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Combining stale seedbed with deep rice planting: a novel approach to herbicide resistance management?

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Abstract

Water seeding is a common cropping strategy in mechanized rice systems. Water seeding of rice can suppress grass weeds, but it can also encourage aquatic weeds and grass ecotypes that escape deep floodwater. In addition, water seeding prevents many cultural methods of weed control and limits available herbicides. Selection pressure from a limited palette of herbicides has resulted in widespread resistance in rice grown in California. This study examined a novel combination of drill seeding and a stale seedbed ("stale-drill") as a means of using a nonselective herbicide to manage weeds before rice emergence. In 2016 and 2017, rice cultivar 'M-206' was drilled at a rate of 120 kg ha^{-1} to 1.3-cm, 2.5-cm, and 5.1-cm depths. Planting rice deeper than 1.3 cm delayed emergence by 3 to 4 d. A postplant-burndown (PPB) treatment of glyphosate at 870 g ha^{-1} was applied just prior to rice emergence. Treatment delays had mixed effects on weed control. PPB treatment was more effective at controlling *Echinochloa* spp. in 2017, reducing density by 30%, 48%, and 73% at 1.3-cm, 2.5-cm, and 5.1-cm seeding depths, respectively. The greatest overall weed control either year was found with applications of glyphosate + pendimethalin followed by penoxsulam + cyhalofop at 1.3-cm planting depth. Rice stand and yield components were more strongly affected by planting depth in 2017 than in 2016, possibly owing to cool weather immediately after seeding. Yields in 2017 were reduced in deeper plantings by up to 72%. Therefore, if the stale-drill method is implemented with higher-vigor cultivars or higher seeding rates, we see potential in this method as a useful tool for reducing herbicide-resistant weeds in rice fields.

Introduction

The California rice growing region comprises approximately 200,000 ha in the Sacramento Valley. The rice cropping system is almost exclusively water-seeded, wherein pre-germinated seed is sown by aircraft into flooded fields. Seeds sink to the soil surface and peg down roots, and seedlings emerge from the water after a few days. Floodwaters are generally kept to a depth of 10 to 20 cm for the entire season. Water seeding was widely adopted in the region in the 1920s as a means to suppress competitive grass weeds (Adair and Engler 1955), and has been the predominant method of rice cultivation in California ever since (Hill et al. 1994). Continuous use of water seeding has resulted in a small spectrum of weed species that are well-adapted to the system, and are very competitive with rice (Hill et al. 1994).

Water seeding conditions encourage aquatic broadleaf weeds such as arrowheads (*Sagittaria* spp.), ducksalad [*Heteranthera limosa* (Sw.) Willd.], resdstems (*Ammannia* spp.), and *Monochoria* spp.; and the sedges ricefield bulrush [*Schoenoplectus mucronatus* (L.) Palla], tall flatsedge (*Cyperus eragrostis* Lam.), and smallflower umbrella sedge (*C. difformis* L.). In addition, grass ecotypes that are able to escape flooding depths of up to 20 cm, such as barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.; Adair and Engler 1955], early watergrass [*E. oryzoides* (Ard.) Fritsch], late watergrass [*E. oryzicola* (Vasinger) Vasinger; Fischer et al. 2000], and bearded sprangletop [*Leptochloa fusca* (L.) Kunth ssp. *fascicularis* (Lam.) N. Snow; Driver et al. 2019] have become an important weed management issue in California rice. Because a permanently flooded cropping system effectively precludes the use of most other cultural weed management practices, for most growers herbicides are the sole means of weed control outside of water management (Hill et al. 2006).

Although effective herbicides have been available for California rice since the 1960s, the nearly exclusive use of the water-seeded system has meant that the number of registered active ingredients remains small, amid water contamination concerns and California's stringent regulatory structure (Hill et al. 1994). To date, there are 13 registered active ingredients for water-seeded rice in California, across nine modes of action (MOAs; Espino et al. 2019). Most MOAs have only one registered active ingredients (UCANR 2018). This limited palette restricts herbicide rotation. Because California's rice acreage is largely planted back to rice each year, the combined effects of water-seeded monoculture, limited available herbicides, and extensive use of individual MOAs on a small weed spectrum has resulted in widespread cases of herbicide resistance in the region (Brim-DeForest et al. 2017b; Hill et al. 2006).

Herbicide resistance has been a major biologic and economic issue in California rice production for decades (Fischer et al. 2000; Hill et al. 1994; Peterson et al. 2018). The lack of diversity of registered herbicide active ingredients and MOAs means that once resistance to a particular MOA arises, it can spread rapidly within and between fields because there may be few alternative herbicides to control the resistant populations. For example, only three effective herbicides are available to treat bearded sprangletop populations that are resistant to clomazone (Driver et al. 2020), and two of those three, cyhalofop and thiobencarb, are subject to long water-holding restrictions after application, which may reduce their utility for some growers. Efforts to combat herbicide resistance in California are also hampered by the fact that rice herbicides are costlier in California than in much of the world. Therefore, many growers are forced to increase herbicide input costs to potentially unsustainable levels in order to control resistant weeds in their fields.

Most cultural methods for weed and resistance management in California are modifications of the dominant water-seeded system (Hill et al. 1994). One such method used by some growers is a stale seedbed. In this method, rice seedbeds are prepared as usual and flushed with water to promote weed germination. Broad-spectrum herbicides are used as a burndown treatment (Hill et al. 2006), and afterward the fields are flooded and seeded as usual. This method can be a useful strategy to manage weeds that are resistant to rice herbicides, and for reducing weed seedbanks. However, use of a stale seedbed can delay rice planting, thus shortening the growing season and potentially depressing yields (Rao et al. 2007).

