Title

An Evaluation of the Stale-Drill Cropping System in California Rice: Implications for Weed Management, Crop Physiology, and Yield Potential

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An Evaluation of the Stale-Drill Cropping System in California Rice: Implications for Weed Management, Crop Physiology, and Yield Potential

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An Evaluation of the Stale-Drill Cropping System in California Rice: Implications for Weed Management, Crop Physiology, and Yield Potential

Abstract

The predominant method of rice crop establishment in California is water seeding (WS), wherein pre-imbibed seed is flown by aircraft into permanently-flooded basins, where the seed settle to the soil surface and put down roots. Water seeding was adopted in the 1920's as a measure to suppress competitive grass weeds. However, this system encourages aquatic broadleaf and sedge weed species, and has selected for the development of flood-adapted populations of the major grass species. Although flooding continues to suppress many weeds, herbicides are the primary means of weed control in WS rice. Due to ecotoxicity and herbicide drift concerns, permanently-flooded rice culture limits available herbicides in California. The constant use of few herbicides on a small spectrum of locally-adapted weed ecotypes has resulted in widespread herbicide resistance in the region. Alternative stand establishment methods may permit the use of herbicides with modes of action that are not currently registered in WS rice, and for which resistance has not developed in the local rice-weed populations. Two such methods are the stale-seedbed, and drill seeding. We hypothesized that drilling dry rice seed below the zone of active weed germination and emergence will delay rice stand emergence until after most weeds have emerged. This novel *stale-drill* method would permit the use of a nonselective herbicide as a postplant-burndown (PPB) treatment to safely control emerged weeds without causing stand injury or yield loss to rice. We also hypothesized that California rice cultivars possessed sufficient vigor to emerge rapidly and evenly from soil depths exceeding 2 cm, with minimal stand reductions. Field and greenhouse experiments were carried out to determine the feasibility of the stale-drill method from 2016 to 2019. Specific studies addressed herbicide protocols, treatment timing, water management, the relative vigor of California rice cultivars, and cultivar responses to seeding depths of up to 6 cm. Initial field experiments confirmed that using glyphosate as a PPB treatment was able to control the majority of grass and sedge weeds, however seeding depth, weather, and planting date had significant effects on the emergence of cultivar M-206. Greenhouse experiments identified M-209 as a cultivar with superior vigor, as seen in rates of belowground elongation, emergence, and early-season growth and development. Further field studies confirmed that stale-drilled M-206 and M-209 can emerge evenly from depths up to 6 cm, and return yields competitive with local averages for WS rice. Planting date had a significant effect on M-209 heading, grain filling, and grain yield, while M-206 development and yield characteristics were relatively stable. As a whole, this research serves as a successful proof of concept for the stale-drill method for rice stand establishment, and adds to the growing body of knowledge of integrated weed management in mechanized crops.

Primum manduca doughnut victoriae tuum

Mom.

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The decade-long journey from Dropout to Doctor has been transformative, in ways far eclipsing mere pedagogy, assimilation, and analysis. I've become a completely different person as a result of this quest, while still remaining who I've always been. Transformation never occurs in a vacuum, and though I remain the final architect of my own successes and failures, I cannot imagine being able to pull off any of this caper without the support, encouragement, criticism, mentoring, friendship, and damn tomfoolery of innumerable professors, classmates, colleagues, and friends over the years. For those who know who you are, you know who you are. For those who do not, I know who you are and I will never forget.

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INTRODUCTION

The California rice [*Oryza sativa* L.] growing region comprises approximately 200 000 ha in the Sacramento Valley. The region, which is among the highest-yielding in the world for rice production (USDA, 2021), is characterized by hot, dry, summers with abundant sunshine, and supports a single crop per year (Hill et al., 2006). 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, emerging from the water after several days. Floodwaters are generally kept to 10 to 20 cm depth 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).

California rice has a limited number of available herbicides, due to the high cost of development and registration (Hill et al., 1994), as well as strict regulations based on concerns of herbicide drift from aerial applications that may damage neighboring orchards (Galla et al., 2018). Herbicide resistance has been a major biologic and economic issue in rice for decades (Hill et al., 1994; Fischer et al., 2000; Peterson et al., 2018). The lack of diversity of registered active ingredients means that once resistance to a particular mode of action arises, it can spread rapidly within and among fields as there may be few alternative herbicides to control the resistant populations. Efforts to promote herbicide resistance mitigation in CA largely focus on rotation of the limited number of available herbicides, while the cropping strategy itself has remained largely static.

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. Nonselective herbicides are used as a burndown treatment (Hill et al., 2006; Pittelkow et al., 2012), 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, as well as reduce weed seedbanks overall. However, due to the time needed to reflood and seed fields, stale seedbed use can delay rice planting, shortening the growing season and potentially depressing yields (Rao et al., 2007).

Stale-seedbed can be followed by drill seeding to shorten the delay between burndown treatment and rice planting. Drill seeding rice typically involves sowing seed to 1.25-2 cm and 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, as the crop is typically sown fairly shallowly, it emerges synchronously with competitive grasses (Smith et al., 1977) reducing the stand's ability to compete and further limiting available herbicides. However, if rice is drilled to depths greater than 2 cm, the stand should emerge later than the majority of grasses. This may allow novel weed management practices to be used without stand injury (Ceseski et al., 2020).

