommers, 1982). Exchangeable K was measured using ammonium acetate displacement (Thomas, 1982), and EC was determined using a saturated paste (Rhoades, 1982).

Annual precipitation each year followed typical patterns for a Mediterranean climate with an average of 371 mm of rainfall occurring primarily outside the growing season. Average maximum

Table 1. Selected soil characteristics at the California Rice Experiment Station and two on-farm sites, Williams and Willows.

Site	pH	Organic C	Total N	Sand–silt–clay	CEC	Olsen P	Exchangeable K	EC
		%			$cmol_c\ kg^{-1}$	mg kg^{-1}		dS m^{-1}
Rice experiment station	5.0	1.06	0.08	29–26–45	34.2	13.4	171	0.36
Williams	6.6	1.59	0.14	13–36–51	44.1	11.0	263	1.60
Willows	7.5	1.66	0.15	18–42–40	33.9	3.8	137	0.64

and minimum temperatures during each growing season were 30.3 and 13.2°C, respectively. Average monthly temperatures and annual precipitation were obtained from an automated California Irrigation Management Information System weather station located 21.5 km from the RES in Durham, CA.

Rice Experiment Station

Rice Establishment Systems

The RES field experiment was arranged as a split-plot randomized complete block design with four replications. Three main plot treatments were investigated: WS conventional, WS stale seedbed, and DS stale seedbed. Main plot rice establishment systems were implemented in individual 0.2-ha size basins (12 total). Adjacent basins were separated by two levees with a drainage ditch running between to prevent lateral water movement. Weed control practices for each establishment system followed current recommendations for California rice production (UCCE, 2013). As detailed below, fertilizer N treatments were applied to subplots as urea or ammonium sulfate (AS) 1 to 2 d before the flood in each system. Each fall following harvest, 25 kg P ha^{-1} and 55 kg K ha^{-1} were applied to the soil surface. All treatments were seeded with a Calrose medium-grain rice variety (M-206), which is widely grown in the region. Following harvest, harvester ruts in the field were eliminated and straw was incorporated with a disc. All systems were flooded each winter to promote straw decomposition (Linquist et al., 2006).

Conventional rice establishment practices for California were represented by the WS conventional treatment. Land preparation consisted of several passes with a chisel-plow and disc to an approximate depth of 15 to 20 cm during mid-April and early May each year, followed by final seedbed preparation with a triplane and roller the week before rice planting. Basins were flooded for seeding and pre-germinated rice seed was broadcast at 168 kg seed ha^{-1}. This reflects commercial rice production practices in the region and is well within the range of seeding rates to obtain maximum tiller density and grain yield (Miller et al., 1991; Mutters et al., 2007).

In stale seedbed systems, zero spring tillage was performed to minimize soil disturbance and prevent weed seeds from being brought to the soil surface. The month before seeding, stale seedbeds were implemented by flush-irrigating basins (i.e., flooding the field to a depth of approximately 5 to 10 cm for 7 to 10 d followed by drainage) to promote weed germination. To eliminate weeds that emerged, glyphosate was applied at a rate of 1.5 kg a.e. ha^{-1} several days before planting. In WS stale seedbed, pre-germinated rice seed was broadcast at 168 kg seed ha^{-1} similar to recommendations for conventional WS rice. Following seeding, water management and weed control practices for both WS systems remained similar throughout the growing season. The DS stale seedbed basins were seeded at 112 kg seed ha^{-1} using a grain drill with 19 cm spacing between rows (Jones and Snyder, 1987). In contrast to WS systems, DS stale seedbed treatments were flush-irrigated several times during stand establishment and the flood generally occurred 25 to 30 d after seeding (Adviento-Borbe et al., 2013; Hill et al., 1994). In all systems, water levels following the permanent flood were maintained at a depth of 10 to 15 cm throughout the growing season and fields were drained approximately 1 mo before harvest.

Fertilizer Nitrogen Management

Options for improved fertilizer N management were evaluated in subplots located within each establishment system main plot for a total of four replications. Fertilizer N treatments were applied to 25 m^2 subplots at rates of 0, 112, 168, and 224 kg N ha^{-1}. All fertilizer N was applied as urea except for a 112 kg N ha^{-1} rate that was also applied as AS. A total of nine treatments were evaluated in each system, either applied as a single dose or split between two applications: 0, 112, 28–84 split, 84–28 split, 112 AS, 168, 126–42 split, 224, and 168–56 kg N ha^{-1} split (Table 2). In most conventional WS rice fields in this region, aqua-ammonia is used as the primary N source (Linquist et al., 2009). However, other N sources must be used in stale seedbed systems where spring tillage is avoided because injection of aqua-ammonia entails considerable soil disturbance. To minimize confounding effects in this study and allow for direct comparisons between stale seedbed and conventional systems, urea was used as the primary N source in all establishment systems.

In California it is common for the majority of N to be applied at seeding with an N topdressing event occurring between mid-tillering and panicle initiation at total N rates near 168 kg N ha^{-1} for conventional WS rice systems (Mutters et al., 2007; Linquist et al., 2009: Williams, 2010). Hence, N fertilizer was either applied as a single dose before the permanent flood (preflood) or split between preflood and a midseason topdressing (occurring between mid-tillering and panicle initiation). Previous work in DS systems outside of CA has suggested that there are a number of ways to split N applications with the potential to improve yields or N uptake by rice (Reddy and Patrick, 1976). Depending on tillage practices, N applications occurring immediately before the flood at rates in the range of 150 to 160 kg N ha^{-1} generally have resulted in maximum yields (Harrell et al., 2011). Hence, for the DS stale seedbed system, fertilizer N was either applied preflood or split between preflood and midseason as above with the exception of one treatment (28–84 kg N ha^{-1}) in which the first portion was applied preplant (i.e., directly before seeding) and the second portion preflood. For these varieties, tillering occurs around 25 d after seeding and panicle initiation occurs at 55 to 60 d (UCCE, 2013). Therefore, with a mid-tillering to panicle initiation window lasting from approximately 35 to 55 d after seeding, topdressing N events occurred at 46 and 47 d after seeding in 2008 and 2009, respectively. For WS conventional, preplant N was incorporated into the soil with a harrow. For both stale seedbed systems, preflood N was broadcast on the soil surface. In all systems, N was broadcast into the floodwater for midseason N applications.

