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Agronomic productivity and nitrogen requirements of alternative tillage and crop establishment systems for improved weed control in direct-seeded rice

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ABSTRACT

Weed control is a primary concern in direct-seeded rice, particularly for herbicide-resistant weed species which stand to threaten the long-term sustainability of California rice systems. In a four-year field study we evaluated the potential for improved weed control using no-till stale seedbed practices in water-seeded (WS) and drill-seeded (DS) rice establishment systems. In addition, as the agronomic performance of alternative tillage and crop establishment methods is not well understood, we assessed the productivity of these systems and estimated economic optimum nitrogen (EON) rates based on yield response to nitrogen (N) trials. Establishment system treatments included: water-seeded conventional tillage (WS conventional), water-seeded conventional tillage stale seedbed (WS stale), water-seeded no-till stale seedbed (WS no-till stale), drill-seeded conventional tillage (DS conventional), and drill-seeded no-till stale seedbed (DS no-till stale). Compared to the WS conventional system, WS stale and WS no-till stale treatments significantly reduced sedge weed biomass by 59 and 95%, respectively. Although redstem (*Ammannia* spp.) was not controlled, alternative WS systems reduced grass weed biomass by more than 99% when present. Within DS systems, no-till stale seedbed practices significantly reduced watergrass (*Echinochloa* spp.) biomass by 75% in the first two years but did not improve watergrass control during the second half of the study. Grain yields were not different for conventional and alternative rice establishment systems each year when N was applied at 168 kg N ha^{-1} and weeds were fully controlled. However, yields were significantly lower for alternative establishment systems compared to the WS conventional system when no N fertilizer was applied, likely as a result of greater soil N losses. The response of grain yield to N rate was significantly different among systems and estimated EON rates indicated that WS stale and WS no-till stale systems required an increase of 30–35 kg N ha^{-1} to maximize yields and returns to N compared to the WS conventional system. Results from this experiment demonstrate that alternative tillage and crop establishment systems can lead to improved weed control while remaining viable from an agronomic and economic standpoint in California. Provided N rates are close to optimal and WS and DS establishment methods are selected to target weed species of concern, these findings suggest that no-till stale seedbed practices should be considered as a component of integrated weed management strategies in direct-seeded rice moving forward.

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1. Introduction

Alternative rice (*Oryza sativa* L.) establishment systems based on innovative technologies and management practices to reduce human labor requirements and external inputs while maintaining or increasing economic productivity have been developed in recent years, primarily in Asia. For example, zero tillage direct-seeded rice systems are being adopted to avoid manual transplanting requirements and alleviate soil degradation problems (Farooq et al., 2011; Ladha et al., 2009). However, direct-seeded systems are distinct from transplanted rice in that weeds and rice emerge in closer temporal proximity and greater efforts are required to manage weed populations and prevent yield loss (Bhagat et al., 1996; Hill et al., 1994). Therefore, weed control in direct-seeded rice remains a significant concern and strategies to reduce weed populations are needed (Ladha et al., 2007; Rao et al., 2007).

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

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In California, rice is grown on approximately 200,000 ha and direct-seeded systems have been used for close to a century to varying degrees, with water-seeded (WS) rice being the primary establishment practice since the late 1920s. Land preparation typically consists of 3 to 5 tillage events using a chisel-plow and disc, followed by several passes with a triplane and roller to create a uniform, level seedbed. Relative to cereal production systems utilizing reduced or no-till practices, intensive tillage can increase energy consumption and equipment costs (Mutters et al., 2007; Saharawat et al., 2010) and contribute to air quality problems (Madden et al., 2008). Fertilizer is commonly applied by ground rig and pre-germinated rice seed is aerially seeded onto flooded fields. Crop rotations are not common due to heavy clay soils in the region, thus cultural and chemical weed control practices generally remain similar year to year. Weed management strategies are focused on achieving early weed control after seeding, but this is becoming increasingly difficult and numerous herbicide applications may be required (Fischer and Hill, 2004). Continuous selection pressure has led to the development of herbicide-resistant weed species (Fischer et al., 2000), with California rice having among the highest number of herbicide-resistant biotypes compared to any other crop or region in the U.S. (Heap, 2011). Herbicide-resistant weeds represent a major challenge facing growers in the region by reducing yields and increasing production costs (Fischer et al., 2000; Fischer and Hill, 2004). In addition, with greater public demands for production systems that minimize environmental impacts, more stringent regulations are limiting the herbicides that can be used along with how they can be applied (Hill et al., 2006). To ensure the long-term sustainability of California rice systems, a shift in management practices is needed to develop more effective weed control strategies and promote resource conservation and environmental quality related to intensive tillage practices.

With integrated cultural and chemical weed control practices, alternative rice establishment systems may help reduce weed pressure. Weed emergence in rice systems is largely driven by water management during crop establishment, thus seeding methods with contrasting water regimes allow for different weed species to be recruited (Bhagat et al., 1999). In drill-seeded (DS) rice systems, aerobic conditions are maintained prior to the permanent flood which may help suppress aquatic weed species that dominate WS rice systems in California (Hill et al., 1994) and allow for new herbicides with different modes of action to be used, for which resistance has not yet evolved (Fischer et al., 2000). Another weed control option that has gained popularity is to implement a stale seedbed prior to planting in combination with reduced tillage or no-till practices (Harrell et al., 2011; Hill et al., 1994). With this technique fields are irrigated after land preparation to promote weed germination and then weeds are eliminated before seeding using a non-selective herbicide to which weeds are not resistant. Stale seedbeds have been shown to reduce weed populations common to direct-seeded rice (Rao et al., 2007) and may be especially effective when combined with no-till practices as weed seeds that are not eliminated prior to rice seeding remain buried in the seedbed (Chauhan et al., 2006). Additionally, because no-till practices have the potential to reduce external inputs and production costs (Bhushan et al., 2007; Ladha et al., 2009), alternative establishment systems may represent an important option for enhancing the sustainability of California rice systems.