Another common practice in mechanized rice cropping systems is drill seeding. Drill seeding typically involves drilling seed to 1.25 cm to 2 cm and then flush-irrigating fields for the first few weeks as the rice stand develops and herbicides are applied, before flooding for the remainder of the season (Gravois and Helms 1994). This method discourages aquatic weeds and algae, but tends to favor grasses (Hill et al. 1994). Furthermore, because the crop is typically sown to a fairly shallow soil depth, it emerges synchronously with competitive grasses (Smith et al. 1977). If rice is drilled to depths greater than 2 cm, however, the rice stand should emerge later than the majority of grasses and sedges. This may allow novel weed management practices to be used without causing injury to the emerging rice (Ceseski et al. 2020).

Although older semidwarf rice cultivars tended to have lower emergence rates from deep plantings (Dilday et al. 1990; McKenzie et al. 1980), higher vigor semidwarf cultivars have been produced in recent years (Alibu et al. 2011; Ju et al. 2007). For example, California rice cultivars are bred for water-seeding, and thus have suitable seedling vigor to emerge through water depths of up to 20 cm (McKenzie et al. 2015). This high vigor may make California rice suitable for drill seeding to depths greater than 2 cm.

If rice cultivars can emerge quickly and evenly from deeper planting, it may be possible to combine a stale seedbed with drill seeding. This "stale-drill" method could permit the use of herbicidal MOAs not registered for use in water-seeded rice. This would allow growers to safely manage herbicide-resistant weeds and reduce seedbanks prior to rice stand emergence, without injuring stands, delaying planting, or shortening the season. If used in rotation with water seeding, stale-drill can also vary the weed spectrum year over year, thereby reducing the tendency of a small number of species to dominate. In this way, the stale-drill method might be a useful tool for herbicide resistance management in mechanized rice production worldwide. The purpose of this study was to test the hypothesis that drilling rice below the zone of active weed germination would delay rice stand emergence sufficiently to allow a safe application of a nonselective postplant-burndown (PPB) herbicide treatment.

Materials and Methods

Field Location and Conditions

Field experiments were conducted at the Rice Experiment Station in Biggs, CA, in 2016 and 2017. The study field location is approximately 39.45°N, 121.72°W. Soils at the site are classified as Esquon-Neerdobe (Vertisols: fine, smectitic, thermic, Xeric Epiaquerts or Duraquerts), with an average pH of 5.1, and 2.8% organic matter. The rice growing season in the Sacramento Valley is typically from April/May to September/October. Average minimum and maximum temperatures (Figure 1) for the 2016 (May 22 to October 19) growing season were 14.5 C and 32.1 C, respectively, and for 2017 (June 8 to October 27) they were 15.6 C and 37 C, respectively (CADWR 2016–2017). Seedbed preparation and cultural practices followed current University of California guidelines (UCANR 2018).

Study Materials and Experimental Design

Experiments were conducted as a split-plot design, with planting depth as the main plots and herbicide protocol as the subplots, with four replications in 2016, and three replications in 2017. Main plots consisted of 17-m by 18-m blocks that were encased by 2.2-m-wide levees to allow independent flush-irrigation and flooding of each block. The cultivar planted was 'M-206', a Calrose-type medium grain *japonica* that is the most commonly planted cultivar in California (UCANR 2018). Rice was dry-drilled to 1.3-cm, 2.5-cm, and 5.1-cm depths at a rate of 120 kg ha^{-1}, using a mechanical seed drill (Great Plains Manufacturing Inc., Salina, KS) with 17.8-cm row spacing. Planting dates were May 22, 2016, and June 8, 2017 (Table 1).

Within each planting depth, herbicide treatments were applied in 3-m by 6-m subplots (hereinafter referred to as "plots"). Five herbicide treatments were applied (Table 2), plus an untreated control (UTC). Treatment applications were timed on rice emergence or development stages as they were reached at each rice planting depth. Herbicides were applied with a CO_2-pressurized boom sprayer with six 8003XR flat-fan nozzles (TeeJet Technologies, Springfield, IL), calibrated to deliver 187 L ha^{-1}. All plots except UTC received a PPB application of glyphosate (Roundup WeatherMAX®; Bayer CropScience, St. Louis, MO) at 870 g ae ha^{-1} + 2% wt/vol ammonium sulfate applied just as rice seedlings were beginning to emerge, at each planting depth. Follow-up treatments of pendimethalin (Prowl® H_2O; BASF Corporation, Research Triangle Park, NC) at 1,070 g ai ha^{-1} were applied either with or without a foliar mixture of propanil + halosulfuron (RiceEdge® 60 DF; RiceCo LLC, Memphis, TN), cyhalofop (Clincher® CA; Corteva Agriscience, Wilmington, DE), or penoxsulam (Granite® SC; Corteva Agriscience) at 6,730, 52, 270, and 40 g ai ha^{-1}, respectively (Table 2). Foliar herbicides were applied with 2.5% vol/vol crop oil concentrate. Follow-up

Table 1. Timing of crop operations, irrigation events, and herbicide treatments in 2016 and 2017.

Year	Planting date	Planting depth	First rice emergence	Irrigation flushes	Herbicide applications[a]	Flooding date
2016	May 22	1.3 cm	May 29	May 22, May 31, June 8, June 13	PPB, May 30[b]; EPOST, June 12; MPOST, June 19	June 21
		2.5 cm	June 1	May 22, May 31, June 8, June 13, June 21	PPB, June 2; EPOST, June 19; MPOST, June 27	June 30
		5.1 cm	June 2	May 22, May 31, June 8, June 13, June 21	PPB, June 2; EPOST, June 27; MPOST, June 27	June 30
2017	June 8	1.3 cm	June 16	June 8, June 17, June 22	PPB, June 16; EPOST, June 26; MPOST, June 29	July 1
		2.5 cm	June 19	June 8, June 17, June 24, July 1	PPB, June 20; EPOST, July 5; MPOST, July 7	July 9
		5.1 cm	June 20	June 8, June 17, June 24, July 1, July 9	PPB, June 21; EPOST, July 11; MPOST, July 15	July 16

[a]Abbreviations: PPB, postplant-burndown; EPOST, early postemergence; MPOST, mid postemergence.
[b]PPB applications were timed to observed rice emergence at each planting depth, while EPOST and MPOST applications were timed to rice 3-leaf and 5-leaf stages, respectively.