Soil and Plant Sampling

To assess indigenous soil N dynamics for each system, soil from 0N plots was sampled from all four replications during preseason management and early rice growth. To quantify potential soil N denitrification losses, preseason soil sampling events occurred before and after irrigation flushes for stale seedbeds. By using this approach, it was assumed that the majority of NO_3–N that accumulated before flooding was lost through denitrification processes as soils became anaerobic (Linquist et al., 2011). Two factors supporting this assumption were the low hydraulic conductivity of rice soils in this region (0.007–0.074 cm d^{-1}) resulting in minimal leaching losses (X.Q. Liang, personal communication, 2014), and the fact that rice seeds were only at the initial stages of germination, meaning soil N uptake by plants was low. Following seeding, sampling occurred approximately every 10 d. Sampling concluded approximately 7 wk after seeding when indigenous mineral N availability had become negligible.

During each sampling event, five to six soil cores per plot, 3.5 cm in diameter to a depth of 15 cm were composited, placed on ice, and thoroughly homogenized before extraction within 36 h of sampling. Field-moist soils were extracted in triplicate with 2 M KCl (soil/solution ratio of 1:10). Extractions were analyzed colorimetrically for NO_3–N (Doane and Horwath, 2003) and NH_4–N (Verdouw et al., 1978; Forster, 1995). Soil bulk density was determined for each sampling date by obtaining intact soil cores 5.6 cm in diameter to a depth of 15 cm using thin-walled plastic soil cores designed to easily penetrate saturated soils.

Midseason plant samples were obtained from N management subplots in 2009 to assess biomass development and crop N uptake. Mid-tillering and panicle initiation dates for M-206 were determined using previous reports for this region (UCCE, 2013). At mid-tillering, 10 plant density measurements were recorded from each replication of each establishment system using a 0.35 by 0.35 m quadrat. Approximately 60 individual rice seedlings were randomly harvested from each N treatment subplot and composited. Seedlings were counted, separated from roots, and oven-dried to a constant weight at 65°C. Plant density estimates were used to calculate crop biomass and N uptake on an area basis. Since N fertilizer treatments in DS stale seedbed were primarily applied before the permanent flood, which occurred after tillering had initiated, only two treatments were sampled at mid-tillering in DS stale seedbed (i.e., the 0 and 24–84 kg N ha^{-1} treatments).

Table 2. Rice yield, crop N uptake, and fertilizer NRE for each establishment system as affected by N management at the Rice Experiment Station. All fertilizer N was applied as urea except for the 112 AS treatment. Lowercase and uppercase mean separation groupings indicate the effects of N treatment within each establishment system and the effects of establishment system within each N treatment, respectively. Values followed by no letter or the same letter are not significantly different according to Tukey's pairwise comparisons at $P < 0.05$. Values represent 2-yr means.†

System	Total N rate	N treatment‡	Yield	N uptake	NRE
	kg ha^{-1}		Mg ha^{-1}	kg N ha^{-1}	%
WS conventional	0	0	4.8 a B	63 a B	–
	112	112	10.3 bc	135 bc B	63 b
	112	28–84	9.5 b AB	117 b	47 ab
	112	84–28	10.3 bd B	127 bc B	57 ab
	112	112 AS	10.1 bc C	125 bc C	55 ab B
	168	168	10.6 bd	146 cd	48 ab
	168	126–42	11.4 d B	163 d B	59 ab B
	224	224	10.6 bd B	164 d B	45 a B
	224	168–56	10.8 cd B	162 d B	44 a B
WS stale seedbed	0	0	3.6 a A	46 a A	–
	112	112	9.2 cd	108 b A	55
	112	28–84	8.7 bc A	106 b	53
	112	84–28	9.0 bd A	107 b A	55
	112	112 AS	7.7 b A	87 b A	40 A
	168	168	9.9 cd	134 c	55
	168	126–42	10.2 d A	134 c A	52 AB
	224	224	10.2 d B	156 d B	47 B
	224	168–56	10.3 d AB	159 d AB	51 B
DS stale seedbed	0	0	5.5 a B	57 a AB	–
	112	112	9.4 b	112 bc AB	49 bc
	112	28–84	10.1 b B	125 bc	60 c
	112	84–28	9.5 b A	113 bc A	50 bc
	112	112 AS	9.1 b B	107 b B	43 ab A
	168	168	10.0 b	132 c	44 ab
	168	126–42	10.0 b A	125 bc A	40 ab A
	224	224	9.3 b A	127 bc A	31 a A
	224	168–56	9.7 b A	135 c A	35 ab A

† NRE, nitrogen recovery efficiency; AS, ammonium sulfate; WS, water-seeded; DS, drill-seeded.

‡ Treatment labels for N rates applied as single dose indicate the full N rate and labels for split N applications indicate the first and second portion of the split N rate. In WS systems, N fertilizer was applied as a single dose before the permanent flood (preflood) or split between preflood and midseason topdressing between mid-tillering and panicle initiation. For the DS stale seedbed system, fertilizer N was applied preflood or split between preflood and midseason as above with the exception of one treatment (28–84 kg N ha^{-1}) in which the first portion was applied preplant (i.e., directly before seeding) and the second portion preflood.

At panicle initiation, aboveground biomass was harvested using 0.3-m^2 quadrats. As above, shoots were separated from roots and oven-dried to a constant weight at 65°C.

Grain yields and rice biomass were determined at physiological maturity from a 1-m^2 area. Grain yields are reported as rough rice yields adjusted to 14% grain moisture. Harvested grain and residue fractions were dried to a constant weight at 65°C, separated, ground, and analyzed for total N by combustion (Stable Isotope Facility, UC Davis). Fertilizer NRE was calculated as the difference in N uptake from N-fertilized plots relative to unfertilized control plots divided by total N applied and multiplied by 100 to express the value as a percentage (Linquist et al., 2009).

Methane Emissions

Methane emissions from each system were measured over a full cropping cycle using the closed-chamber technique (Hutchinson and Livingston, 1993). Growing season measurements occurred from planting (6 June 2008) until fluxes reached ambient levels following drainage of the permanent flood before harvest (22 Sept. 2008). Fallow period measurements occurred the day before winter flooding (4 Nov. 2008) until fluxes reached ambient levels following drainage of the winter flood in the spring (6 Mar. 2009). Flux measurements were performed at (i) 1- to 2-wk intervals during the rice growing season, (ii) 1- to 2-d intervals during field drainage before harvest in the fall and at the conclusion of winter flooding, and (iii) approximately 3-wk intervals during the winter fallow period.