However, there are potential issues with switching establishment systems that must be addressed, especially concerning agronomic productivity and nitrogen (N) fertilizer management practices to optimize yield. Previous studies have determined that DS systems reduce N uptake and N recovery efficiency compared to WS systems (Westcott et al., 1986), as well as reduce yields in some cases but not others (Bufogle et al., 1997; Singh et al., 2011). No-till practices have also been shown to cause yield reductions in direct-seeded rice (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). Accumulation of organic matter near the soil surface can cause immobilization of N fertilizer (Rice and Smith, 1984) and large amounts of surface residue may increase N losses through ammonia volatilization (Griggs et al., 2007). Furthermore, N is typically applied to the soil surface in no-till systems, whereas in conventional systems it can be incorporated with tillage which has been shown to reduce losses (Cao et al., 1984). These factors may contribute to reduced crop N uptake and yields in no-till systems (Kundu and Ladha, 1999; Lal, 1986). In addition, although native soil N is an important nutrient source for rice and its availability in flooded soils has been thoroughly investigated (Cassman et al., 1996; Dobermann et al., 1994), little is known about the effects of no-till practices. Straw is generally either not incorporated or incorporated to a lesser extent which may influence native soil N availability and alter N fertilizer requirements (Eagle et al., 2000; Linquist et al., 2006). When native soil N supply is low and N uptake by rice is limited, increased N fertilizer is often required to reach maximum yield (Cassman et al., 1996; Kai et al., 1984).

To address the growing problem of herbicide resistance in California rice production systems while ensuring limited environmental impacts, this study was conducted to assess the potential for improved weed control using no-till stale seedbed practices in WS and DS rice establishment systems. Agronomic performance and N fertilizer requirements of each system were also investigated. The specific objectives were to (i) evaluate weed dynamics as influenced by establishment system, (ii) assess system productivity over time, and (iii) estimate economic optimum N rates for each system based on the yield response to N fertilizer.

2. Materials and methods

2.1. Site description and experimental design

A four-year field experiment was conducted from 2004 to 2007 at the CA Rice Experiment Station near Biggs, CA (39°27′31″ N, 121°44′23″ W). The experimental area was 4 ha in size. Soils at this site are classified as an Esquon-Neerdobe Complex (fine, smectitic, thermic Xeric Epiaquerts and Duraquerts). Selected soil characteristics for the 0–15 cm depth include: pH 5.0, 34.2 $cmol_c\ kg^{-1}$ CEC, 1.06% organic C, 0.08% total N, 0.36 $dS\ m^{-1}$ EC, 29% sand, 26% silt, and 45% clay. Annual precipitation followed typical patterns for a Mediterranean climate with an average of 541 mm of rainfall occurring primarily outside the growing season. Average maximum and minimum temperatures during the growing season were 29.2 and 12.7 °C, respectively.

The field trial was arranged as a randomized complete block design with four replications. Rice establishment systems were implemented in individual 0.2 ha size plots (i.e. rice basins) that were separated by levees and a ditch to prevent lateral water movement between plots. In addition to weed control characteristics, agronomic performance and N fertilizer requirements were investigated to better understand the yield potential of these systems and develop improved fertility management practices. Therefore, the layout for each basin included (i) the main plot under typical fertility and weed control practices, (ii) an area for weed recruitment which received no herbicides with the exception of preplant glyphosate in stale seedbed treatments and (iii) a set of N fertility trials (Fig. 1). The location of N trials moved each year but weed recruitment zones were permanent. Other aspects of this experiment were previously reported on by Linquist et al. (2008).

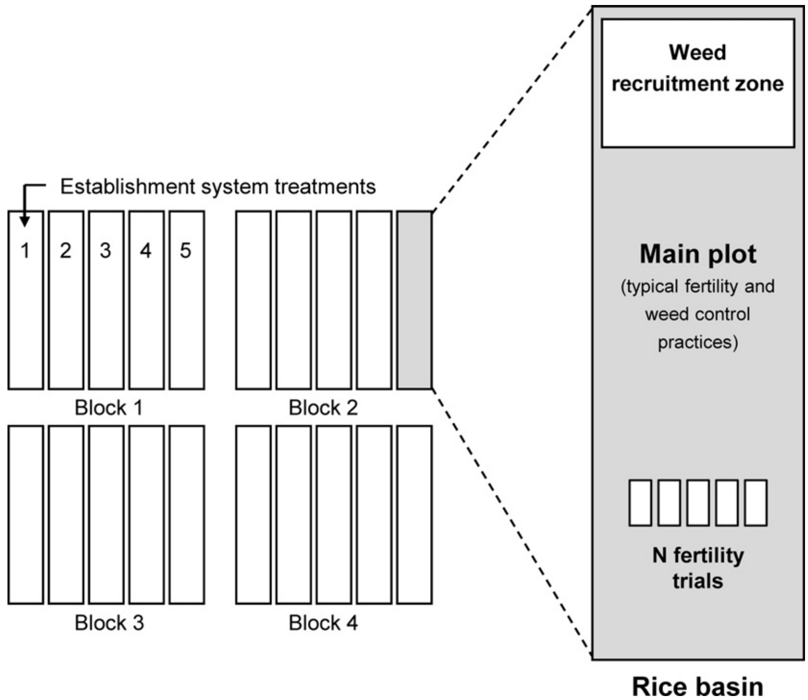

Fig. 1. Experimental plot layout. Individual basins were 0.2 ha in size and contained (i) the main plot, (ii) a permanent area for weed recruitment which received no herbicides except preplant glyphosate in stale seedbed treatments, and (iii) N fertility trials which moved locations each year.