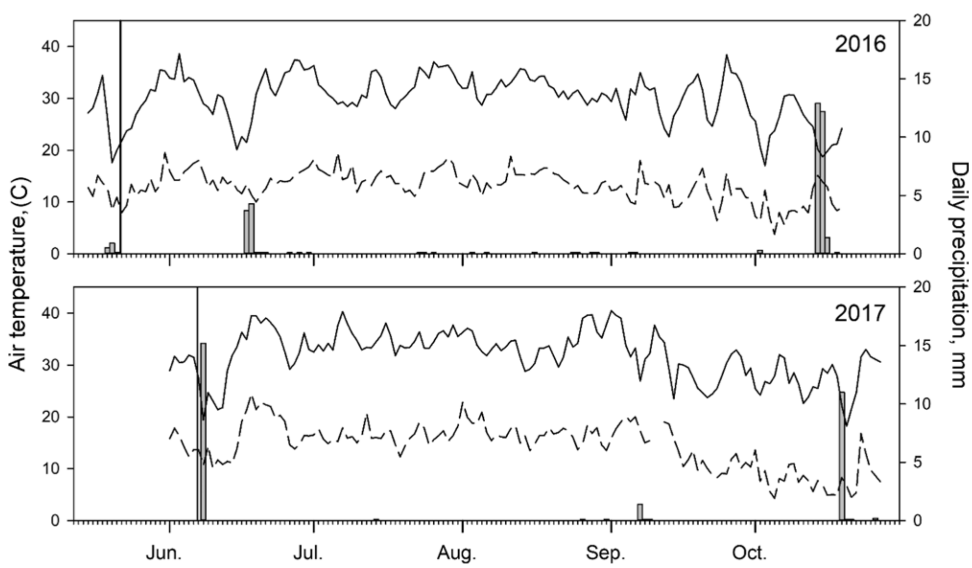

Figure 1. Daily temperature extremes and daily rainfall for 2016 and 2017 seasons. Solid and dashed lines are daily maximum and minimum temperatures (in degrees C), respectively. Bars are daily precipitation (mm). Vertical lines are planting dates of May 22, 2016, and June 8, 2017.

treatments were applied either as early postemergent (EPOST) or mid postemergent (MPOST) treatments to rice at the 3-leaf (3 LS) or 5-leaf (5 LS) stage, respectively.

Experimental blocks were separated from each other by 6 m to minimize seepage interference between blocks. Flushing for each block was carried out by using a powered water pump. All blocks were flushed immediately after planting; subsequent flushes were applied to each block independently, as needed (Table 1). Individual blocks were flooded after final herbicide applications, and in-block water levels were maintained at 10 cm by pumping as needed. After final herbicide applications, the field was flooded to an average water depth of 10 cm for the remainder of the season. Harvest dates were October 19, 2016, and October 27, 2017.

Data Collection

Weed Control

Weed control evaluations measured the overall efficacy of herbicide programs using glyphosate as a PPB treatment, and the contributions of PPB treatments to overall control. Because rice planting depth also affected herbicide treatment timing, these "depth effects" on weed control were also of interest. Weed density in plots was estimated at 60 d after treatment by counting plants in 30-cm by 30-cm quadrat samples, with three to four samples per plot. The *Echinochloa* spp. barnyardgrass, early watergrass, and late watergrass were by far the most commonly observed weeds in the study field, followed by ducksalad, smallflower umbrella sedge, ricefield bulrush, bearded sprangletop, and *Ammania* spp. (Brim-DeForest et al. 2017a, 2017b). Young seedlings of *Echinochloa* species are difficult to differentiate in the field; therefore, these species were grouped together as a genus for density counts and analysis.

Rice Growth and Development

Rice growth parameters and responses to herbicide treatment and planting depth were measured throughout the season. Of particular interest were crop responses to PPB applications of glyphosate, as well as the effects of planting depth and weediness on stand development and yield components. Date of emergence was estimated visually as when at least 10% of rice seedlings were visible at the soil surface for a given planting depth; this date was used to time PPB herbicide treatments for each planting depth. Rice stand density was recorded at 20 d after planting (DAP) by counting plants in 30-cm by 30-cm quadrats, with three samples per plot. Time to 50% heading was estimated visually. Tiller density was determined at 60 DAP by counting tillers in 30-cm by 30-cm quadrats, with three samples per plot. Plant height was measured by meter-stick at 120 DAP.

Prior to field harvest, 10 panicles per plot were randomly selected, hand-harvested, and dried for 3 d at 50 C. Grain yield

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Table 2. Herbicide treatments applied to rice drilled to three seeding depths in 2016 and 2017.[a]

Treatment	Herbicide[b]	Application rate	Crop timing	Treatment timing
		g ai or ae ha^{-1}		
UTC	—	—	—	
T1	Glyphosate	870	Emergence	PPB
T2	Glyphosate	870	Emergence	PPB
	Pendimethalin	1,070	3 LS	EPOST
T3	Glyphosate	870	Emergence	PPB
	Pendimethalin	1,070	3 LS	EPOST
	Propanil + halosulfuron	6,730 + 52	3 LS	EPOST
T4	Glyphosate	870	Emergence	PPB
	Pendimethalin	1,070	5 LS	MPOST
	Propanil + halosulfuron	6,730 + 52	5 LS	MPOST
T5	Glyphosate	870	Emergence	PPB
	Pendimethalin	1,070	3 LS	EPOST
	Cyhalofop	270	3 LS	EPOST
	Penoxsulam	40	3 LS	EPOST

[a]Abbreviations: ai, active ingredient; ae, acid equivalent; EPOST, early post-emergence; LS, rice leaf stage; MPOST, mid post-emergence; PPB, postplant-burndown; UTC, untreated control.
[b]Herbicides were applied with manufacturer recommended or required adjuvants, where applicable.

per panicle and 1,000-grain weight were measured, and adjusted to 14% moisture content. Filled and total florets per panicle were counted, and percentage of unfilled florets was calculated. Whole plots were harvested, and yields were determined with a small-plot combine harvester (ALMACO, Nevada, IA) with a swath width of 2.3 m. Yields were adjusted to 14% moisture content.