To prevent disturbing rice growth in N treatment subplots, round PVC chamber bases with a diameter of 25 cm were placed in an area of the field directly adjacent to N subplots at seeding and remained for the duration of the growing season. This surrounding field area received the same agronomic management as N subplots except that 168 kg N ha^{-1} was applied as urea before the permanent flood in each system in accordance with typical N rates in this region (Linquist et al., 2009). Boardwalks were installed in each basin to prevent soil disturbance while sampling. Flux measurements were performed by placing air-tight chamber lids and extensions, 30, 60, or 90 cm in size depending on the height of rice plants, on top of bases and collecting gas samples at 0, 30, and 60 min after sealing the lid. Chamber lids and extensions were covered with reflective insulation and equipped with vent tubes, battery operated fans to ensure sufficient mixing of headspace air, thermometers to measure headspace air temperatures, and gas sampling ports. To collect gas samples, the needle of a polypropylene syringe was inserted through the sampling port septum and 24 mL of headspace air was slowly withdrawn and immediately transferred into evacuated 12 mL glass vials with grey butyl rubber septa.

Gas sampling events occurred between 0900 and 1200 h when soil temperatures were expected to represent average daily values (Bossio et al., 1999). Diurnal emissions were measured from each system twice during the growing season by sampling chambers at 3-h intervals for a period of 30 h. As no evidence of significant diurnal variations was observed on either sampling date (data not shown), measured flux rates were assumed to represent average daily values.

All gas samples were analyzed on a Shimadzu 2014 gas chromatograph (GC) equipped with a flame ionization detector (FID) connected to an autosampler (Shimadzu AOC-5000). Gas species were separated by 3 m long Haysep D (80/100 mesh) and 2.5 m long 5 Å molecular sieve (60/80 mesh) columns. Oven and FID temperatures were 80 and 250°C, respectively. The CH_4 detection limit of the GC was 0.1 ppm. The instrument was calibrated daily using analytical-grade CH_4 standards (Airgas Inc., Sacramento, CA). Gas fluxes were calculated from the linear rate of change in chamber concentration, chamber volume, and soil surface area (Hutchinson and Mosier, 1981). Chamber gas concentrations determined by GC (volumetric ppm) were converted to mass-per-volume units assuming ideal gas relations and using measured chamber air temperature values. Estimates of cumulative CH_4 emissions for four replications of each establishment system were calculated by assuming measured fluxes represented daily fluxes and linear interpolation between daily fluxes.

On-Farm Experiments

Fertilizer N experiments were conducted in two commercial WS stale seedbed rice fields in 2009, each field being larger than 6.5 ha in size. At each site, experiments were arranged as a randomized complete block design with four replications. Fertilizer N treatments and harvest methods were implemented exactly as described above for the WS stale seedbed system at the RES. For split N treatments, topdressing occurred at 43 and 44 d after seeding at Williams and Willows, respectively.

Similar to practices at the RES, land preparation at on-farm sites included zero spring tillage. Several weeks before planting, fields were flushed once to promote weed germination and glyphosate was applied several days before permanent flooding and aerial seeding. All management practices with the exception of fertilizer application were performed by the grower. The rice variety M-206 was planted at Williams and M-104 at Willows. Both of these varieties are medium-grain, public rice varieties (Calrose) that have been bred for high yields and improved seedling vigor, lodging resistance, and blanking resistance (UCCE, 2013). The primary difference between varieties is that M-206 is early maturing, whereas M-104 is very early maturing, which allows for earlier planting in slightly cooler production areas (UCCE, 2013). Fields remained continuously flooded from seeding until approximately 1 mo before harvest. Planting and harvest dates at Williams were 8 June and 2 October, respectively. Planting and harvest dates at Willows were 3 June and 22 September, respectively.

At both sites, grain yields and biomass were determined at physiological maturity from a 1-m^2 area. Biomass was dried to a constant weight at 65°C and grain and residue fractions were separated, ground, and analyzed for total N by combustion (Stable Isotope Facility, UC Davis).

Data Analysis

Analysis of variance was performed on all results using linear mixed effects models and the restricted maximum likelihood method in the nlme package in R (version 2.15.0, R Core Team, 2012; Pinheiro et al., 2013). Within each model, N treatment was designated as a fixed effect and block as a random effect. For fertilizer N experiments, which occurred over a 2-yr period, year was treated as a random effect and values are presented as 2-yr means.

Data for yield, N uptake, and NRE at the RES were analyzed using a split-plot design. Initial data analysis indicated significant main plot × subplot interactions, meaning the response to N treatment differed at the different levels of establishment system. Following standard experimental design and analysis for split-plot designs (Steel et al., 1997), the effects of N treatment were subsequently assessed within establishment system and the effects of establishment system were subsequently assessed within each N treatment.

Data for cumulative CH_4 emissions and indigenous soil N dynamics were analyzed using a randomized complete block design as sampling only occurred within main plots or 0N plots, respectively. Per standard conventions for GHG work (e.g., Cai et al., 2003), cumulative CH_4 emissions were assessed separately for the growing season, fallow period, and full annual rice production cycle. Results for soil indigenous N were analyzed separately for each sampling date and significant differences between systems are discussed in the text. Data for yield, N uptake, and NRE at on-farm experiments were analyzed separately by location using a randomized complete block design.

For all analyses, significant differences between treatments were determined based on Tukey's pairwise comparisons ($P < 0.05$) using the multcomp package in R. Data were transformed where necessary using $\log_{10}$ or power functions to meet ANOVA assumptions of normality and homogeneity of variance (assessed by Shapiro-Wilk and Levene's tests, respectively). Means are presented as de-transformed values where appropriate.

Economic optimum nitrogen (EON) rates were calculated following Pittelkow et al. (2012). In brief, mixed-effects quadratic N response models were fit to mean yields for each system using the nlme package in R with total N rate as a fixed effect and year and block as random effects. Model coefficients were used to determine EON rates based on an average N cost/rice price ratio of 6 observed in California during the 2001–2010 period. This ratio was calculated based on the average price of rice in California and the average cost of urea fertilizer (USDA-NASS, 2011) as well as the estimated cost of custom service N fertilizer application for rice grown in this region (Mutters et al., 2007). During this period, the price of rice ranged from US\$0.1164 to US\$0.6063 kg^{-1} and the price of urea from US\$0.4577 to US\$1.323 kg N^{-1} (USDA-NASS, 2011), while the cost of custom service N fertilizer application by air was estimated to be US\$0.5360 kg N^{-1} (Mutters et al., 2007).

RESULTS

Fertilizer Nitrogen Management

When evaluating the effects of establishment system within individual N treatments, yields and N uptake significantly decreased by 25 and 27%, respectively, for control treatments in WS stale seedbed compared with WS conventional. At the split N rate of 84–28 kg N ha^{-1}, yields and N uptake were greater in WS conventional compared with both stale seedbed systems. Similarly, yields and N uptake for the 112 kg N ha^{-1} AS treatment were greatest in WS conventional, followed by DS stale seedbed and then WS stale seedbed. At several larger N rates (126–42, 224, and 168–56 kg N ha^{-1}), yields, N uptake, and NRE were also significantly greater in the WS conventional than in the DS stale seedbed system. However, at 168 kg N ha^{-1}, which is considered a typical N rate in this region, no significant differences were observed among systems for yield, N uptake, or NRE.