2.2. Rice establishment systems

Five establishment systems were evaluated in this experiment (Table 1). The treatment layout did not change over the course of the experiment, thus each basin was under 4 years of continuous system management. Each establishment system represented a unique combination of tillage (conventional or no-till), seedbed preparation (regular or stale seedbed), and rice seeding method (WS or DS). The five treatments were water-seeded conventional tillage (WS conventional), water-seeded conventional tillage stale seedbed (WS stale), water-seeded no-till stale seedbed (WS no-till stale), drill-seeded conventional tillage (DS conventional), and drill-seeded no-till stale seedbed (DS no-till stale).

Agronomic management for each system followed typical N fertilizer (168 kg N ha^{-1}) and weed control practices for the region in accordance with current recommendations for California rice production (Fischer and Hill, 2004; Williams, 2010). N fertilizer was applied as urea except for topdress applications where N was applied as ammonium sulfate. To ensure that other nutrients were not limiting, 22 kg P ha^{-1} as triple super phosphate and 45 kg K ha^{-1} as potassium chloride were applied each spring prior to tillage or the previous fall after harvest. Conventional tillage practices consisted of several passes with a chisel-plow and disc, followed by final seedbed preparation with a triplane and roller. No-till practices in this study referred specifically to spring tillage events prior to crop establishment. In all systems and years, basins were seeded with a Calrose medium grain rice variety widely grown in the region (M-202). To determine grain yield, an area of 33 m^2 was harvested at rice physiological maturity with a small plot combine. Following harvest, combine ruts in the field were eliminated and straw was incorporated with a disc except in the first year where straw was removed. All basins were flooded each winter to promote straw decomposition.

The WS conventional treatment represented the conventional rice establishment practice for California and served as the control when assessing agronomic performance and weed control characteristics of alternative establishment systems. Pre-germinated rice seed was broadcast in all WS systems at 168 kg seed ha^{-1}, which 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). Basins were flooded several days prior to seeding and a permanent flood of 10–15 cm was maintained until the field was drained approximately one month prior to harvest. Two alternative WS establishment systems, both using the stale seedbed technique, were assessed. Weed recruitment irrigation flushes were performed to implement stale seedbeds the month prior to seeding. Depending on the year, rice basins were flooded and drained either once or twice to maximize weed emergence. Glyphosate was applied at a rate of 1.5 kg a.e. ha^{-1} several days before planting to eliminate weeds that had emerged. The WS stale treatment consisted of conventional tillage as described above followed by stale seedbed practices. For the WS no-till stale treatment, no-till management was combined with stale seedbed practices (Table 1). Following seeding, water management and weed control practices were similar for WS treatments throughout the growing season. Depending on the year, combinations of post-emergence herbicides (clomazone (0.7 kg a.i. ha^{-1}), propanil (6.7 kg a.i. ha^{-1}), bensulfuron (0.04 kg a.i. ha^{-1}), penoxsulam (0.04 kg a.i. ha^{-1})) were applied for broad spectrum control of primarily sedge and broadleaf weed species in WS systems (Fischer and Hill, 2004).

Two DS treatments were evaluated in this experiment. The DS conventional treatment consisted of conventional tillage as described above followed by DS crop establishment practices. For the DS no-till stale treatment, no-till management was combined with stale seedbed practices (Table 1). All DS systems were seeded with M-202 at 112 kg seed ha^{-1} using a grain drill with 19 cm spacing between rows. Although it has been shown that seeding rates of 25–30 kg ha^{-1} can be used successfully in DS systems (e.g. Gathala et al., 2011; Jat et al., 2009), this rate was selected based on previous reports indicating that panicle density and yields are maximized in DS systems between approximately 90 and 140 kg seed ha^{-1} (Harrell and Blanche, 2010; Jones and Snyder, 1987). During stand establishment, basins were flooded and drained 2–4 times and

Table 1
Crop establishment practices for water-seeded (WS) and drill-seeded (DS) rice establishment systems and corresponding dates of management each year.

Year	System	Tillage initiated	Weed recruitment flush 1	Weed recruitment flush 2	Glyphosate application	Seeding date	Permanent flood[a]	Harvest
2004	WS conventional	24 April	–	–	–	17 May	14 May	1 October
	WS stale	24 April	14 May	26 May	31 May	4 June	2 June	6 October
	WS no-till stale	No-till	14 May	26 May	31 May	4 June	2 June	11 October
	DS conventional	24 Apr	–	–	–	12 May	5 June	30 September
	DS no-till stale	No-till	14 May	26 May	31 May	3 June	23 June	12 October
2005	WS conventional	18 April	–	–	–	31 May	28 May	5 October
	WS stale	18 April	5 May	–	26 May	31 May	28 May	5 October
	WS no-till stale	No-till	5 May	–	26 May	31 May	28 May	5 October
	DS conventional	18 April	–	–	–	27 May	28 June	12 October
	DS no-till stale	No-till	5 May	–	26 May	27 May	28 June	12 October
2006	WS conventional	1 May	–	–	–	1 June	31 May	11 October
	WS stale	1 May	11 May	–	29 May	1 Jun	31 May	11 October
	WS no-till stale	No-till	11 May	–	29 May	1 June	31 May	11 October
	DS conventional	1 May	–	–	–	30 May	16 June	11 October
	DS no-till stale	No-till	11 May	–	29 May	30 May	16 June	11 October
2007	WS conventional	2 April	–	–	–	31 May	22 May	15 October
	WS stale	2 April	1 May	13 May	29 May	1 June	31 May	15 October
	WS no-till stale	No-till	1 May	13 May	29 May	1 June	31 May	15 October
	DS conventional	2 April	–	–	–	30 May	16 June	22 October
	DS no-till stale	No-till	1 May	13 May	29 May	30 May	16 June	22 October

[a] Prior to the permanent flood in DS systems, basins were flooded and drained several times for crop establishment.

the permanent flood generally occurred 20–30 d after seeding (Table 1). Water levels were maintained at 10–15 cm throughout the growing season and fields were drained approximately one month prior to harvest. Weed control practices were similar for DS treatments following seeding and depending on the year combinations of herbicides (pendimethalin (1.1 kg a.i. ha^{-1}), cyhalofop-butyl (0.3 kg a.i. ha^{-1}), propanil (6.7 kg a.i. ha^{-1})) were applied before the permanent flood for broad spectrum control in DS systems (Fischer and Hill, 2004).