Statistical Analysis

All data recorded were subjected to ANOVA and linear regression using the AGRICOLAE and EMMEANS packages in R (R Core Team 2021). Significant year-by-depth and year-by-treatment interactions were observed, therefore data were re-analyzed and presented by year. Data for weed density, rice stand characteristics, yield, and yield components met assumptions of homogeneity of variance. Means separations for all analyzed data were performed using Tukey honestly significant difference test at $\alpha = 0.05$.

Results and Discussion

Weed Control

The aim of this study was to assess the feasibility of combining a stale seedbed with deep rice seeding depth as a means to accommodate a nonselective weed burndown treatment without delaying planting. If implemented correctly, this PPB method may provide a novel cultural tool for combatting herbicide resistance in rice. Deep-seeding of rice sufficiently delayed stand emergence to allow a PPB treatment of glyphosate without injuring rice seedlings. However, burndown timing effects on weed density varied by year.

Grasses were the dominant weeds observed in both study years. The sedges smallflower umbrella sedge and tall flatsedge were present in small numbers in 2016; however, no sedges of any species were observed in 2017. Therefore, sedge data were not included in analysis. No broadleaf species were detected in either study year. *Echinochloa* grasses outcompeted all other weeds and rice in the more heavily infested plots. Differences in application timing of PPB and subsequent treatments due to differential rice emergence from different planting depths (hereinafter: treatment timing) had mixed effects on weed control. Overall weed control was greatest with Treatment 5 (T5, glyphosate PPB followed by [fb] pendimethalin + cyhalofop + penoxsulam EPOST) in either year, regardless of rice planting depth. In both years, UTC, T1 (glyphosate PPB), and T2 (glyphosate PPB fb pendimethalin EPOST) plots were very weedy at all planting depths.

Weed population density varied between years. *Echinochloa* pressure was greater in 2017 than in 2016, with 2017 UTC plots roughly 3.75-fold weedier than 2016 UTC plots. *Echinochloa* plant density generally decreased with more comprehensive herbicide treatments in both years (Table 3), although decreases were more consistent in 2016. In 2016 glyphosate PPB alone (T1) reduced *Echinochloa* density from that of the UTC by 40%, 19%, and 6% in 1.3-cm, 2.5-cm, and 5.1-cm rice planting depths, respectively, whereas glyphosate PPB fb pendimethalin (T2) reduced *Echinochloa* density by 72%, 36%, and 17% over the same depths. The effects of herbicide application timing on *Echinochloa* densities in 2016 were only significant for T5; however, *Echinochloa* density was generally greater in plots with deeper-seeded rice. In 2017, glyphosate PPB alone (T1) reduced *Echinochloa* density by 30%, 31%, and 73% in 1.3-cm, 2.5-cm, and 5.1-cm planting depths, respectively, while glyphosate PPB fb pendimethalin (T2) reduced *Echinochloa* density by 58%, 66%, and 80%, across the same depths. All other treatments reduced *Echinochloa* density by 87% or more. Treatment timing affected *Echinochloa* density only in T3 (glyphosate PPB fb pendimethalin + propanil + halosulfuron EPOST) and T4 (glyphosate PPB fb pendimethalin + propanil + halosulfuron MPOST) in 2017.

Given that PPB treatments were timed to observed rice emergence, we expected to see greater overall *Echinochloa* control at greater rice planting depths in 2016, as the PPB application was delayed in deeper-seeded plots. However, in 2017, delaying PPB by 5 d at the 5.1-cm planting depth did reduce *Echinochloa* density considerably, even though *Echinochloa* pressure was far greater that year. It is possible that the added PPB treatment delay in 2017 afforded more time for grasses to emerge and be controlled with the treatment. Because *Echinochloa* was not reduced 100% by glyphosate PPB alone at any depth or year, it is evident that *Echinochloa* emergence is nonsynchronous at the study site, which is in agreement with previous studies (Boddy et al. 2012; Brim-DeForest et al. 2017b). Nonsynchronous emergence may provide some insight into the inconsistent effects of PPB treatment delay with greater rice planting depth. It is also interesting that in both years, *Echinochloa* densities in T3 through T5 (Table 2) were higher with increasing rice planting depth. It is likely that reduced rice stands in these plots resulted in concomitant reduced competition from rice, potentially allowing more *Echinochloa* seedlings to establish (Chauhan and Johnson 2010; Macías et al. 2009). In addition, delayed flooding at 2.5-cm and 5.1-cm planting depths may also have allowed later-emerging weeds to avoid flooding suppression.

Bearded sprangletop densities were lower than those of *Echinochloa* in either year (Table 3). Treatment effects on bearded sprangletop density were apparent only at the 1.3-cm rice planting depth either year, with T4 (glyphosate PPB fb pendimethalin + propanil + halosulfuron MPOST) having the highest density of 37 plants m^{-2} in 2016, and 48 plants m^{-2} in 2017. T4 was also the only treatment with significant timing effects on bearded sprangletop density, with lower density at greater rice planting depth either year.

Table 3. Weed densities 60 d after final herbicide treatments in 2016 and 2017.