When evaluating the effects of N treatment within each establishment system, yields increased in WS conventional with the addition of fertilizer N. However, few differences in yield were observed between N application rates of 168 and 224 kg N ha^{-1} (Table 2). In several cases, single and split N applications at 112 kg N ha^{-1} resulted in lower yields than split applications of 126–42 and 168–56 kg N ha^{-1}. Crop N uptake was maximized at single and split N application rates of 168 and 224 kg N ha^{-1}, with N uptake at these rates ranging from 146 to 164 kg N ha^{-1}. However, NRE was similar across N treatments with the exception that both 224 kg N ha^{-1} treatments resulted in lower NRE (44–45%) than the single preflood application of 112 kg N ha^{-1} (63%).

In WS stale seedbed, yields continued to respond to N treatments at 126–42, 224, and 168–56 kg N ha^{-1}. These treatments produced 14 to 18% greater yields on average than 28–84 kg N ha^{-1} in this system. Crop N uptake for WS stale seedbed was greatest at 168–56 and 224 kg N ha^{-1}, but no differences in NRE were observed among N treatments (NRE ranged from 40 to 55%). In the DS stale seedbed system, there was a significant yield response to the addition of fertilizer N, yet few differences were observed between N application treatments (Table 2). Maximum N uptake occurred at N rates of 112 kg N ha^{-1} and higher in the DS stale seedbed, with 168 kg N ha^{-1} significantly increasing N uptake compared with the 112 kg N ha^{-1} AS treatment. In contrast, the largest NRE (60%) was observed at the low N rate of 112 kg N ha^{-1}. In some cases NRE decreased at high N rates, for example, with the lowest NRE (31%) occurring at 224 kg N ha^{-1}.

Regarding the timing of N application, split N applications did not lead to greater yields, N uptake, or NRE compared with treatments where the full N rate was applied as a single dose within each system. With regard to N source, application of AS at 112 kg N ha^{-1} did not result in different yields or N uptake compared with urea within WS conventional or DS stale seedbed systems. However, a significant yield disadvantage of 16% was observed for AS in the WS stale seedbed system compared with a single application of urea at 112 kg N ha^{-1}. Based on the yield response to N within each system, the estimated EON rate for WS stale seedbed was approximately 30 kg N ha^{-1} greater than that for the WS conventional system (Table 3). In contrast, the estimated EON rate for DS stale seedbed was 18 kg N ha^{-1} lower than that for the WS conventional system. In addition, predicted yields based on EON rates were 7 to 9% lower for WS stale seedbed and DS stale seedbed systems compared with the WS conventional system.

There was a significant yield and N uptake response ($P < 0.0001$) to fertilizer N addition at both on-farm sites under WS stale seedbed management (Table 4). However, few differences in yield occurred between treatments other than the control treatment without N addition. At Williams, the 168–56 kg N ha^{-1} treatment resulted in greater yields than 168, 28–84, and 84–28 kg N ha^{-1} treatments. At Willows, the 28–84 kg N ha^{-1} treatment yielded lower than all other N treatments except the single rate of 112 kg N ha^{-1}. In contrast, N uptake increased at larger N rates of 168 and 224 kg N ha^{-1}. At Williams, 224 and 168–56 kg N ha^{-1} increased N uptake by 30 and 25%, respectively, compared with 112 kg N ha^{-1}. At Willows, the N rates of 168, 126–42, 224, and 168–56 kg N ha^{-1} increased N uptake by 31, 23, 61, and 46%, respectively, compared with 112 kg N ha^{-1}. Within a given N rate at each site, split applications did not lead to greater yields or NRE compared with treatments where the full N rate was applied as a single dose. Among N treatments, NRE remained similar with the exception of the split 28–84 kg N ha^{-1} treatment having the lowest NRE at both sites (29 and 31% at Williams and Willows, respectively). The 112 kg N ha^{-1} AS treatment produced yields, N uptake, and NRE similar to urea at both sites.

Table 3. Yield response models, estimated EON rates, and predicted yields for each establishment system at the Rice Experiment Station. Yields were evaluated as a function of N rate (x) in kg N ha^{-1}.†

System	Model	EON rate	EON range‡	Yield	Yield range§
		kg N ha^{-1}		Mg ha^{-1}	
WS conventional	$y = 4827 + 68.6x - 0.189x^2$	166	141–195	11.0	9.3–13.0
WS stale seedbed	$y = 3520 + 61.9x - 0.142x^2$	197	158–249	10.2	8.1–12.9
DS stale seedbed	$y = 5552 + 53.7x - 0.161x^2$	148	126–174	10.0	8.7–11.4

† EON rate, economic optimum nitrogen rate; WS, water-seeded; DS, drill-seeded.

‡ Range is based on linear and quadratic model coefficients ± SE [linear and quadratic coefficients for WS conventional (64.1, 73.0) and (−0.206, −0.172), WS stale seedbed (56.9, 67.0) and (−0.161, −1.123), DS stale seedbed (50.1,57.3) and (−0.175,-0.148), respectively].

§ Range is based on intercept, linear, and quadratic model coefficients ± SE as above.

Table 4. Rice yield, crop N uptake, and fertilizer N recovery efficiency for WS stale seedbed rice establishment systems at two on-farm sites, Williams and Willows, as affected by N management. All fertilizer N was applied as urea except for the AS treatment. Within each column, values followed by no letter or the same letter are not significantly different according to Tukey's pairwise comparisons at $P < 0.05$.†

Total N rate	N treatment‡	Yield		N uptake		N recovery efficiency	
		Williams	Willows	Williams	Willows	Williams	Willows
kg ha^{-1}		Mg ha^{-1}		kg N ha^{-1}		%	
0	0	6.3 a	6.6 a	65 a	62 a	–	–
112	112	10.6 cd	9.5 bc	133 cd	111 b	60 b	43 ab
112	28–84	9.0 b	8.6 b	96 b	95 b	29 a	31 a
112	84–28	9.9 bc	10.3 c	116 bc	118 bd	44 ab	51 b
112	112 AS	10.3 cd	10.0 c	118 bc	119 bc	46 ab	50 b
168	168	10.2 c	10.4 c	157 def	146 ce	55 b	50 b
168	126–42	10.8 cd	10.3 c	137 ce	137 cde	44 ab	45 ab
224	224	10.4 cd	10.7 c	174 f	180 f	50 b	53 b
224	168–56	11.2 d	10.2 c	166 ef	162 ef	44 ab	45 ab

† WS, water-seeded; AS, ammonium sulfate; DS, drill-seeded.