We hypothesized that planting California rice cultivars below the zone of active weed germination and emergence would delay rice emergence, yet not result in reduced rice stand. This would allow us to combine drill seeding with a stale seedbed as an integrated approach to weed management. This "stale-drill" method would permit the use of a novel mode of action in a postplant-burndown

(PPB) treatment, which would safely manage weeds prior to stand emergence, without injury or delayed planting.

CHAPTER ONE details field trials conducted in 2016-2017. We explored the feasibility of stale-drill planting, by planting cv. M-206 to depths up to 5.1 cm and evaluating stand establishment and herbicide programs. Aquatic broadleaf weeds and algae were suppressed by water management, and were not present in either study year. We applied glyphosate at 870 g a.e. ha as a PPB treatment just prior to rice emergence, either alone or in conjunction with other herbicides. Treatment delays had mixed effects on weed control. Glyphosate PPB 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 depths, respectively. The greatest overall weed control either year was found with glyphosate + pendimethalin followed by (f.b.) penoxsulam + cyhalofop with rice seeded to 1.3 cm depth. Planting rice deeper than 1.3 cm delayed emergence by 3 to 4 days in both study years. We found that 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%.

CHAPTER TWO outlines research conducted in glasshouses, with the aim of elucidating relative vigor of four California rice cultivars. Two experiments were conducted to evaluate rice cultivars for traits that would facilitate the stale-drill cropping methodology. Cultivars M-105, M-205, 'M-206', and M-209 were evaluated for differences in germination, elongation, emergence, and early-season morphology. M-205 and M-209 were found to have greater rates of total below-soil elongation, and greater rates of mesocotyl and coleoptile elongation overall, across depths. M-205 and M-209 were also found to have higher rates of emergence across depths. Differences between cultivars in aboveground growth parameters of emerged seedlings were only found for rice planted at 0 cm, 6.4 cm, and 7.6 cm planting depths. Based on observed below- and above-soil growth and development, M-205 and M-209 exhibited greater vigor overall, as well as high levels of emergence from depths greater than 2 cm.

CHAPTER THREE describes research conducted in the field in 2018-2019. Rice cultivars M-206 and M-209 were drill seeded to 3 cm and 6 cm depths. A PPB application of glyphosate at 870 g a.e. ha^{-1} was applied 6-7 days after planting at rice emergence, which controlled >50% of grass and sedge weeds. Aquatic broadleaf weeds and algae were suppressed by water management, and were not present in either study year. Glyphosate PPB caused rice first-leaf dieback, but no other symptoms developed. Planting depth and cultivar did not affect date of emergence either year. Deeper seeding reduced M-206 and M-209 stands by 15.4% and 5.2%, respectively, in 2018, but not in 2019. Increased tillering compensated for stand reductions in 2018. Panicle yield components were largely unaffected by planting depth in 2018, however florets panicle^{-1} and filled grains panicle^{-1} were slightly greater for both cultivars seeded at 6 cm, compared to 3 cm planting depth. In 2019, M-209 suffered reductions in florets panicle^{-1} and grain filling when planted to 6 cm depth. Grain yields were not affected by planting depth in either study year. M-206 and M-209 grain yields were 10.2 T ha^{-1} and 12.2 T ha^{-1} respectively, in 2018, and 9.4 T ha^{-1} and 9.1 T ha^{-1} respectively, in 2019.

This body of research has identified high-vigor California rice cultivars that are suitable for planting to depths up to 6 cm. In doing so, we identified critical rice vigor traits that may aid breeders in selection for lines that can rapidly escape deep seeding. It also serves as a successful proof-of-concept for the stale-drill method as an alternative stand establishment method in mechanized rice production. Finally, it establishes that using stale-drill permits the safe use of a PPB treatment with a nonselective herbicide at stand emergence. Proper water management and scouting are essential to ensure that PPB treatments do not injure emerging rice to the extent that weak or reduced stands result. However, by way of permitting the use of novel herbicidal modes of action, this method may be a useful rotational strategy in fields with difficult-to-control weeds, including herbicide-resistant populations or weedy rice.

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CHAPTER 1

Combining Stale Seedbed with Deep Rice Planting: A Novel Approach to Herbicide Resistance Management

Alex R. Ceseski, Amar S. Godar, and Kassim Al-Khatib

Submitted to Crop Protection

Abstract

Water-seeding is a common cropping strategy in mechanized rice systems. Water-seeding of rice can suppress grass weeds, but it can 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 California rice. This study examined a novel combination of drill seeding and a stale seedbed ("stale-drill") as a means to use 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 days. 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. Glyphosate PPB 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 glyphosate + pendimethalin followed by (f.b.) 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.

1.1. Introduction

The California rice [*Oryza sativa* L.] growing region comprises approximately 200 000 ha in the Sacramento Valley. The rice cropping system is almost exclusively water-seeded (WS), wherein pre-germinated seed is sown by aircraft into flooded fields. Seeds sink to the soil surface and peg down roots, emerging from the water after several days. Floodwaters are generally kept to 10 to 20 cm depth 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 [S*choenoplectus 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. As the 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 1960's, the nearly exclusive use of the water-seeded system has meant that the number of registered active ingredients (A.I.) 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 A.I. (UCANR 2019). This limited palette restricts herbicide rotation. Since 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 rice for decades (Fischer et al., 2000; Hill et al., 1994; Peterson et al., 2018). The lack of diversity of registered herbicide A.I.'s and modes of action means that once resistance to a particular MOA arises, it can spread rapidly within and among fields as there may be few alternative herbicides to control the resistant populations. For example, *L. fusca* populations resistant to clomazone have only three other effective herbicides available (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 more costly in California than in much of the world. Therefore, many growers are burdened with potentially unsustainable herbicide costs 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 (Brim-DeForest et al., 2017b; Hill et al., 1994; Pittelkow et al., 2012). 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. Nonselective 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 current rice herbicides, as well as reducing weed seedbanks. However, due to the time needed to reflood and seed fields afterwards, stale seedbed use can delay rice planting, shortening the growing season and potentially depressing yields (Rao et al., 2007).