2.3. Weed recruitment zones

To investigate the potential for improved weed control using no-till and stale seedbed practices in WS and DS rice systems, weed recruitment zones were established in each rice basin. While all other management practices remained the same as the main plot, herbicides were not applied to an area of approximately 300 m^2 each year with the exception of preplant glyphosate in stale seedbed treatments (Fig. 1). In the absence of chemical weed control after rice seeding, weed growth in these zones remained unchecked throughout the growing season. The location of this zone within each basin remained the same each year. Weed seed bank dynamics, early season emergence, and competition with rice were monitored throughout the experiment. A full analysis of these results is beyond the scope of the present paper and will be reported elsewhere. To assess the effects of each establishment system on weed control, weed biomass was determined at harvest. Nine aboveground biomass samples were obtained from each weed recruitment zone using 0.09 m^2 quadrats in randomly selected locations. Weed biomass was separated into the following species and subsequently dried to a constant weight at 65 °C: watergrass (*Echinochloa* spp.), sprangletop (*Leptochloa fascicularis*), smallflower umbrella sedge (*Cyperus difformis*), ricefield bulrush (*Schoenoplectus mucronatus*), and redstem (*Ammannia* spp.).

2.4. Nitrogen fertility trials

Optimum management of N fertilizer was investigated using N fertility trials in each establishment system (Fig. 1). Trials were arranged as a split-plot design and were moved to a new location within main plots each year to avoid the residual effects of N fertilizer over time (Reddy and Patrick, 1978). N fertilizer in the form of urea was applied to 37.2 m^2 sub-plots at the following rates: 0, 112, 168, and 224 kg N ha^{-1}. Due to differences in water management between WS and DS systems as well as requirements for no-till and stale seedbed establishment practices, timing and placement of N applications varied among systems. In WS systems, N fertilizer was either applied completely preflood (i.e. prior to the permanent flood at planting) or split between preflood and midseason (i.e. topdressed between mid-tillering and panicle initation). Previous work in DS systems has suggested 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). Therefore, in DS systems N fertilizer was either applied preflood, split between preplant (i.e. directly before seeding) and preflood, or split between preflood and midseason. For WS conventional and DS conventional systems, preplant N was incorporated into the soil with a harrow. For all other systems and midseason applications, N was broadcast on the soil surface or into the floodwater. At physiological maturity, yields were determined in N sub-plots from an area 0.6–1 m^2 in size depending on the year. All grain yield results reported represent rough rice yields adjusted to 14% grain moisture content.

2.5. Data analysis

Analysis of variance was performed on weed biomass and grain yield results using the PROC GLM procedure of SAS® software, version 9.1 of the SAS System for Windows (SAS Institute Inc., 2004). If results violated ANOVA assumptions they were transformed accordingly using $\log_{10}$ or power functions. For presentation of results all means were de-transformed where necessary. Significant differences between systems were determined using LS MEANS pairwise comparisons ($P < 0.05$). For weed biomass results, weed species were considered to be present when the mean was significantly different from zero. Analysis of variance for weed biomass and grain yields was initially performed across years but results were subsequently analyzed by year when significant year by treatment interactions were detected.

Nitrogen fertility trial results were used to evaluate the relationship between grain yield and N rate. Based on recent work indicating that quadratic yield response functions provide the best model fit and are the most reliable across soils and varieties for

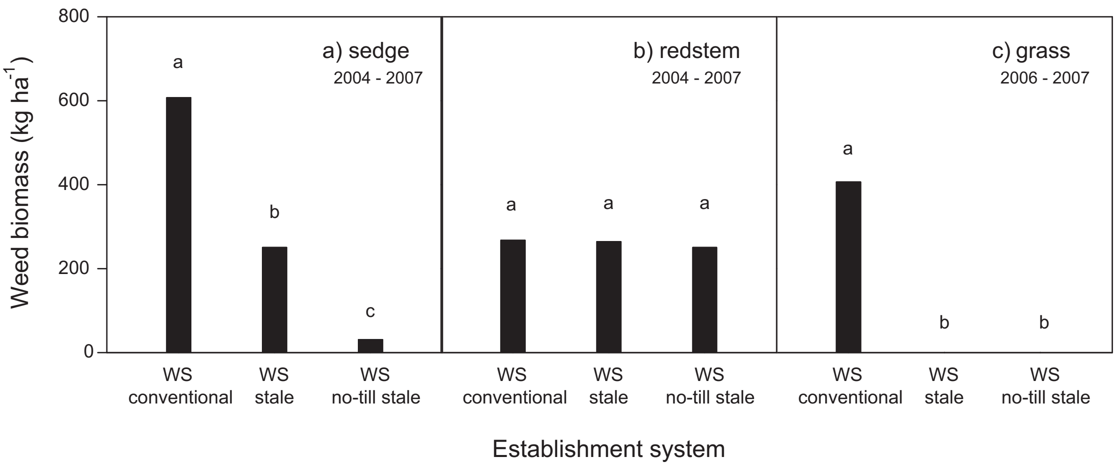

Fig. 2. Weed biomass in weed recruitment zones of WS systems at rice harvest. Means for (a) sedge species (smallflower umbrella sedge and ricefield bulrush) and (b) redstem were averaged over 2004–2007 as there was no year by system interaction. Means for (c) grass species (watergrass and sprangletop) were averaged over 2006–2007 as grasses were not present in 2004–2005. See Table 1 for treatment descriptions. Within each panel, bars with the same letter are not significantly different at $P < 0.05$.