‡ Treatment labels for N rates applied as single dose indicate the full N rate and labels for split N applications indicate the first and second portion of the split N rate. In WS systems, N fertilizer was applied as a single dose before the permanent flood (preflood) or split between preflood and midseason topdressing between mid-tillering and panicle initiation. For the DS stale seedbed system, fertilizer N was applied preflood or split between preflood and midseason as above with the exception of one treatment (28–84 kg N ha^{-1}) in which the first portion was applied preplant (i.e., directly before seeding) and the second portion preflood.

Indigenous Soil Nitrogen Dynamics and Midseason Crop Nitrogen Uptake

At the onset of soil sampling before tillage or flush-irrigation events in the spring, indigenous soil NO_3–N and NH_4–N availability was similar among plots ($P = 0.69$ and 0.42, respectively). During non-flooded periods before seeding, indigenous NO_3–N accumulated in all establishment systems (Fig. 1a, b, c). However, soil NO_3–N availability decreased rapidly following (i) stale seedbed flush-irrigation events (Fig. 1b, c), (ii) the flood in both WS systems (Fig. 1a, b), and (iii) flush-irrigation events for crop establishment in DS stale seedbed (Fig. 1c). Although more frequent, decreases in NO_3–N were smaller in magnitude for DS and WS stale seedbed systems compared with WS conventional, particularly before permanent flooding WS systems ($P = 0.004$). Hence, cumulative N losses due to denitrification (i.e., decreases in NO_3–N following stale seedbed flush events, permanent flooding in WS systems, crop establishment flushes in DS stale seedbed, and permanent flooding in DS stale seedbed) did not differ among systems (estimates averaged 27.9 kg N ha^{-1}, $P = 0.47$).

In contrast to NO_3–N, indigenous soil NH_4–N availability remained relatively low (<4 kg N ha^{-1}) during preseason flushes and tillage events before seeding in all systems. However, within 3 wk following the establishment of the permanent flood in WS systems, NH_4–N accumulation was greater by 14 to 21 kg N ha^{-1} in WS conventional than WS stale seedbed ($P < 0.001$) (Fig. 1a, b). Unlike WS systems, soil NH_4–N availability did not increase during the period of flush-irrigation for crop establishment in DS stale seedbed (Fig. 1c). In all systems, indigenous NH_4–N availability decreased to negligible levels (<0.5 kg N ha^{-1}) by approximately 50 d after seeding.

Rice biomass and N uptake at the RES in 2009 were generally similar across N rates at mid-tillering in WS conventional, although single applications of 112 AS and 168 kg N ha^{-1} resulted in higher biomass and N uptake than several other N treatments. At panicle initiation, treatments at the total N rate of 224 kg N ha^{-1} increased N uptake by more than 42 to 58% compared with the 168 kg N ha^{-1} treatment (Table 5). In WS stale seedbed, biomass and N uptake were similar across N treatments with the exception that the 28–84 kg N ha^{-1} rate resulted in significantly lower biomass and N uptake. At panicle initiation in WS stale seedbed, treatments at 168 and 224 kg N ha^{-1} increased N uptake by 30 to 50 kg N ha^{-1} or more relative to the average of urea N rates at 112 kg N ha^{-1}. In DS stale seedbed, the split 24–84 kg N ha^{-1} treatment resulted in greater biomass and N uptake at mid-tillering than the control without N addition. However, at panicle initiation results were similar to WS conventional, where treatments of 224 kg N ha^{-1} produced the largest biomass and N uptake, approximately 14 and 75% greater, respectively, than the 168 kg N ha^{-1} treatment.

Methane Emissions

Methane emissions began to occur 3 to 4 wk following flooding in each system (Fig. 2). Methane emissions in WS conventional and WS stale seedbed ranged from 3 to 6 kg CH_4–C ha^{-1} d^{-1} for much of the growing season. However, emissions in DS stale seedbed began approximately 1 mo later than WS systems and did not reach the same maximum emissions, even toward the end of the growing season. Across systems, a substantial increase in emissions lasting for 2 to 3 d was observed during field drainage before harvest. These peak emission events were 32 to 104% greater than the largest emissions recorded during the growing season within each system. Emissions remained low throughout the winter fallow period for all systems with only a small increase in fluxes observed during field drainage in the spring.

Cumulative CH_4 emissions were significantly different among systems (Fig. 3). During the growing season, WS conventional and WS stale seedbed systems had similar cumulative CH_4 emissions (334.7 and 340.5 kg CH_4–C ha^{-1}, respectively), whereas DS stale seedbed resulted in a 47% reduction (175.8 kg CH_4–C ha^{-1}) compared with WS conventional. In contrast, cumulative emissions during the fallow period remained similar across systems, overall representing less than 5% of total emissions during the full cropping cycle.

DISCUSSION

Fertilizer Nitrogen Management

At the RES, rice yields responded differently to N treatments depending on establishment system. Overall, the yield response in WS conventional was typical for California rice systems. The EON rate for WS conventional was estimated to be 166 kg N ha^{-1}, which is similar to the average N rate of 165 kg N ha^{-1} applied in this region (Linquist et al., 2009; Pittelkow et al., 2012; Williams, 2010). In contrast, the estimated EON rate was approximately 30 kg N ha^{-1} higher in WS stale seedbed compared with WS conventional (Table 3). These findings indicate that changes in fertilizer N rate are required to ensure that yields are not reduced following adoption of resource-conserving cropping systems based on stale seedbed practices. These results are in agreement with previous work on WS stale seedbed establishment systems in California (Pittelkow et al., 2012), along with several other studies focusing on reduced tillage or no-tillage practices in rice (Gathala et al., 2011; Lal, 1986).

The greater yield response at lower N rates in WS conventional may in part be explained by differences in fertilizer N placement. Surface-applied N has been shown to be more susceptible to losses compared with N placed in the soil profile (Cao et al., 1984; Linquist et al., 2009; Mikkelsen et al., 1978). In the present study, N was applied to the soil surface in stale seedbed treatments but incorporated in WS conventional. It should also be noted that residue remaining on the soil surface (Griggs et al., 2007) as well as accumulation of soil organic matter (Rice and Smith, 1984) may cause greater volatilization or temporary immobilization of applied N, possibly influencing the availability of fertilizer N in stale seedbed treatments. Lastly, differences in early season soil N availability likely influenced crop N uptake, potentially altering the fertilizer N requirements of WS stale seedbed compared with the WS conventional system.