Another common rice cropping system in mechanized rice is drill seeding (DS). Drill seeding rice typically involves drill seeding dry seed to 1.25-2 cm and 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, as the seed is typically sown to fairly shallow depths, it emerges synchronously with competitive grasses (Smith et al., 1977). However, if rice is drilled to depths greater than 2 cm, the rice 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 vigor to emerge through water depths of up to 20 cm (McKenzie et al., 2015). This high vigor may make California rice varieties suitable for drill seeding to depths greater than 2 cm.

If rice cultivars can emerge quickly and evenly from deeper plantings, it may be possible to combine a stale seedbed with drill seeding. This "stale-drill" method could permit the use of modes of herbicidal action 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 rice, delaying planting, or shortening the season. If used in rotation with water seeding, stale-drill can also vary the weed spectrum year over year, 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 is to test the hypothesis that drilling rice below the zone of active weed germination will delay rice stand emergence sufficiently to allow a safe application of a nonselective postplant-burndown (PPB) herbicide treatment.

1.2. Materials and Methods

1.2.1 Field location and conditions

Field experiments were conducted at the Rice Experiment Station (RES) 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 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 (Fig. 1.1) for the 2016 (22 May – 19 October) growing season were 14.5°C and 32.1°C, respectively, and for 2017 (08 June – 27 October) were 15.6°C and 37°C, respectively (CIMIS 2016-2017)**.** Seedbed preparation and cultural practices followed current University of

California guidelines (UCANR 2018). The study site weed seedbank is previously described in Brim-DeForest et al. (2017a) and (2017b).

1.2.2 Study materials and experimental design

Experiments were conducted as a split-plot design, with planting depth as the main plots and herbicide treatment as the subplots, with four replications in 2016, and three replications in 2017. Main plots were 17 x 18 m blocks that were encased by 2.2-meter 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, Kansas, USA) with 17.8 cm row spacing. Planting dates were 22 May 2016 and 08 June 2017 (Table 1.2).

Within each planting depth, herbicide treatments were applied in 3 x 6 m subplots (hereinafter referred to as "plots"). Five herbicide treatments were applied (Table 1.1), 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, Illinois, USA), calibrated to deliver 187 L ha^{-1}. All plots except UTC received a postplant-burndown (PPB) application of glyphosate (Roundup WeatherMAX®, Bayer CropScience, St Louis, MO, USA) at 870 g a.e. ha^{-1} + 2 % w/v ammonium sulfate (AMS), applied just as rice was beginning to emerge at each planting depth. Follow-up treatments of pendimethalin (Prowl® H_2O, BASF Corporation, Research Triangle Park, NC, USA) at 1070 g a.i. ha^{-1}, were applied either with or without foliar tankmix partner herbicides of propanil + halosulfuron (RiceEdge® 60 DF, RiceCo LLC, Memphis, TN, USA), cyhalofop (Clincher® CA, Corteva Agriscience, Wilmington, DE, USA), or penoxsulam (Granite® SC, Corteva Agriscience), at 6730, 52, 270, and 40 g a.i. ha^{-1}, respectively (Table 1.1). Foliar herbicides were applied with 2.5% v/v crop oil concentrate (COC). Follow-up treatments were either applied as early post-emergent (EPOST) or mid post-emergent (MPOST) treatments to 3-leaf (3 LS) or 5-leaf (5 LS) stage rice respectively.

Blocks were separated from each other by 6 m to minimize seepage interference between blocks. Flushing for each block was done by powered water pump. All blocks were flushed immediately after planting; subsequent flushes (Table 1.2) were applied to each block independently, as needed. 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 10 cm average water depth for the remainder of the season. Harvest dates were 19 October 2016, and 27 October 2017.

1.2.3 Data collection

1.2.3.1 Weed control

Weed control evaluations measured the overall efficacy of herbicide programs utilizing glyphosate as a PPB treatment, as well as 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 DAT by counting plants in 30 cm x 30 cm quadrat samples, with 3 – 4 samples per plot. *Echinochloa* spp. and sedges were grouped as genera for quadrat count ratings.

1.2.3.2 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 >10% of fist-leaf rice was visible at the soil surface, and was used to time PPB herbicide treatments. Rice stand density was recorded at 20 days after planting (DAP) by counting plants in 30 cm x 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 x 30 cm quadrats, with three samples per plot. Plant height was measured by meter-stick at 120 DAP.

Prior to field harvest, ten panicles per plot were randomly selected, hand-harvested, and dried for three days at 50°C. Grain yield per panicle and 1000-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, Iowa, USA) with a swath width of 2.3 m. Yields were adjusted to 14% moisture content.

1.2.4 Statistical analysis

All data recorded were subjected to ANOVA analysis and linear regression using the *agricolae* and *emmeans* packages in R (R core team). Significant year-by-depth and year-by-treatment interactions were observed, therefore data were re-analyzed and presented by year. Visual weed control data were subject to log-transformation prior to analysis, and back-transformed estimates are presented as percent-control relative to UTC, with a value of 0 signifying complete coverage of the weed in a plot, with no estimable difference from UTC, and a value of 100 signifying total absence of the weed from the plot. 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 HSD at $\alpha = 0.05$.