	2016			2017		
	Rice planting depth, cm[a]					
	1.3	2.5	5.1	1.3	2.5	5.1
Treatment	*Echinochloa* spp.[d] m^{-2}					
UTC[b]	394[c] a A	427 a A	256 a A	1091 a A	1211 a A	1754 a A
T1	238 ab A	348 ab A	241 a A	756 ab A	625 b A	467 b A
T2	111 bc A	274 abc A	212 a A	456 b A	411 bc A	352 bc A
T3	92 bc A	190 bcd A	182 a A	6 c B	87 c AB	228 bc A
T4	82 bc A	56 d A	136 a A	35 c B	39 c B	196 c A
T5	7 bc B	74 cd AB	132 a A	59 c A	107 c A	124 c A
	Bearded sprangletop m^{-2}					
UTC	2 b A	0 a A	10 a A	15 b A	7 a A	0 a A
T1	0 b A	0 a A	1 a A	0 b A	4 a A	0 a A
T2	0 b A	0 a A	1 a A	7 b A	7 a A	0 a A
T3	18 b A	3 a A	0 a A	11 b A	0 a A	0 a A
T4	37 a A	5 a B	10 a B	48 a A	4 a B	0 a B
T5	0 b A	0 a A	10 a A	0 b A	0 a A	0 a A

[a]Effects of rice planting depth on herbicide treatment timing are described in Table 1.
[b]Abbreviations: UTC, untreated control; T1, glyphosate (at rice emergence); T2, glyphosate followed by pendimethalin (early-POST); T3, glyphosate followed by pendimethalin, propanil, and halosulfuron (early-POST); T4, glyphosate followed by pendimethalin, propanil, and halosulfuron (late-POST); T5, glyphosate followed by pendimethalin, cyhalofop, and penoxsulam (early-POST).
[c]Lowercase letters in a column compare treatment differences for a given year and rice planting depth. Uppercase letters in a row compare treatment timing differences imposed by rice planting depth within years. Means with the same letters are not different at a 5% significance level, according to Tukey's honestly significant difference test.
[d]*Echinochloa* species observed were barnyardgrass, early watergrass, and late watergrass.

Grasses in general are the most competitive weeds in drill-seeded rice (Boddy et al. 2012; Brim-DeForest et al. 2017a; Kumar and Ladha 2011), but *Echinochloa* tend to emerge earlier and more vigorously than sedges and bearded sprangletop (Brim-DeForest et al. 2017b; Driver et al. 2019), and can easily dominate fields where control measures are inadequate. In either year, high *Echinochloa* densities in UTC, T1 (glyphosate PPB), and T2 (glyphosate PPB fb pendimethalin EPOST) plots effectively suppressed bearded sprangletop, accounting for discrepancies between visual control estimates at 20 DAP, and weed density counts at 60 DAP. However, bearded sprangletop was more competitive in T3 (glyphosate PPB fb pendimethalin + propanil + halosulfuron EPOST) and T4 (glyphosate PPB fb pendimethalin + propanil + halosulfuron MPOST) at 1.3-cm planting depth, reflecting reduced *Echinochloa* density and the lack of an effective POST herbicide for bearded sprangletop in those treatments. Bearded sprangletop can become a dominant species when *Echinochloa* and sedges are suppressed in drill-seeded rice systems (Ceseski et al. 2020). Delaying PPB application at 2.5-cm and 5.1-cm depths in T3 and T4 appeared to enhance bearded sprangletop control, however; therefore, PPB treatments afforded by planting rice deeper can aid in bearded sprangletop management efforts, particularly in fields where bearded sprangletop resistance to cyhalofop may a problem (Yuan et al. 2019).

Rice Growth and Development

Maximum air temperature at seeding was 21.8 C in 2016, and increased to greater than 30 C by the time rice emerged (Figure 1). In 2017, the maximum air temperature on the day of seeding was 27.5 C, however, the following day there was 15.2 mm of rain, and the maximum temperature fell to 19.4 C and remained below 25 C for several days.

Rice began to emerge from 1.3-cm planting depths 7 DAP in 2016, and 8 DAP in 2017 (Table 1). Planting rice deeper than 1.3 cm delayed stand emergence similarly in both years; emergence for rice planted to 2.5 cm and 5.1 cm was delayed by 3 and 4 d, respectively.

The minor differences in emergence between 2.5-cm and 5.1-cm planting depths is not surprising, as rice seedlings elongate quickly in soil once seed reserves are mobilized (Mgonja et al. 1988; Setter et al. 1994; Turner et al. 1981). In a related study of California rice cultivars, below-soil seedling elongation for the most vigorous cultivars increased markedly after 6 DAP (Ceseski and Al-Khatib 2021), resulting in reduced delays in seedling emergence as planting depth increased.

Applying glyphosate just as rice was beginning to emerge did not result in any observable crop injury in either year. In 2016, overall rice stand establishment (Table 4) was not affected by herbicide treatment or planting depth, although rice stand density generally decreased with planting depth, averaging 178, 119, and 101 plants m^{-2} at 1.3-cm, 2.5-cm, and 5.1-cm depths, respectively, averaged across herbicide treatments. Untreated plots in 2017 were exceptionally weedy; therefore, the rice stand was impossible to estimate for UTC plots at 2.5-cm and 5.1-cm planting depths. Nevertheless, there were no stand density differences among treatments at any given seeding depth in 2017. Planting depth did affect rice stand density in 2017, however. Rice stands in treated plots decreased by an average 89% and 96%, at 2.5-cm and 5.1-cm depths, respectively. Several days of cooler weather coincided with planting in 2017 (Figure 1). Colder temperatures can reduce seedling vigor (Jones and Peterson 1976; McKenzie et al. 1994) and slow elongation in heavy soil. A related study found that lower-vigor California rice cultivars continued to emerge at low rates after 21 DAP (Ceseski et al. 2018). It is therefore possible that cool weather just after planting in 2017 slowed the emergence of deeper-seeded rice, resulting in somewhat higher final rice plant density than was measured at 20 DAP. In water-seeded systems, rice is typically seeded at 170 to 200 kg ha^{-1} to overcome seed loss due to wind or predation. Drilling seed at a higher rate may likewise overcome stand and tillering loss from deeper planting in stale-drill systems.