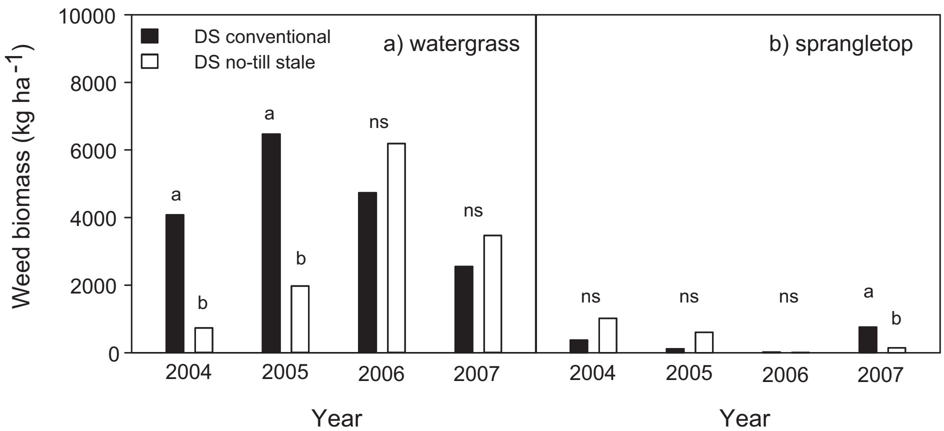

Fig. 3. Weed biomass in weed recruitment zones of DS systems at rice harvest. Means for (a) watergrass and (b) sprangletop are presented by year due to a significant year by system interaction. Aquatic weed species (smallflower umbrella sedge, ricefield bulrush, and redstem) were not present in DS systems. See Table 1 for treatment descriptions. Within each year, bars with the same letter are not significantly different at $P < 0.05$.

rice production systems (Watkins et al., 2010), a quadratic yield response function including fixed and random effects was fit to N fertility trial data for 2004–2007 using the PROC MIXED procedure of SAS software, version 9.1 (SAS Institute Inc., 2004). The final model included fixed effects of N rate, N rate × N rate, System, and System × N rate. Year and block were designated as random effects with a random slope and intercept estimated for each block-year combination using an unstructured covariance matrix (Linquist et al., 2009; Miguez and Bollero, 2006). Terms for non-significant effects were removed to increase model parsimony (this included system × N rate × N rate and system × year interactions). In a few cases, where N was either applied in a manner inconsistent with established best management practices or treatment N rates changed over time, treatments were excluded from the analysis (e.g. several N rates in 2004 were experimental and not repeated in later years, thus only yield results for 0 and 168 kg N ha^{-1} plots were included). Analysis of variance was performed with the regression model and contrasts were used to further partition the sum of squares. Intercepts and initial slopes (i.e. N rate coefficients) were considered significantly different between systems at $P < 0.05$.

Economic optimum nitrogen (EON) rates were calculated for each establishment system using the quadratic yield response functions described above. EON rates are based on the price of rice and cost of N fertilizer and reflect the point at which maximum returns to N are achieved for a given yield function. Model coefficients were used to determine EON rates following Bullock and Bullock (1994) and Watkins et al. (2010). Economic input values included the average price of rice in California and the average cost of urea fertilizer over the duration of the study period (USDA National Agricultural Statistics Service, 2011), as well as the cost of custom service N fertilizer application for rice grown in this region (Mutters et al., 2007). Since the relationship between N fertilizer cost and rice price can vary substantially year to year, multiple N cost/rice price ratios were considered. EON rates were estimated using the range of N cost/rice price ratios observed in California for the period 2000–2010 to enable growers to maximize returns to N despite price fluctuations (Dobermann et al., 2011).

3. Results

3.1. Weed recruitment zones

In weed recruitment zones, grass weed species (watergrass and sprangletop) represented more than 99% of total weed biomass across years in DS systems. Aquatic weed species (smallflower umbrella sedge, ricefield bulrush, and redstem) were not present in DS systems. In WS systems, aquatic species (smallflower umbrella sedge, ricefield bulrush, and redstem) represented more than 95% of total weed biomass during the first two years and 80% during the second two years (data not shown). Grass species (watergrass and

Table 2
Rice grain yield for main plots where 168 kg N ha^{-1} was applied and full weed control occurred. Mean values for 2004–2007 are presented under a separate column as there was no year by system interaction. Within a column, values followed by the same letter are not significantly different at $P < 0.05$.

System	Grain yield, kg ha^{-1}				
	2004	2005	2006	2007	Mean
WS conventional	10,652	8170	8874	7859	8954 a
WS stale	9437	7342	8265	8047	8273 b
WS no-till stale	10,420	8175	8352	9029	8994 a
DS conventional	10,802	8410	9117	8398	9130 a
DS no-till stale	10,294	8292	10,042	9454	9520 a
ANOVA results	ns	ns	ns	ns	$P = 0.007$

sprangletop) were not present in WS systems the first two years, but became a problem in the WS conventional system and represented approximately 55% of total weed biomass in the last two years (Fig. 2). In both DS and WS systems, weed control was significantly improved when alternative establishment practices were implemented (Figs. 2 and 3). In the WS conventional system, sedge species (smallflower umbrella sedge and ricefield bulrush) produced approximately 600 kg biomass ha^{-1} each year. Stale seedbed and no-till stale seedbed practices significantly reduced sedge biomass by 59 and 95%, respectively (Fig. 2a). Alternative WS systems reduced grass biomass by more than 99% when present, but the aquatic redstem escaped control (Fig. 2b and c). In DS systems, weed dynamics differed and a significant year by treatment interaction was observed. Watergrass and sprangletop represented 90% and 10%, respectively, of total grass weed biomass (Fig. 3). The DS no-till stale system significantly reduced watergrass biomass by 75% compared to the DS conventional system in the first two years, but these effects were not consistent over time and reductions were not observed during the last two years (Fig. 3a). Sprangletop only represented a minor portion of grass weed biomass and the DS no-till stale system improved sprangletop control in one year (Fig. 3b).