1.3. Results

1.3.1 Weed control

Echinochloa spp. (*Echinochloa)* were the dominant weeds present in both years, followed by *Leptochloa fusca* ssp. *fascicularis* (*L. fusca)* and sedges. *Cyperus difformis* and *C. eragrostis* (sedges) were the only sedges present in 2016; no sedges were present in 2017. *Echinochloa* largely outcompeted other weeds and rice in the more heavily infested plots. No broadleaf species were present in either year. Treatment timing differences due to rice planting depth (treatment timing) had mixed effects on weed control, however, overall weed control was greatest with treatment 5 (T5, Table 1.1) either year, regardless of rice planting depth. In both years, UTC, T1, and T2 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 1.3), although decreases were more consistent in 2016. In 2016 glyphosate alone (T1) reduced *Echinochloa* spp. density from UTC by 40%, 19%, and 6% in 1.3 cm, 2.5 cm, and 5.1 cm rice planting depths, respectively, whereas glyphosate f.b. pendimethalin (T2) reduced *Echinochloa* spp. 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 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 f.b. 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 only effected *Echinochloa* density in T3 and T4 in 2017.

L. fusca densities were lower than those of *Echinochloa* in either year (Table 1.3). Treatment effects on *L. fusca* density were only apparent at 1.3 cm rice planting depth either year, with T4 having the highest density of 37 *L. fusca* plants m^{-2} in 2016, and 48 plants m^{-2} in 2017. T4 was also the only treatment with significant timing effects on *L. fusca* density, with lower density at greater rice planting depth either year. Sedge densities in 2016 were affected by herbicide treatment at each rice planting depth. Glyphosate alone (T1) reduced sedge density from UTC by 40%, 23%, and 86% in 1.3 cm, 2.5 cm, and 5.1 cm rice plantings, respectively, while glyphosate f.b. pendimethalin (T2) reduced sedge density by 74%, 45%, and 86% over the same planting depths. Treatments with POST herbicides (T3, T4, T5) reduced sedge density the most at any rice planting depth, with an average 95% reduction.

1.3.2 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 of rice emergence (Fig. 1.1). In 2017, the maximum air temperature at day of seeding was

27.5°, however, the following day saw 15.2 mm of rainfall, and maximum temperature fell to 19.4°C, remaining below 25°C for several days. Rice began to emerge from 1.3 cm planting depths seven days after planting (DAP) in 2016, and 8 DAP in 2017 (Table 1.2). 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 three and four days, respectively. Time to 50% heading was also delayed by 1-2 days for rice planted to 2.5 and 5.1 cm.

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 1.4) was not affected by herbicide treatment or planting depth, although stands generally decreased with planting depth, averaging 178, 119, and 101 plants m^{-2} at 1.3 cm, 2.5 cm, and 5.1 cm depth, 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 differences among treated plots at any given seeding depth in 2017. Planting depth did affect rice stands in 2017, however. Stands in treated plots decreased by an average 89% and 96%, at 2.5 cm and 5.1 cm depths, respectively.

Rice tiller density was significantly affected by herbicide treatment and planting depth in both years (Table 1.4). Across planting depths in 2016, tiller density was 1.6 times greater than in UTC for glyphosate alone (T1) and glyphosate f.b. pendimethalin (T2), increasing to 2.4 times greater than UTC with T5. 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.

Rice plant heights were affected by herbicide treatment in both years (Table 1.4), however, no planting depth effects were observed in 2016. In 2016, plant height was generally higher in T3, T4, and T5, averaging 95 cm, whereas plants in UTC, T1, and T2 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 1.5), 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 POST herbicides (T3, T4, T5). Planting depth effects on panicle yield were likewise only apparent in weedier plots (UTC, T1, T2). Thousand-grain weights were lower UTC plots either year, although there were no differences among treated plots or planting depths. 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. Both florets per panicle and unfilled florets were generally greater in 2017 than in 2016.

Rice yield was significantly affected by herbicide treatment in both years (Fig. 1.2), 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 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, while yields in plots treated with glyphosate f.b. 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 POST 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, T4, and T5 decreased from those at the 1.3 cm planting depth by 48%, 28%, and 24%, and by 67%, 72%, and 54%, respectively.

1.4. Discussion

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 postplant-burndown (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 of glyphosate without injuring rice stands. However, burndown timing effects on weed density varied by year. In 2016, *Echinochloa* control with glyphosate PPB alone was reduced at deeper rice plantings. Given that PPB treatments were timed to rice emergence, we expected to see greater *Echinochloa* control as PPB application was delayed in deeper-seeded plots. However, in 2017 delaying PPB by 5 days in the 5.1 cm planting depth plots 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. As *Echinochloa* plants were not reduced 100% by glyphosate PPB alone in 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 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.