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Table 4. Rice stand components for rice planted to 1.3-cm, 2.5-cm, and 5.1-cm soil depth in 2016 and 2017.

	2016			2017		
	Rice planting depth, cm[a]					
	1.3	2.5	5.1	1.3	2.5	5.1
Treatment	Rice plants m^{-2}					
UTC[b]	148 [c] A	156 a A	110 a A	317 a -	ND[d]	ND
T1	162 a A	89 a A	80 a A	332 a A	36 a B	15 a B
T2	179 a A	122 a A	70 a A	343 a A	49 a B	19 a B
T3	208 a A	110 a A	107 a A	319 a A	17 a B	4 a B
T4	156 a A	120 a A	120 a A	315 a A	41 a B	15 a B
T5	217 a A	115 a A	120 a A	379 a A	49 a B	11 a B
	Rice tillers m^{-2}					
UTC	315 d A	226 c A	335 b A	48 c -	ND	ND
T1	529 c A	425 b A	389 b A	409 b A	28 b B	7 c B
T2	595 bc A	371 bc B	458 ab AB	407 b A	92 b B	137 c B
T3	721 ab A	544 ab A	616 a A	641 a A	341 a B	362 ab B
T4	671 abc A	696 a A	592 a A	585 a A	337 a B	337 b B
T5	793 a A	648 a A	620 a A	681 a A	411 a B	474 a B
	Rice plant height, cm					
UTC	87 ab A	87 ab A	88 ab A	64 b -	ND	ND
T1	85 b A	85 b A	86 b A	67 b A	70 b A	66 b A
T2	87 ab A	87 ab A	88 ab A	72 b AB	68 b B	79 a A
T3	94 a A	94 a A	95 a A	93 a A	91 a A	88 a A
T4	95 a A	95 a A	96 a A	92 a A	91 a A	84 a A
T5	94 a A	94 a A	95 a A	94 a A	90 a AB	83 a B

[a]Effects of rice planting depth on herbicide treatment timing are described in Table 1.
[b]Abbreviations: UTC, untreated control; T1, glyphosate (at rice emergence); T2, glyphosate followed by pendimethalin (early-POST); T3, glyphosate followed by pendimethalin, propanil, and halosulfuron (early-POST); T4, glyphosate followed by pendimethalin, propanil, ad halosulfuron (late-POST); T5, glyphosate followed by pendimethalin, cyhalofop, and penoxsulam (early-POST).
[c]Lowercase letters in a column compare treatment differences for a given year and rice planting depth. Uppercase letters in a row compare treatment timing differences imposed by rice planting depth within years. Means with the same letters are not different at a 5% significance level, according to Tukey's honestly significant difference test.
[d]ND, no data available.

Rice tiller density was significantly affected by herbicide treatment and planting depth in both years (Table 4). Across planting depths in 2016, tiller density was 1.6 times greater than in UTC for glyphosate PPB alone (T1) and glyphosate PPB fb pendimethalin (T2), increasing to 2.4 times greater than UTC with T5 (glyphosate PPB fb pendimethalin + cyhalofop + penoxsulam EPSOT). Tillering in 2016 decreased by an average of 19% in deeper plantings. In 2017 tiller density was greatest (681 tillers m^{-2}) with T5 at 1.3-cm depth, and lowest (0 tillers m^{-2}) in UTC plots at 5.1-cm depth. Compared to 1.3-cm planting depth, tiller density in treated plots decreased by 60% and 56% at 2.5-cm and 5.1-cm depths, respectively, in 2017.

In either year, rice tiller density was reduced by a lesser degree than rice plant density, by either treatment or depth. Tillers per plant would be expected to increase as rice plant density decreases (Mutters and Thompson 2009), reaching up to 5 to 6 tillers per plant with California cultivars. However, comparing rice tiller and plat densities for deeper plantings in 2017 suggests up to 10 tillers per plant by 60 DAP, which seems unlikely and further suggests a weather-induced delay of rice emergence, as noted above. Ultimately, although tiller density in treated plots decreased at depths greater than 1.3 cm, planting depth effects seem to diminish between 2.5-cm and 5.1-cm depths, in accordance with a related study on depth effects on California rice (Ceseski and Al-Khatib 2021).

Rice plant heights were affected by herbicide treatment in both years (Table 4); however, no planting depth effects were observed in 2016. In 2016, rice plant height was generally higher in T3 (glyphosate PPB fb pendimethalin + propanil + halosulfuron EPOST), T4 (glyphosate PPB fb pendimethalin + propanil + halosulfuron MPOST), and T5 (glyphosate PPB fb pendimethalin + cyhalofop + penoxsulam EPSOT), averaging 95 cm; whereas plants in UTC, T1 (glyphosate PPB), and T2 (glyphosate PPB fb pendimethalin EPOST) averaged 87 cm. In 2017 rice heights decreased as planting depth increased. Plant heights in 2017 were greatest in T3, T4, and T5, averaging a combined 93 cm, 91 cm, and 85 cm at 1.3-cm, 2.5-cm, and 5.1-cm planting depths, respectively.