With the aim of improving yields and NRE, options other than N rate were investigated, including split N applications and the use of AS rather than urea. In contrast to Patrick and Reddy (1976), who reported that NRE increased with split N treatments compared with a single early season N application in DS rice, split N treatments in this study did not increase yields or NRE at a given N rate, regardless of establishment system. In fact, the split treatment 28–84 kg N ha^{-1} resulted in significantly lower midseason biomass and N uptake in WS stale seedbed (Table 5),

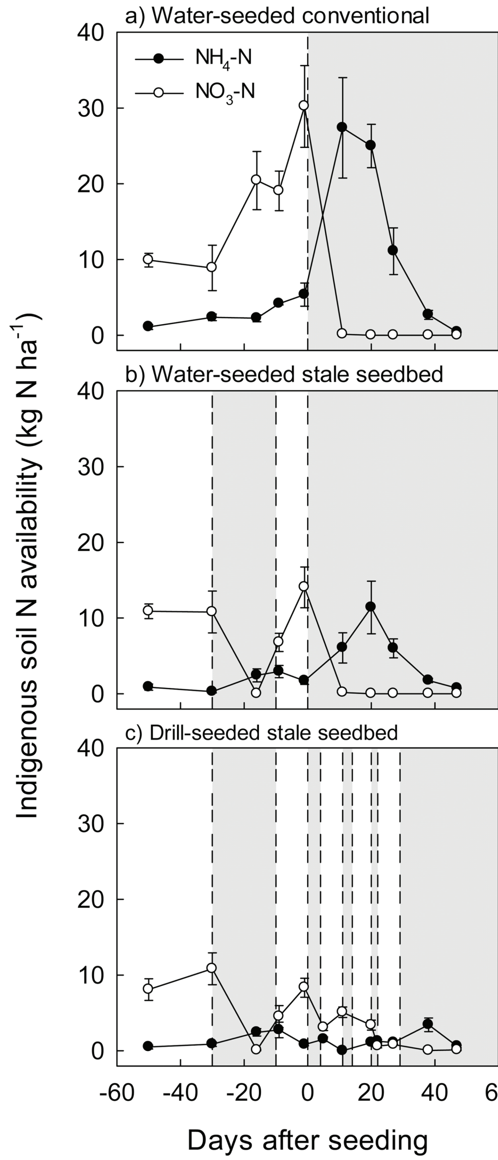

Fig. 1. Indigenous soil NO_3–N and NH_4–N dynamics for (a) WS conventional, (b) WS stale seedbed, and (c) DS stale seedbed establishment systems in response to land preparation and water management practices at the Rice Experiment Station in 2009. Gray shading indicates flooded periods. Error bars represent standard error. WS, water-seeded; DS, drill-seeded.

lower yields at Williams, and lower NRE at both on-farm sites (Table 4). Because the split treatment of 28–84 kg N ha^{-1} was the only treatment for WS stale seedbed in which a small amount of fertilizer was applied at seeding and the majority at mid-tillering, these results highlight the importance of early season N availability, either derived from indigenous soil N or applied fertilizer N, such that N is available in sufficient quantities before the onset of rapid crop N uptake to ensure yields and NRE are maximized.

Regarding N source, the findings of this study are generally in line with a number of studies showing that AS results in similar crop productivity as urea (Bufogle et al., 1998; Reddy and Patrick, 1978). This was observed in WS conventional and DS stale seedbed at the RES and both on-farm sites. However, AS reduced yields in the WS stale seedbed system at the RES. Broadbent et al. (1958) showed that urea in solution moved into deeper soil layers more quickly than AS following surface application, likely due to

Table 5. Rice biomass and N uptake for each establishment system at mid-tillering and panicle initiation as affected by N management at the Rice Experiment Station in 2009. All fertilizer N was applied as urea except for the AS treatment. Within each system and column, values followed by the same letter are not significantly different according to Tukey's pairwise comparisons at $P < 0.05$.†

System	Total N rate	N treatment‡	Mid-tillering		Panicle initiation	
			Biomass	N uptake	Biomass	N uptake
	kg ha^{-1}		kg ha^{-1}	kg N ha^{-1}	kg ha^{-1}	kg N ha^{-1}
WS conventional	0	0	973 a	23 a	3820 a	38 a
	112	112	1089 a	42 bd	7184 bd	98 b
	112	28–84	1085 a	31 ab	6226 b	102 b
	112	84–28	1127 ab	41 bc	6694 bc	96 b
	112	112 AS	1501 c	58 cd	7103 bd	107 b
	168	168	1402 bc	57 d	7017 bc	115 b
	168	126–42	1248 ac	49 cd	6794 bc	119 b
	224	224	1151 ab	48 bd	7786 cd	163 c
	224	168–56	1199 ab	49 cd	8530 d	181 c
WS stale seedbed	0	0	607 a	12 a	2998 a	27 a
	112	112	1221 c	44 bc	6260 cd	85 bd
	112	28–84	912 b	22 a	4512 b	67 bc
	112	84–28	1259 c	42 bc	6329 cd	88 cd
	112	112 AS	1224 c	37 b	5131 bc	53 ab
	168	168	1372 c	53 c	6992 de	109 de
	168	126–42	1300 c	48 bc	7728 e	127 e
	224	224	1271 c	51 c	6650 de	136 e
	224	168–56	1310 c	50 c	7417 de	133 e
DS stale seedbed	0	0	214 a	6 a	4016 a	42 a
	112	112	–	–	6815 b	101 ab
	112	28–84	330 b	10 b	7330 bc	135 bc
	112	84–28	–	–	6866 bc	107 b
	112	112 AS	–	–	7200 bc	125 bc
	168	168	–	–	7545 bc	145 bc
	168	126–42	–	–	7235 bc	157 bc
	224	224	–	–	8572 c	252 d
	224	168–56	–	–	8126 bc	185 cd

† AS, ammonium sulfate; WS, water-seeded; DS, drill-seeded.

‡ Treatment labels for N rates applied as single dose indicate the full N rate and labels for split N applications indicate the first and second portion of the split N rate. In WS systems, N fertilizer was applied as a single dose before the permanent flood (preflood) or split between preflood and midseason topdressing between mid-tillering and panicle initiation. For the DS stale seedbed system, fertilizer N was applied preflood or split between preflood and midseason as above with the exception of one treatment (28–84 kg N ha^{-1}) in which the first portion was applied preplant (i.e., directly before seeding) and the second portion preflood.