Echinochloa pressure was considerably higher in 2017 than in 2016, which had significant effects on the relative competitiveness of *L. fusca* and sedges. Grasses in general are the most competitive weeds in DS 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 *L. fusca* (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, and T2 plots effectively suppressed *L. fusca*, accounting for discrepancies between visual control estimates at 20 DAP, and weed density counts at 60 DAP. However, *L. fusca* was more competitive in T3 and T4 at 1.3 cm planting depth, reflecting reduced *Echinochloa* density, and the lack of an effective POST herbicide for *L. fusca* in those treatments. *L. fusca* can become a dominant species when *Echinochloa* and sedges are suppressed in DS rice systems (Ceseski et al., 2020). Delaying PPB application at 2.5 and 5.1 cm depths in T3 and T4 appeared to enhance *L. fusca* control, however, therefore PPB treatments afforded by planting rice deeper can aid in *L. fusca* management efforts, particularly in fields where *L. fusca* resistance to cyhalofop may a problem (Yuan et al., 2019).

Planting rice deeper than 1.3 cm delayed stand emergence by several days, although the differences between 2.5 cm and 5.1 cm planting depths were minor. This 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 emergence delays as planting depth increased. In either year, stand establishment tended to decrease with greater planting depth, however, stand establishment with deeper seeding was much lower in 2017, as several days of cooler weather coincided with planting in 2017. 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 emergence of deeper-seeded rice, resulting in final rice stands somewhat larger than those measured at 20 DAP. In WS systems, rice is typically seeded at 170 - 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.

In either year, rice tiller density was reduced by a lesser degree than stand density, by either treatment or depth. Tillers per plant would be expected to increase as stand density decreases (Mutters and Thompson, 2009), reaching up to 5-6 tillers per plant with California cultivars. However, comparing tiller and stand densities for deeper plantings in 2017 suggests up to ten 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).

Glyphosate alone (T1) and glyphosate f.b. pendimethalin (T2) provided sufficient weed control to limit yield reductions due to weed competition to 23 – 65% in 2016, however, in 2017 yield reductions in those treatments were up to 100%. Planting rice deeper than 1.3 cm did not have an effect on yields in 2016, but yields were reduced with increased planting depth in 2017. Yield decreases in 2017 were greater than tillering decreases, suggesting that tiller die-off in deeper plantings reduced final panicle density that year.

Yield components were little changed by treatment effects on weed density or planting depth. As panicle yields and 1000-grain weights were consistent across years for the less-weedy plots, it is apparent that planting depth does not affect grain quantity or 1000-grain weight. It is 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), while 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.

Conclusions

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

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Tables and Figures

Table 1.1. Herbicide treatments applied to M-206 rice drilled to three seeding depths in 2016 and 2017.

Treatment	Herbicide[a]	Application rate[b] g a.i. or a.e. ha^{-1}	Crop timing[c]	Treatment timing[d]
UTC	---	---	---	
T1	glyphosate	870	emergence	PPB
T2	glyphosate	870	emergence	PPB
	pendimethalin	1070	3 LS	EPOST
T3	glyphosate	870	emergence	PPB
	pendimethalin	1070	3 LS	EPOST
	propanil +	6730	3 LS	EPOST
	halosulfuron	52	3 LS	EPOST
T4	glyphosate	870	emergence	PPB
	pendimethalin	1070	5 LS	MPOST
	propanil +	6730	5 LS	MPOST
	halosulfuron	52	5 LS	MPOST
T5	glyphosate	870	emergence	PPB
	pendimethalin	1070	3 LS	EPOST
	cyhalofop	270	3 LS	EPOST
	penoxsulam	40	3 LS	EPOST

[a] Herbicides were applied with manufacturer recommended or required adjuvants, where applicable.

[b] a.i., active ingredient; a.e., acid equivalent.

[c] LS, rice leaf stage.

[d] PPB, postplant-burndown; EPOST, early post-emergence; MPOST, mid post-emergence.

Table 1.2. Timing of crop operations, irrigation events, and herbicide treatments in 2016 and 2017.

Year	Planting date	Planting depth	Rice emergence	Irrigation flushes	Herbicide applications[a]	Flooding dates
2016	22 May	1.3 cm	29 May	22 May 31 May 08 June 13 June	PPB: 30 May EPOST: 12 June MPOST: 19 June	21 June
		2.5 cm	01 June	22 May 31 May 08 June 13 June 21 June	PPB: 02 June EPOST: 19 June MPOST: 27 June	30 June
		5.1 cm	02 June	22 May 31 May 08 June 13 June 21 June	PPB: 02 June EPOST: 27 June MPOST: 27 June	30 June
2017	08 June	1.3 cm	16 June	08 June 17 June 22 June	PPB: 16 June EPOST: 26 June MPOST: 29 June	01 July
		2.5 cm	19 June	08 June 17 June 24 June 01 July	PPB: 20 June EPOST: 05 July MPOST: 07 July	09 July
		5.1 cm	20 June	08 June 17 June 24 June 01 July 09 July	PPB: 21 June EPOST: 11 July MPOST: 15 July	16 July

[a] PPB, postplant-burndown; EPOST, early post-emergence; MPOST, mid post-emergence.

Table 1.3. Weed densities 60 days after treatment in 2016 and 2017. 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 HSD.

	2016			2017		
	Rice planting depth, cm[a]					
	1.3	2.5	5.1	1.3	2.5	5.1
Treatment	——— *Echinochloa* spp[c]. m^{-2} ———					
UTC[b]	394 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
	——— *L. fusca* 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
	——— Sedges[d] m^{-2} ———					
UTC	268 a B	175 a B	502 a A	NP[e]	NP	NP
T1	159 b A	135 b AB	70 b B	NP	NP	NP
T2	70 c A	97 b A	72 b A	NP	NP	NP
T3	9 c A	51 bc A	0 b A	NP	NP	NP
T4	24 c A	0 c A	2 b A	NP	NP	NP
T5	0 c A	3 c A	25 b A	NP	NP	NP

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[a] Effects of rice planting depth on herbicide treatment timing are described in Table 2.