3.2. System productivity

Outside of weed recruitment zones where N was applied at 168 kg N ha^{-1} and weeds were controlled in accordance with current recommendations, grain yields were not different for conventional and alternative rice establishment systems each year (Table 2). However, when analyzed over the duration of the study period, yields for the WS stale system were significantly lower than the other four systems. Mean yields ranged from 8273 kg ha^{-1} in the WS stale system to 9520 kg ha^{-1} in the DS no-till stale system, with WS and DS conventional systems producing 8954 and 9130 kg ha^{-1} on average, respectively. Overall, mean yields from this experiment were very close to statewide yield averages observed during this period (USDA National Agricultural Statistics Service, 2011).

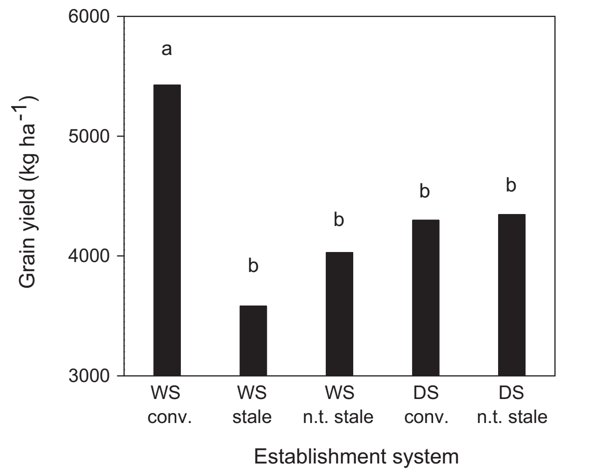

Fig. 4. Rice grain yield when no N fertilizer was applied and full weed control occurred. Values for 2004–2007 were averaged as there was no year by system interaction. See Table 1 for treatment descriptions. Bars with the same letter are not significantly different at $P < 0.05$.

3.3. Nitrogen management

When no N fertilizer was applied, yields for control plots were significantly lower for alternative establishment systems compared to the WS conventional system (Fig. 4). Yields without N fertilizer ranged from 3580 kg ha^{-1} in the WS stale system to 4343 kg ha^{-1} in the DS no-till stale system, with the WS conventional system producing 5424 kg ha^{-1} on average. The response of grain yield to N rate was significantly different among systems (Fig. 5 and Table 3). The regression analysis indicated a significant linear and quadratic effect of N on grain yield, as well as a significant system × N rate interaction (Fig. 5). The quadratic parameter of the model was not significantly different between systems, thus it was held constant at −0.117 for EON calculations. In WS systems, modeled intercepts were lower for both WS stale and WS no-till stale systems as compared to the WS conventional system. The yield response to N rate was similar for WS conventional and DS conventional systems (Table 3).

Estimated EON rates were lowest for the WS conventional system and highest for WS stale and WS no-till stale systems (Table 4). Depending on the N cost/rice price ratio, WS stale and WS no-till stale systems required around 30–35 kg N ha^{-1} more than the WS conventional system. In contrast, both DS systems required a similar amount of N fertilizer as the WS conventional system to maximize returns. Predicted yields and returns to N were comparable among systems, with the WS no-till stale system having slightly larger and the DS no-till stale system having slightly smaller values with respect to the WS conventional system. When the N cost/rice price ratio increased or decreased relative to the average value of 6, EON rates shifted approximately 10–15 kg N ha^{-1} and differences between systems remained similar in magnitude.

Table 3
Regression analysis results for the response of grain yield to N rate in water-seeded (WS) and drill-seeded (DS) rice establishment systems. A quadratic yield response function was fit to N fertility trial data for 2004–2007 using a mixed-effects model.

ANOVA		Model coefficients					Contrasts	P-value	
Fixed effect	P-value	System	Intercept	SE	Linear	SE		Intercept	Linear
N	<0.0001	WS conventional	5205	429	46.5	3.7	WS conv. vs. WS stale	<0.0001	0.009
N × N	<0.0001	WS stale	3445	414	54.3	3.6	WS conv. vs. WS no-till stale	0.016	0.025
System	0.002	WS no-till stale	4161	416	53.4	3.6	WS stale vs. WS no-till stale	0.085	0.747
System × N	0.032	DS conventional	4466	452	48.3	3.8	WS conv. vs. DS conv.	0.112	0.573
		DS no-till stale	4298	456	48.1	3.5	DS conv. vs. DS no-till stale	0.954	0.954

Table 4
Economic optimum nitrogen (EON) rates, predicted grain yields, and returns to N fertilizer for the range of N cost/rice price ratios observed in California during 2000–2010.

System	N cost/rice price ratio								
	9			6			3		
	EON (kg ha^{-1})	Yield (kg ha^{-1})	Returns ($ ha^{-1})	EON (kg ha^{-1})	Yield (kg ha^{-1})	Returns ($ ha^{-1})	EON (kg ha^{-1})	Yield (kg ha^{-1})	Returns ($ ha^{-1})
WS conventional	160	9653	2197	173	9750	2332	186	9807	2478
WS stale	194	9580	2119	207	9676	2280	219	9734	2451
WS no-till stale	190	10,077	2253	203	10,173	2412	215	10,231	2580
DS conventional	168	9288	2089	181	9384	2231	194	9442	2382
DS no-till stale	167	9082	2037	180	9178	2178	193	9236	2329

4. Discussion

4.1. Weed recruitment zones

A more detailed analysis of weed emergence, competition with rice, and community dynamics as affected by establishment system will be reported in another paper. Three key concepts based on weed biomass results at rice harvest will be discussed here. First, rice seeding method had a significant impact on weed recruitment. Aquatic weeds were primarily present in WS systems while grasses were exclusively present in DS systems. Therefore, both DS systems provided complete control of aquatic weeds relative to the WS conventional system. This can be attributed to differences in water management practices during crop establishment and corresponding soil moisture and temperature conditions that are known to influence weed germination (Caton et al., 2002; Juraimi et al., 2011). In terms of long-term weed management strategies for California, these results suggest that alternating between WS and DS establishment systems may form part of an ecological approach for suppressing aquatic weed species.