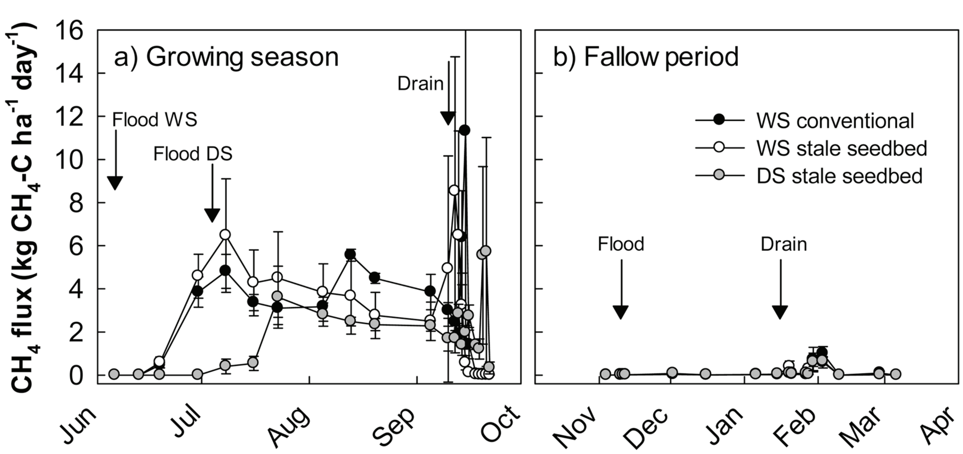

Fig. 2. Methane emissions during the (a) rice growing season and (b) winter fallow period for WS conventional, WS stale seedbed, and DS stale seedbed establishment systems at the Rice Experiment Station in 2008–2009. Error bars represent standard error. Arrows indicate field flooding and drainage dates for WS and DS systems. WS, water-seeded; DS, drill-seeded.

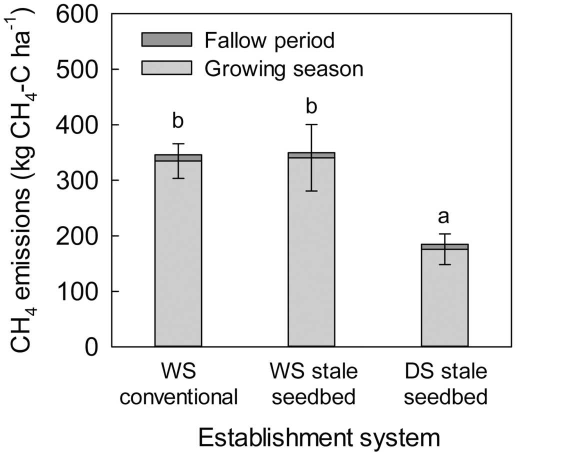

Fig. 3. Cumulative CH_4 emissions during the rice growing season and winter fallow period for WS conventional, WS stale seedbed, and DS stale seedbed establishment systems at the Rice Experiment Station in 2008–2009. Error bars represent standard error of the annual rice production cycle (growing season plus fallow period). Values with the same letter are not significantly different for the annual rice production cycle according to Tukey's pairwise comparisons at $P < 0.05$. WS, water-seeded; DS, drill-seeded.

adsorption of ammonium near the soil surface. It is possible this difference may have been further exacerbated in WS stale seedbed, meaning the urea treatment was less susceptible to losses.

In this study, NRE remained largely independent of N rate, despite a range of N rates and application methods. In general, NRE was consistent with previous reports for a range of different N rates and sites in this region (Linquist et al., 2009; Mikkelsen, 1987). For example, Linquist et al. (2009) recorded NRE ranging from 11 to 73% for conventional WS systems in California, with application of surface compared with subsurface N resulting in 38 vs. 53% NRE, respectively. Although NRE in this study may be greater than some rice production areas in Asia (e.g., Ju et al., 2009), it is closer to the global average of 46% determined by Ladha et al. (2005). For DS systems, NRE for N rates of 112 and 168 kg N ha^{-1} were similar to the range of 40 to 60% reported previously by Bufogle et al. (1997) and slightly lower than findings of Harrell et al. (2011), where NRE remained above 50% even at N rates well above 200 kg N ha^{-1}. When comparing DS stale seedbed and WS conventional systems, NRE results from this study contrasted those of Bufogle et al. (1997), who reported that DS systems tended to either have similar or slightly increased NRE compared with WS systems across several sites and years. More specifically, NRE was significantly lower in DS stale seedbed at 126–42, 224, and 168–56 kg N ha^{-1} compared with WS conventional. These decreases in NRE may be related to higher N application rates than Bufogle et al. (1997).

In total, these findings suggest that for WS and DS stale seedbed systems, N rates should be applied as a full dose in the form of urea before the permanent flood. This practice would satisfy both agronomic and environmental goals of N management by ensuring that rice growth is not limited by low early season N availability and that NRE remains similar across N treatments. Moreover, this practice would help avoid extra costs incurred either by aerial midseason N topdressing events or the relatively higher cost of AS compared to urea.

Indigenous Soil Nitrogen Supply

It is well-recognized that indigenous soil N supply is a vital component of meeting N demand in flooded rice systems (Cassman et al., 1996; Dobermann et al., 1994). Based on results of Pittelkow et al. (2012), it was hypothesized that cumulative indigenous soil N denitrification losses following field flooding events before planting would be greater in stale seedbed systems due to flush-irrigation practices. Contrary to this hypothesis, estimated cumulative NO_3–N losses resulting from early season field flooding and drainage events were similar among systems (i.e., despite the decreases in NO_3–N during individual flooding events being smaller in magnitude for DS stale seedbed and WS stale seedbed compared with WS conventional, cumulative losses were similar to WS conventional due to a greater overall number of flooding events in stale seedbed systems). The smaller accumulation of NO_3–N in stale seedbed systems may have been because the period between stale seedbed flush events and permanent flooding was not long enough for soils to dry out and promote rapid nitrification, thereby limiting subsequent denitrification (George et al., 1993).

When linking soil N supply to fertilizer N management, it is of interest that an increase in indigenous NH_4–N availability following permanent flooding in WS conventional was observed. This increase may be explained by soil N mineralization following tillage (Grace et al., 1993; Kundu and Ladha, 1998) and could have played an important role in the response of each system to fertilizer N addition. For instance, midseason rice biomass and N uptake at midtillering and panicle initiation were greater in WS conventional than WS stale seedbed, particularly at low N rates where greater N deficiency in terms of yield was observed in WS stale seedbed. Kundu and Ladha (1998) also reported increased N uptake and consequently greater yields as a result of tillage. Therefore, it is possible that WS stale seedbed was more dependent on fertilizer N inputs to meet crop N demand than WS conventional due to lower early season N availability. This is further evidenced by greater estimated EON rates in WS stale seedbed than WS conventional at the RES, as well as the fact that N uptake and yields continued to increase at N rates up to 224 kg N ha^{-1} at both on-farm sites.