[b] PPB, postplant-burndown; EPOST, early post-emergence; MPOST, mid post-emergence.

[c] *Echinochla* spp. observed were *E. crus-galli, E. oryzicola, E. oryzoides.*

[d] Sedges observed were *Cyperus difformis, C. eragrostis, Schoenoplectus mucronatus*.

[e] NP, weeds not present.

Table 1.4. Rice stand components for rice planted to 1.3 cm, 2.5 cm, and 5.1 cm soil depth in 2016 and 2017. Lowercase letters for a given parameter compare by-treatment means within a column for a given year and depth. Uppercase letters in a given parameter compare by-depth means within a row for a given year and treatment. Means with the same letters are not different at a 5% significance level, according to Tukey HSD.

	2016			2017		
	Planting depth, cm					
	1.3	2.5	5.1	1.3	2.5	5.1
Treatment	Rice plants m^{-2}					
UTC[a]	148 a A	156 a A	110 a A	317 a -	ND[b] - -	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

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[a] Treatment abbreviations and herbicide protocols are described in Table 1.

[b] ND, no data available.

Table 1.5. Yield components for rice planted to 1.3 cm, 2.5 cm, and 5.1 cm soil depth in 2016 and 2017. Lowercase letters for a given parameter compare by-treatment means within a column for a given year and depth. Uppercase letters in a given parameter compare by-depth means within a row for a given year and treatment. Means with the same letters are not different at a 5% significance level, according to Tukey HSD.

	2016			2017		
	Planting depth, cm					
Treatment	1.3	2.5	5.1	1.3	2.5	5.1
	Panicle yield, g					
UTC[a]	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
	1000-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	5.7 c -	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 aAB	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

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[a] Treatment abbreviations and herbicide protocols are described in Table 1.

[b] ND, no data available.

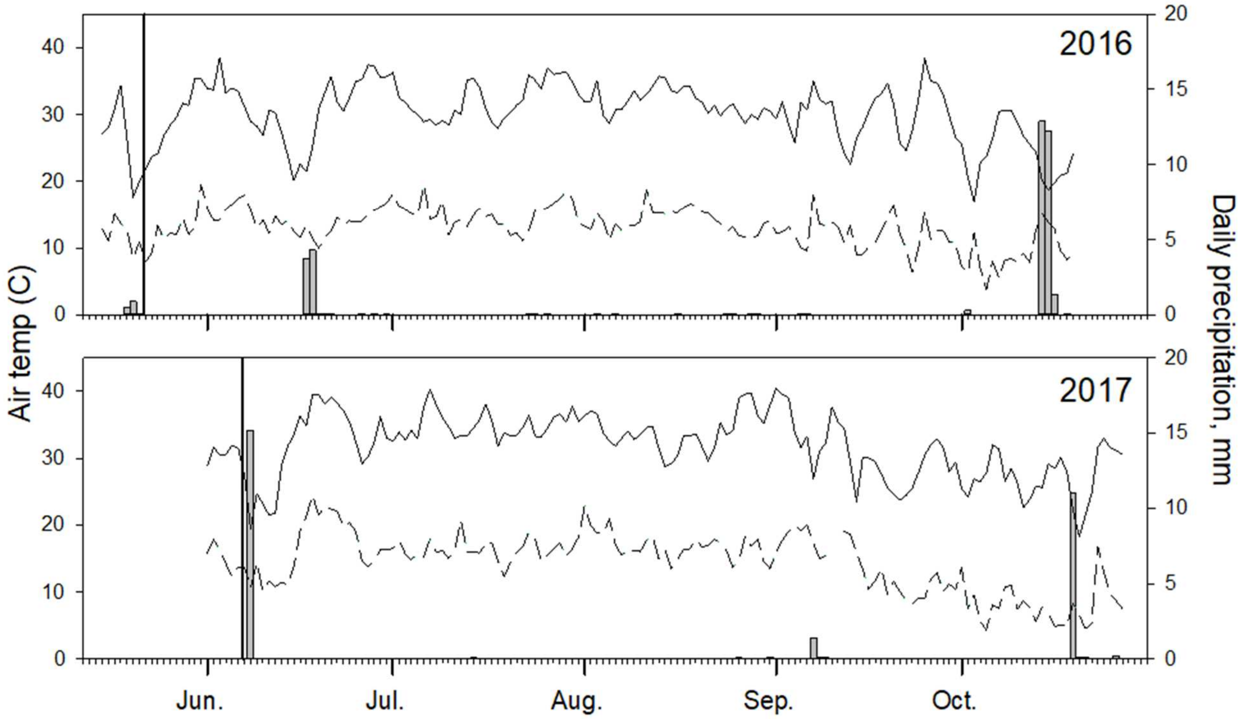

Figure 1.1. Daily temperature extremes and daily rainfall for 2016 and 2017 seasons. Solid and dashed lines are daily maximum and minimum temperatures (°C), respectively. Bars are daily precipitation (mm). Vertical lines are planting dates of 22 May 2016 and 08 June 2017.