Second, while stale seedbed practices significantly improved sedge and grass weed control in WS systems, when combined with no-till practices even more dramatic reductions were achieved (Fig. 2a and c). On the contrary, Chauhan and Johnson (2009) reported that no-till practices alone increased weed germination and Shad and De Datta (1986) found total weed biomass was often greater and decreased yields. Therefore, no-till practices on their own may not be an effective weed management tool and should be combined with stale seedbed practices and other integrated weed management strategies (Murphy and Lemerle, 2006; Rao et al., 2007). In particular, strategies for late-season broadleaf control are needed as alternative systems did not reduce redstem biomass (Fig. 2b), likely due to poor germination of redstem during stale seedbed implementation and delayed emergence with respect to rice.

Third, no-till stale seedbed practices were more effective in WS compared to DS systems. Although the DS no-till stale system reduced watergrass biomass by 75% during the first two years of this study, it performed similar to the DS conventional system during the second half. This is most likely because the seedbed is disturbed by drill openers at planting in DS systems, bringing more weed seeds to the surface where germination rates are higher (Chauhan and Johnson, 2009). In addition, because weeds were not controlled each season in weed recruitment zones, seeds likely became concentrated at the soil surface over time (Chauhan et al., 2006). Increased germination of surface seeds in no-till systems may have potentially outweighed weed control benefits observed in the first two years. Alternatively, further fine-tuning of stale seedbed practices to specifically target shallow seeds might allow for a substantial portion of the seed bank to be eliminated prior to rice seeding in no-till systems. Along with other weed control considerations, these aspects of WS and DS systems must be evaluated to determine the most suitable establishment system for a given context (e.g. in areas where manual or mechanical weeding is practiced instead of chemical weed control, DS systems with defined rows and inter-rows may be favored over broadcast WS systems).

4.2. System productivity

Results from this four-year field experiment indicate that under recommended fertility and weed control practices, alternative rice establishment systems consistently produce grain yields similar to conventional establishment practices (Table 2). This is an important finding in light of the pressing global need for development and adoption of rice production systems that maintain agronomic productivity while conserving natural resources (Gupta and Seth, 2007; Timsina and Connor, 2001).

In support of our findings, prior research has shown that WS and DS systems with conventional tillage produce equal yields

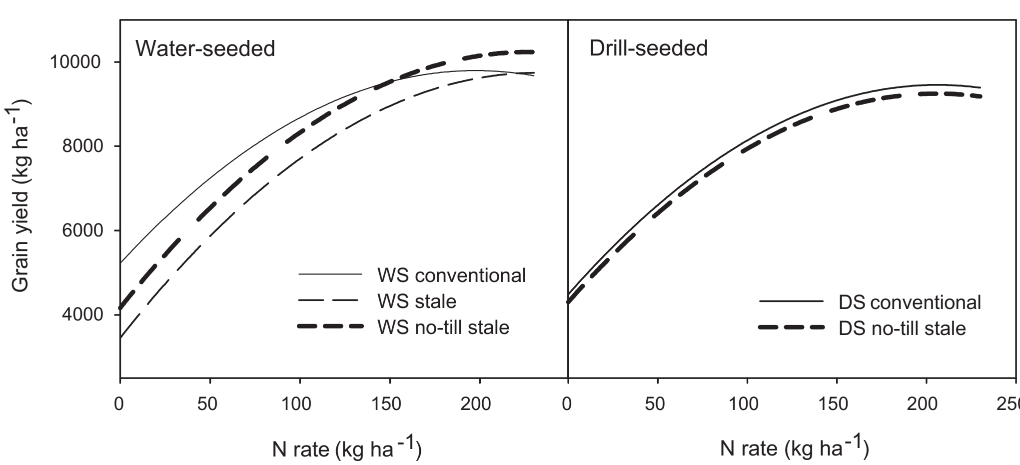

Fig. 5. The response of rice grain yield to N rate in water-seeded and drill-seeded rice establishment systems as modeled by a mixed-effects quadratic yield response function fit to N fertility trial data for 2004–2007. Regression analysis results are displayed in Table 3.

(Choudhury et al., 2007; Westcott et al., 1986). Moreover, while evaluating no-till management for WS rice systems, Bhattacharyya et al. (2008) found no differences in yield between conventional and no-till practices over a four-year period. Likewise, Saharawat et al. (2010) reported that comparable yields were achieved in WS systems with conventional tillage and DS systems under no-till management. Along with prior work in the region (Bhushan et al., 2007), Saharawat et al. (2010) indicated that alternative systems significantly reduced machine labor and other inputs which led to higher net returns. Although not directly quantified in our study, it was observed that considerable savings in labor and energy were associated with no-till practices while yields remained similar, suggesting net returns may also increase with no-till practices in California. The economic performance of alternative establishment systems is important and further research on this topic is warranted.

More recently, a four-year study on alternative seeding and tillage practices reported inconsistent yield results across sites in northern India (Singh et al., 2011). In one portion of the study alternative establishment systems maintained yield levels of WS conventional systems at multiple research locations. In contrast, at the primary research site it was found that DS systems with conventional tillage yielded significantly lower than WS systems and furthermore, that no-till practices reduced yields within DS systems. Our results do not support this data; however, these differences may in part be explained by irrigation practices. In our study a permanent flood was maintained in both WS and DS systems after crop establishment, whereas in Singh et al. (2011) crops relied on rainfall and supplemental irrigation. These authors noted that similar yields among systems were primarily achieved at sites which received large amounts of supplemental irrigation, suggesting that the potential for yield loss under alternative establishment practices may increase in areas where it is difficult to meet crop water demands.