In general, results for the WS stale seedbed system at the RES were similar to those from the on-farm experiments. Particularly regarding N rate, yields and N uptake across the three sites responded to greater N rates of 168 and 224 kg N ha^{-1}. However, the combined EON rate for both on-farm sites was 175 kg N ha^{-1} (data not shown), which was lower than the 197 kg N ha^{-1} estimated EON rate for the WS stale seedbed system at the RES (Table 2). This may be related to the total N content of soils at both on-farm sites (Table 1). Yields from control plots without N addition were greater at Williams and Willows as compared with the RES (6.3 and 6.6, respectively, vs. 3.6 Mg ha^{-1}). As a result, the yield response to fertilizer N was smaller at the on-farm sites relative to the RES, possibly leading to a reduced EON rate.

Methane Emissions

Over the course of a full growing season and fallow period, results from this study indicated that CH_4 emissions were significantly lower under DS than WS rice establishment practices (Fig. 3). Water management practices are known to play a critical role in regulating CH_4 emissions from rice systems (Yan et al., 2005; Zou et al., 2005). Many studies have investigated the use of midseason drainage practices, among other techniques, to keep soil redox potential outside the range favoring soil CH_4 production (e.g., Itoh et al., 2011; Johnson-Beebout et al., 2009; Yan et al., 2003). However, to our knowledge, this is the first study in which DS establishment practices were directly compared with continuously flooded WS rice.

The substantial reduction in cumulative CH_4 emissions under DS management may have been due to aerobic soil conditions resulting from flush-irrigation during the first month of crop establishment (Ratering and Conrad, 1998). Although soil redox potential was not measured in this study, it was assumed that soils became aerobic under non-flooded conditions. Alternatively, the greater length of time between the previous fallow period and the permanent flood in the DS system may have also reduced CH_4 emissions. Interestingly, toward the end of the rice growing season, the magnitude of daily CH_4 fluxes remained different across systems (Fig. 2). The potential for drill-seeding to result in more than a temporary delay in CH_4 emissions warrants future research.

To assess the global warming potential (GWP) of DS rice, nitrous oxide (N_2O) fluxes also need to be considered. With an increased frequency of field drainage events under drill-seeding, N_2O emissions may likewise increase due to aerobic soil conditions triggering spikes in N_2O emissions (Akiyama et al., 2005; Zou et al., 2005). Although N_2O emissions were not monitored simultaneously with CH_4 emissions in this investigation, during the 2009 growing season N_2O emissions from each establishment system were measured during non-flooded periods as part of another study (Burger and Horwath, 2012). In DS plots that did not receive N fertilizer before permanent flooding, cumulative N_2O emissions were greater than WS systems due to flush-irrigation practices for crop establishment in DS rice (285 g N_2O–N ha^{-1} in DS stale seedbed vs. 4 and 154 g N_2O–N ha^{-1} in WS conventional and WS stale seedbed, respectively). However, considering these cumulative emissions were relatively low with respect to the large CH_4 emissions measured in 2008, these increases in N_2O emissions were not great enough to offset the reduction in CH_4 emissions.

To illustrate this point, potential growing season GWP can be estimated for these systems by calculating CO_2 equivalents (CO_2 eq) over a 100-yr time horizon using a radiative forcing potential of 298 for N_2O and 25 for CH_4 relative to CO_2. In this scenario, the overall GWP of DS systems remains lower than WS systems, where estimated total growing season GWP for WS conventional, WS stale seedbed, and DS stale seedbed were 11.2, 11.4, and 6.0 Mg CO_2 eq, respectively. Similar to these results, other studies in California have documented the relatively minor contribution of N_2O to total GWP in WS and DS rice systems (Adviento-Borbe et al., 2013; Pittelkow et al., 2013). Therefore, although clear trade-offs exist between N_2O and CH_4 emissions in flooded rice systems, field drainage practices have largely been shown to result in GWP mitigation due to the substantial decrease in CH_4 emissions, which typically outweighs any increase in N_2O emissions (Linquist et al., 2012; Zou et al., 2005).

Consistent with other recent work on annual CH_4 emissions from California rice systems (Adviento-Borbe et al., 2013; Pittelkow et al., 2013), the results of this study show that fallow period CH_4 emissions remained relatively low across systems. First, this finding suggests that fallow period CH_4 emissions are independent of crop establishment practices employed during the growing season. Second, these results provide evidence that winter flooding practices may not necessarily contribute to large increases in cumulative CH_4 emissions observed by Fitzgerald et al. (2000) and McMillan et al. (2007). These findings would imply that CH_4 mitigation strategies should target water management during the growing season, either through DS management or other practices that reduce periods of soil submergence. However, carryover effects of winter flooding also need to be taken into account when developing mitigation strategies, if fallow period flooding increases CH_4 emissions during the subsequent growing season as shown in other studies (Cai et al., 2003; Xu and Hosen, 2010).

A number of rice growing regions in Asia are starting to move toward DS or dry-seeded rice establishment practices as a result of labor and resource constraints, but outcomes in terms of crop productivity and grower adoption of DS rice systems can be variable (Jat et al., 2009; Kumar and Ladha, 2011). In part, this may be because flush-irrigation practices can be difficult to implement during the critical phase of crop establishment, depending on field leveling practices and access to irrigation water. Moreover, weed management may become a serious concern in DS rice due to the practice of field flushing rather than flooding during crop establishment (Hill et al., 1994; Pittelkow et al., 2012). However, similar yields can be obtained for DS and WS rice given proper management (Bufogle et al., 1997, Pittelkow et al., 2012; Westcott et al., 1986). Although the results of this study suggest that DS represents a promising CH_4 mitigation option, it should also be considered that DS may come at increased risk in situations where growers may be unfamiliar with flush-irrigation practices or face barriers to its effective implementation.

CONCLUSIONS

This study investigated aspects of N management and CH_4 emissions under stale seedbed rice establishment practices. Split N applications and the use of AS instead of urea did not increase yields or NRE at a given N rate regardless of system. In addition, over a wide range of N treatments that maximized yield, NRE remained relatively independent of N rate. Possibly owing to decreased soil N availability following flooding as well as differences in fertilizer N placement, WS stale seedbed required an increase in the EON rate by approximately 30 kg N ha^{-1} compared with WS conventional. From these results it can be concluded that yields will be optimized without negatively impacting NRE when N is applied at the EON rate as a single dose before the permanent flood in the stale seedbed systems assessed here. Growing season CH_4 emissions were substantially reduced under DS compared with conventional WS practices. This was likely due to a longer period of aerobic soil conditions during crop establishment or a greater length of time between the previous fallow period and the permanent flood. In an effort to increase sustainability with respect to N cycling and CH_4 emissions, this study highlights the importance of assessing multiple outcomes to identify potential benefits as well as tradeoffs in stale seedbed direct-seeded rice establishment systems.

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