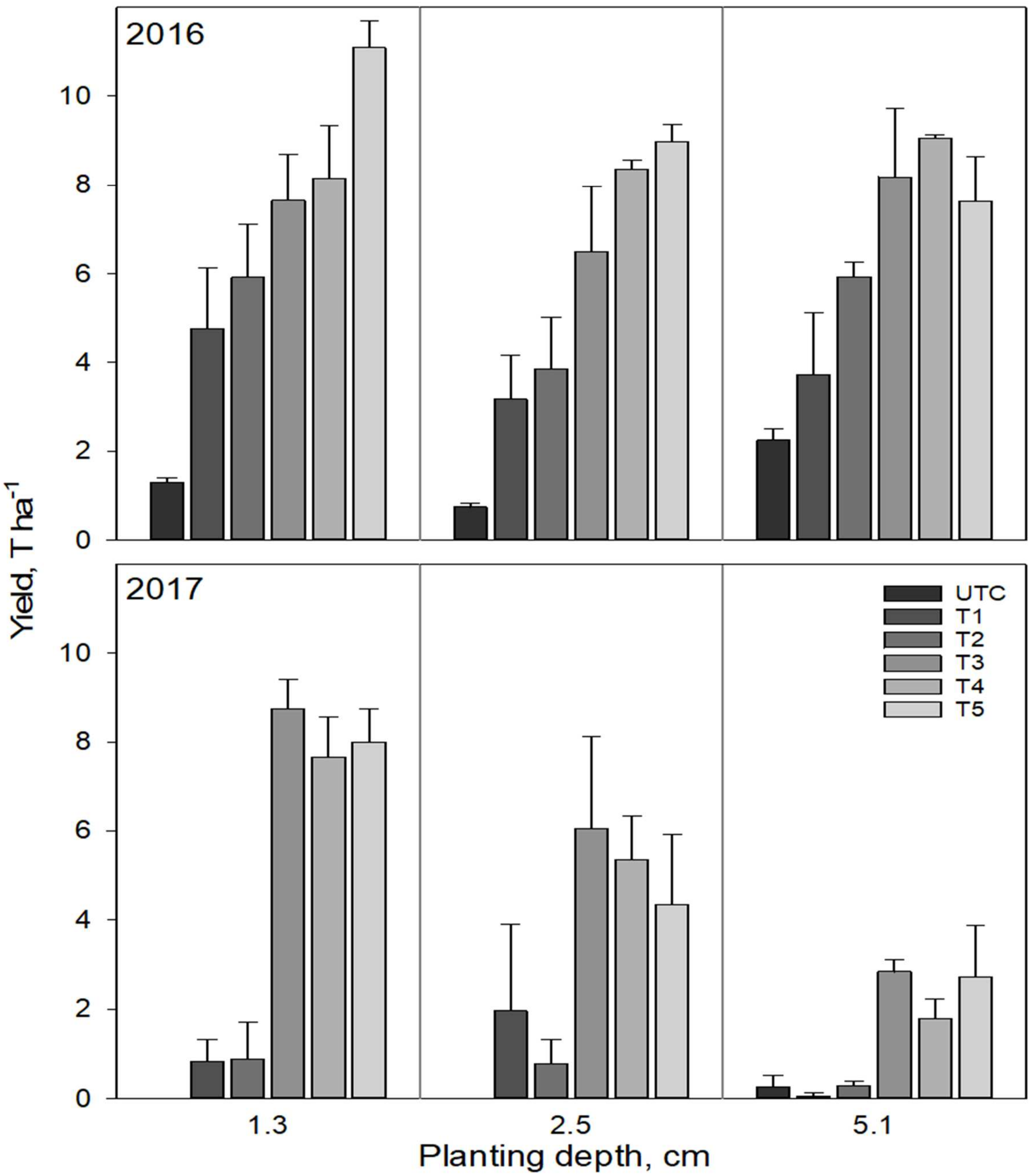

Figure 1.2. Grain yield of rice cv. M-206 planted in 2016 and 2017, as affected by planting depth and herbicide treatments. Error bars are ± mean standard error, and can be used to compare data between treatments and planting depths in a given year. Herbicide treatment abbreviations and protocols are described in Table 1.

CHAPTER 2

Seeding Depth Effects on Elongation, Emergence, and Early Development of California Rice Cultivars

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Abstract

The continuous use of a water-seeded cropping system for California rice [*Oryza sativa* L.], along with a limited palette of available herbicides, have selected for flood-tolerant grasses, aquatic species, and herbicide resistant weed populations throughout the region. Alternative cropping methods such as stale-seedbed and deeper drill seeding may be combined to allow novel herbicide modes of action and combat resistance while providing economically competitive yields. Two experiments were conducted to evaluate rice cultivars for vigorous traits that would facilitate such a stale-drill cropping methodology. Four cultivars of California rice were grown in glasshouses and evaluated for differences in germination, elongation, emergence, and early-season morphology. Cultivars M-205 and M-209 were found to have greater rates of total below-soil elongation, and greater rates of mesocotyl and coleoptile elongation overall, across depths. M-205 and M-209 were also found to have higher rates of emergence across depths. Differences in aboveground growth parameters of emerged seedlings were only found at 0 cm, 6.4 cm, and 7.6 cm planting depths. Based on observed below- and above-soil growth and development, M-205 and M-209 exhibited greater vigor overall, as well as high levels of emergence from depths greater than 2 cm. Therefore, these cultivars should be suitable for stale-drill seeding as a strategy for managing herbicide resistance in California.