Yield components were largely unaffected by herbicide treatment or planting depth in 2016 (Table 5), however, in 2017 differences in panicle grain yield, number of florets, and unfilled florets were apparent. In 2017 there were no harvestable panicles in UTC plots seeded at 2.5-cm and 5.1-cm planting depths, or in T1 plots seeded at the 5.1-cm depth. In either year, panicle grain yields were generally higher in less-weedy plots, particularly in plots with foliar herbicides (T3, T4, T5). Planting depth effects on panicle yield were likewise only apparent in weedier plots (UTC, T1, T2). Thousand-grain weights were not affected by herbicide treatment or planting depth, and were only different in UTC plots either year. In both years, florets per panicle were greater in less-weedy plots, particularly with T3, T4, and T5. Florets per panicle in less-weedy plots also increased as planting depth increased. Floret filling appeared to be little affected by plot weediness or planting depth either year, and observed differences in unfilled florets were inconsistent. Florets per panicle and unfilled florets were generally greater in 2017 than in 2016.

Because panicle yields and 1,000-grain weights were consistent across years for the less-weedy plots, it is apparent that planting depth does not affect grain quantity or 1,000-grain weight. It is

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Table 5. Rice stand components for rice planted to 1.3-cm, 2.5-cm, and 5.1-cm soil depth in 2016 and 2017.[c,d]

	2016			2017		
	Rice planting depth, cm[a]					
	1.3	2.5	5.1	1.3	2.5	5.1
Treatment	Panicle yield, g					
UTC[b]	1.5 b AB	0.9 c B	2.1 b A	0.1 b A	0.0 b A	0.0 b A
T1	2.4 ab A	2.1 bc A	2.4 ab A	0.6 b AB	1.1 b A	0.0 b B
T2	2.5 ab A	2.2 b A	2.8 ab A	1.2 b B	1.0 b B	3.0 a A
T3	2.8 a A	3.1 ab A	3.3 ab A	2.9 a A	3.2 a A	3.5 a A
T4	2.8 ab A	3.5 a A	3.4 a A	3.0 a A	3.6 a A	3.2 a A
T5	3.1 a A	3.4 ab A	3.4 a A	2.7 a A	2.8 a A	3.4 a A
	1,000-grain wt, g					
UTC	24.8 a A	14.1 b B	28.8 a A	8.0 b	ND[b]	ND
T1	27.8 a A	27.5 a A	28.3 a A	24.1 a A	18.1 a A	ND
T2	28.1 a A	27.7 a A	29.1 a A	26.3 a A	25.0 a A	26.7 a A
T3	29.0 a A	28.5 a A	28.8 a A	29.4 a A	29.1 a A	28.4 a A
T4	29.0 a A	30.5 a A	29.2 a A	29.3 a A	29.6 a A	28.4 a A
T5	25.8 a A	29.6 a A	29.3 a A	28.8 a A	27.6 a A	28.6 a A
	Florets panicle^{-1}					
UTC	59.8 b AB	32.5 b B	72.6 b A	5.7c -	ND	ND
T1	86.7 ab A	75.2 ab A	83.2 ab A	39.0 bc A	48.7 b A	ND
T2	87.9 ab A	79.6 a A	96.1 ab A	65.0 b B	50.3 b B	127.0 a A
T3	96.0 ab A	107.7 a A	113.4 ab A	113.3 a A	142.0 a A	148.3 a A
T4	96.1 ab A	115.1 a A	118.1 a A	120.0 a A	149.0 a A	131.7 a A
T5	128.3 a A	113.4 a A	116.2 ab A	115.3 a A	133.3 a A	133.3 a A
	Unfilled florets, %					
UTC	4.4 a A	7.7 a A	7.3 a A	48.0 a	ND	ND
T1	9.5 a A	6.6 b A	5.1 a A	37.5 a A	21.8 a B	ND
T2	8.7 a A	6.1 b A	7.3 a A	30.7 a A	19.0 a AB	12.3 a B
T3	10.1 a A	10.7 b A	11.6 a A	14.5 b A	22.9 a A	17.3 a A
T4	9.0 a A	6.5 b A	10.1 a A	14.5 b A	19.3 a A	14.4 a A
T5	6.4 a A	8.3 b A	8.4 a A	17.8 b AB	23.8 a A	11.8 a B

[a]Effects of rice planting depth on herbicide treatment timing are described in Table 1.
[b]Abbreviations: UTC, untreated control; T1, glyphosate (at rice emergence); T2, glyphosate followed by pendimethalin (early-POST); T3, glyphosate followed by pendimethalin, propanil, and halosulfuron (early-POST); T4, glyphosate followed by pendimethalin, propanil, and halosulfuron (late-POST); T5, glyphosate followed by pendimethalin, cyhalofop, and penoxsulam (early-POST).
[c]Lowercase letters in a column compare treatment differences for a given year and rice planting depth. Uppercase letters in a row compare treatment timing differences imposed by rice planting depth within years. Means with the same letters are not different at a 5% significance level, according to Tukey's honestly significant difference test.
[d]ND, no data available.

interesting that both florets per panicle and unfilled florets were both higher overall in 2017, resulting in similar filled grains per panicle in both years. Higher temperatures can play a role in increasing florets per panicle (Kovi et al. 2011), whereas cooler nighttime weather during anthesis can cause sterility in rice (Board et al. 1980), yet there were no such phenomena in 2017 to explain the elevated florets per panicle or percentage of unfilled florets.