Importantly, yields for alternative establishment systems did not decline over this four-year study. Yield stability is a critical aspect of alternative cropping systems that has received little attention despite the potential for no-till practices to influence soil properties and therefore agronomic productivity over time (Jat et al., 2009; Timsina and Connor, 2001). Although some variation was observed in our results, yields for no-till systems in particular remained consistent. Gathala et al. (2011) reported similar findings from a seven-year study on no-till DS systems, with additional data indicating that soil physical properties relevant to crop production improved under no-till management. If these systems are to be adopted by growers in the future, yield and yield stability need to be maintained in addition to soil quality. Indeed, short-term monetary gain rather than resource conservation tends to be the primary driver of on-farm experimentation and adoption (Erenstein et al., 2008).

4.3. Nitrogen management

Our results indicate that grain yield response to N is significantly different among systems (Table 3), with alternative establishment practices generally requiring more N fertilizer to attain yields similar to conventional systems (Table 4). Efficient N management is an important aspect of environmental quality that has often been overlooked in previous studies on alternative systems (Farooq et al., 2011), and these results highlight the need for careful consideration of N inputs and management when undertaking research and extension efforts in the future.

In control plots where no N fertilizer was applied, grain yields were lower for alternative establishment systems. In particular, when stale seedbed practices were combined with conventional tillage, yield was reduced by approximately 1800 kg ha^{-1} compared to the WS conventional system. Since other nutrients were not limiting in this study, the observed differences in grain yield suggest there was a decrease in soil N supply under alternative establishment practices. Preseason water management including flood–drain events during stale seedbed implementation may have contributed to greater N losses prior to rice seeding (George et al., 1993). When soil is subjected to aerobic–anaerobic cycles, nitrate concentrations tend to increase during aerobic periods but then rapidly decrease when fields are flooded, with soil nitrate presumably lost through denitrification processes (Becker et al., 2007; Linquist et al., 2011). These cycles have been shown to significantly reduce the total N content of soil (Patrick and Wyatt, 1964), thereby decreasing soil N available to the crop. Moreover, because tillage increases soil N mineralization and nitrification processes (Grace et al., 1993), it is likely that preseason N losses were exacerbated in the WS stale system where stale seedbed flushes directly followed spring tillage. This potentially explains why yields from control plots were lowest for this system. While preseason N losses are known to occur and can be substantial for rice systems (George et al., 1993), it is also possible that there were differences in N availability following seeding (Kundu et al., 1996). Overall these results suggest that soil N supply, which underpins the agronomic productivity of flooded rice production (Cassman et al., 1996), is strongly influenced by establishment system and further research on this topic is needed.

Based on yield response to N functions and three different ratios for the cost of N relative to the price of rice, estimated EON rates for the WS conventional system were in agreement with current recommendations for California rice production (Williams, 2010). However, EON rates for alternative systems indicated that an increase of 30–35 kg N ha^{-1} was needed to maximize yields and returns to N in WS stale and WS no-till stale systems. It has previously been documented that higher N rates are required as a result of no-till practices in transplanted rice (Gathala et al., 2011; Lal, 1986), but few investigations have been conducted in WS systems. Reductions in native soil N supply, evidenced by low yields from control plots as discussed above, likely contributed to the increased need for N fertilizer in alternative systems. For example, the WS stale system had the lowest yield without addition of N fertilizer and in turn required the highest N rate to attain yields equivalent to the WS conventional system (Fig. 4; Table 4).

The higher N requirements of the WS stale system likely explain why grain yields were significantly lower when 168 kg N ha^{-1} was applied in main plots compared to the WS conventional system over the four-year study period (Table 2). Conversely, yield differences in main plots were not observed for DS systems compared to the WS conventional system, as estimated EON rates for these systems more closely matched each other (Table 4). Overall, within DS systems our results are consistent with prior work showing N requirements are similar for conventional tillage and reduced or no-till stale seedbed practices (Griggs et al., 2007; Harrell et al., 2011). Moreover, they are supported by conclusions for DS systems on clay soils where maximum yields and returns to N were achieved around 180 kg N ha^{-1} (Watkins et al., 2010).

Despite higher EON rates in some cases, our results show that predicted yields and returns to N were comparable among systems and remained relatively stable across a wide range in N fertilizer cost/rice price ratios. This indicates that alternative systems are viable from an economic standpoint provided N rates are close to optimal (Watkins et al., 2010). Furthermore, these results suggest that improvements in N fertilizer efficiency may lead to greater returns in alternative systems. One option to increase N recovery and yield by rice is to split N applications (De Datta, 1987; Patrick and Reddy, 1976); however, within our N fertility trials yield results for split N rates were inconsistent among establishment systems and varied by year (data not shown). Therefore, further research on

N timing is needed to better synchronize N availability with crop N demand in alternative systems, particularly those having greater N requirements.

5. Conclusions

Adequate weed control to prevent yield loss is a primary challenge in direct-seeded rice. This study evaluated weed recruitment and biomass dynamics, agronomic productivity, and N management strategies to meet yield potential in a range of alternative WS and DS rice establishment systems in California. No-till stale seedbed practices were effective at reducing weed populations in the first two years in DS systems and throughout the study in WS systems. These findings suggest that along with alternating between WS and DS systems, no-till stale seedbed practices may form part of an ecological approach for long-term weed control in California. Adding to a growing body of literature, our results demonstrate that agronomic productivity was similar for alternative tillage and seeding practices assessed in this study. However, likely due to differences in water management and corresponding soil N losses, estimated economic optimum N rates were 30–35 kg N ha^{-1} higher in alternative compared to conventional WS systems. Despite higher N requirements, predicted yields and returns to N were similar among establishment systems and across ratios for the price of rice relative to the cost of N fertilizer. These results highlight the fact that alternative establishment systems are capable of providing improved weed control while remaining viable from an agronomic and economic standpoint, yet careful consideration of N inputs and management is needed when undertaking research and extension efforts related to these systems in the future.

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