Rice yield was significantly affected by herbicide treatment in both years (Figure 2). Glyphosate PPB alone (T1) and glyphosate PPB fb pendimethalin (T2) provided sufficient weed control to limit yield reductions due to weed competition to 23% to 65% in 2016, however, in 2017 yield reductions in those treatments were up to 100%. but was less influenced by planting depth in 2016 than in 2017. In either year, yields were generally greater in less-weedy plots. In 2016, yields in plots treated with glyphosate PPB alone (T1) were 2.4-fold, 3.6-fold, and 1.7-fold greater than UTC in 1.3-cm, 2.5-cm, and 5.1-cm plantings, respectively, whereas yields in plots treated with glyphosate PPB fb pendimethalin (T2) increased 2.9-fold, 4.4-fold, and 2.6-fold over UTC, at the same planting depths. In 2017, yields were generally higher in plots that received postemergence herbicides (T3, T4, T5), though yields decreased as planting depth increased. Additionally, in 2017 yields in plots planted to 2.5-cm and 5.1-cm depths, and treated with T3 (glyphosate PPB fb pendimethalin + propanil + halosulfuron EPOST), T4 (glyphosate PPB fb pendimethalin + propanil + halosulfuron MPOST), and T5 (glyphosate PPB fb pendimethalin + cyhalofop + penoxsulam EPOST) decreased from those at the 1.3-cm planting depth by 48%, 28%, and 24%, and by 67%, 72%, and 54%, respectively. Yield decreases in 2017 were greater than tillering decreases, suggesting that tiller die-off in deeper plantings reduced final panicle density that year.

Conclusions

Overall, we found that planting depth had a greater effect on rice emergence and development than it had on weed control. Using a glyphosate postplant-preemergence burndown treatment prior to rice emergence did not affect rice stand establishment or development. Delaying PPB treatments by planting rice deeper had inconsistent effects on visual weed control and weed density, although bearded sprangletop control appeared enhanced in deeper rice plantings. Sedge and broadleaf suppression appeared to be achieved primarily by flush-irrigating plots for the first 30 to 40 d of the season, as anticipated. Combining deeper drill-seeding with a stale seedbed has great potential for refinement and future

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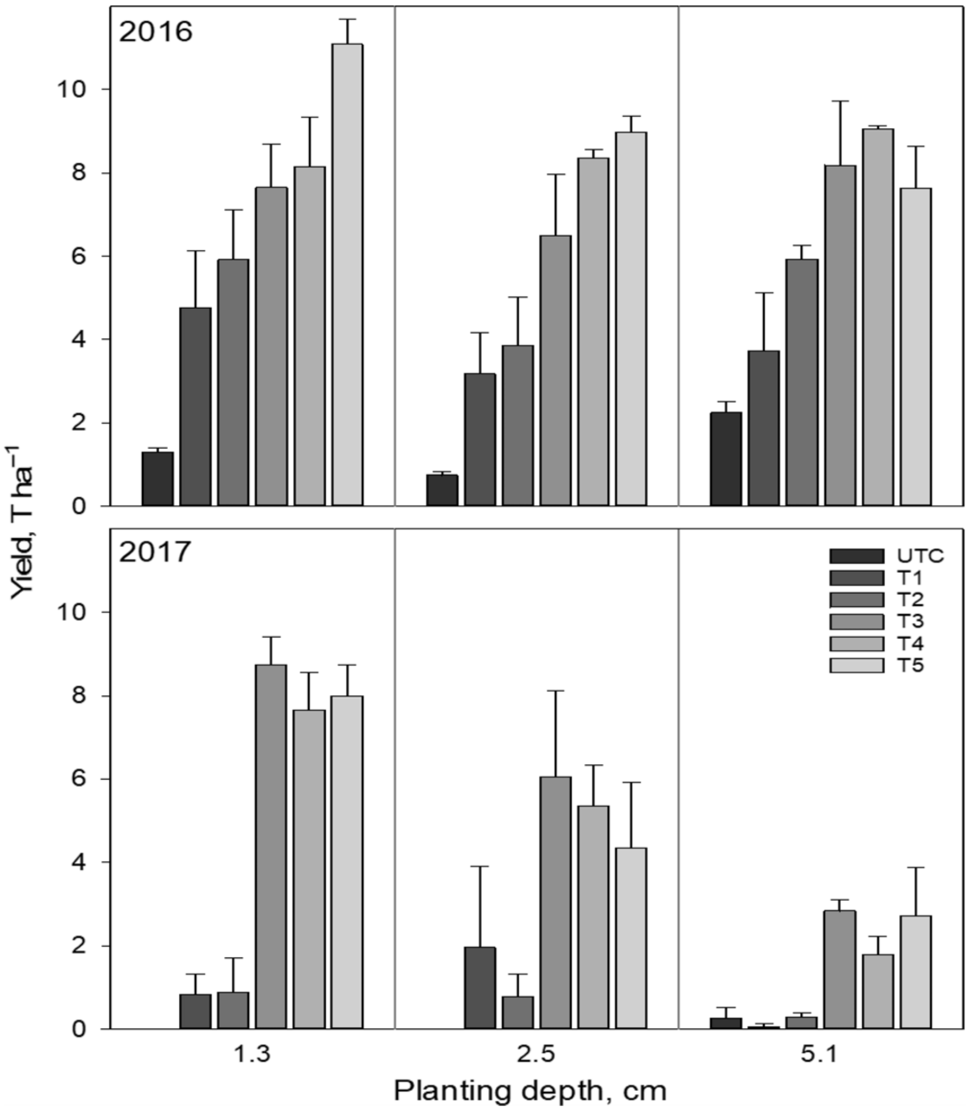

Figure 2. Grain yield of rice cultivar 'M-206' planted in 2016 and 2017, as affected by planting depth and herbicide treatments. Error bars are ± mean standard error, and can be used to compare data between treatments and planting depths in a given year. UTC, untreated control; T1, glyphosate (at rice emergence); T2, glyphosate followed by pendimethalin (early-POST); T3, glyphosate followed by pendimethalin, propanil, and halosulfuron (early-POST); T4, glyphosate followed by pendimethalin, propanil, and halosulfuron (late-POST); T5, glyphosate followed by pendimethalin, cyhalofop, and penoxsulam (early-POST).

utility. Further studies investigating the responses of high-vigor rice cultivars to seeding depth across soil types, as well as burndown application timing, are warranted in order to more fully understand the potential of this system to serve as a tool for herbicide resistance management in rice.

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