2.1. Introduction

Rice [*Oryza sativa* L.] is grown on about 200 000 ha in northern California (CA). Due to its hot, dry summer climate, the CA rice environment is especially conducive to competitive grass weeds, particularly *Echinochloa* species. For this reason, CA rice is predominantly water-seeded, in order to suppress the growth and emergence of grasses (Adair & Engler, 1955). In water-seeding, pre-germinated rice seed is broadcast by aircraft into permanently flooded basins, where the seed settles on the soil surface and pegs-down roots. Decades of this practice with little to no crop rotation, however, have selected for populations of grass species that can escape flooding, among them early watergrass [*Echinochloa oryzoides* (Ard.) Fritsch], late watergrass [*E. oryzicola* (Vasinger) Vasinger] (Adair & Engler, 1955; Fischer, Comfort, Bayer, & Hill, 2000) and bearded sprangletop [*Leptochloa fusca* (L.) Kunth ssp. *fascicularis* (Lam.) N. Snow] (Driver, Al-Khatib, & Godar, 2019). In addition, seasonlong flooding favors aquatic weeds and promotes the early season growth of algae. Aquatic weeds and algae can shade underwater rice seedlings and delay or reduce rice emergence and early-season vigor, which can negatively impact the stand's competitiveness with emerged weeds (Hill, Smith, & Bayer, 1994). Although good water management and other cultural practices continue to provide grass weed suppression for many CA rice growers, the vast majority rely on herbicides as their principal means of weed management (Hill, Williams, Mutters, & Greer, 2006).

California rice has a limited number of available herbicides, due to high costs of development and registration (Hill et al., 1994), as well as regulations based on concerns of herbicide drift from aerial applications that may damage neighboring orchards (Galla, Al-Khatib, & Hanson, 2018). Similarly, the modes of action (MOAs) of available herbicides are also limited, and in most cases there is only one herbicide for a given MOA (Hill et al., 1994). Repeated yearly applications of the same herbicides for control of specific weeds in many CA rice fields have thus resulted in widespread herbicide resistance in the region. Herbicide resistance management has become a paramount concern for rice growers, researchers, and the CA rice industry (Hill et al., 2006). Efforts to promote herbicide resistance mitigation in CA largely focus on rotation of the limited number of available herbicides, while the cropping strategy itself has remained largely static.

Given a robust and fully-amortized infrastructure for water-seeding, any alternative seeding and management techniques for California rice must be economical and provide competitive yields to be appealing to growers (Hill et al., 2006). Alternative rice cropping strategies in CA typically only involve modifications to the current water-seeded continuously-flooded system (Hill et al., 1994). One strategy used by some growers is the "stale seedbed" method. In this method, rice seedbeds are prepared in the spring, and shallowly irrigated to promote weed germination and emergence. Emerged weeds can then be managed via cultural methods such as cultivation, or via chemical methods such as nonselective herbicides such as glyphosate or paraquat (Hill et al., 2006). Afterwards, the fields are flooded and seeded as usual. This method can accomplish a reduction of the general soil seedbank, as well as a reduction of herbicide-resistant weeds in a field (Rao, Johnson, Sivaprasad, Ladha, & Mortimer, 2007). However, high-clay CA fields take several weeks to dry-down enough for field equipment after spring rains, and there is a general perception among CA growers that stale seedbed usage will delay rice planting by too long, shortening the season and potentially depressing yields. For this reason, stale seedbed implementation is usually limited to fields with severe herbicide resistance problems. Another rice cropping strategy used in other parts of the US in conjunction with a stale seedbed, and which could be adapted to aid herbicide resistance management efforts in California, is drill seeding.

Drill seeding of rice is uncommon in California, though it is widely practiced in the US Mid-South. In that region, dry rice seed is drilled to 1.25 - 2 cm, and fields are typically flush-irrigated for the first few weeks as the rice stand develops and herbicides are applied, after which the field is flooded for the remainder of the season (Gravois & Helms, 1994). This cropping method discourages aquatic weed species and early-season algal growth (Hill et al., 1994), but it can encourage grasses that emerge at the same time as the rice, especially when the crop is sown to the same depth as competitive weeds like barnyardgrass (*Echinochloa crus-galli (L.) P. Beauv.*) (Smith, Flinchum, & Seaman, 1977).

The germination and emergence of weeds in rice fields vary with soil depth and water regime. It is commonly accepted that weed germination will be higher in aerobic soils such as found in drill seeded fields, though germination will generally decrease with increasing seed burial depth (Chauhan & Johnson, 2010). For instance, Benvenuti, Macchia, and Miele (2001) found that barnyardgrass seedling emergence was 20% or less at burial depths greater than 4 cm, and that mean time to emergence was 10 days or more at these depths. Chauhan and Johnson (2011), however, found that barnyardgrass emergence was less than 5% at greater than 4 cm depth, with a mean time to emergence of greater than seven days. Seeding rice deeper than 4 cm could place the rice below the zone of maximal weed germination, thus delaying stand emergence and allowing the safe use of nonselective herbicides on emerged weeds just prior to rice emergence. This deep-drilled modification of the stale seedbed preparation could allow rice growers to plant on time while managing herbicide resistance.

Deeper planting of rice is generally not recommended for U.S. Mid-South cultivars, as lower seedling vigor may decrease rice emergence. Koger, Walker, and Krutz (2006) found that a 3.8 cm seeding depth reduced the emergence of ‘Lemont’, ‘Cocodrie’, and ‘Wells’ cultivars by 32%, 34%, and 20%, respectively at 21 days after planting (DAP). Stand emergence is a principal concern of deep-seeded rice, as reduced or uneven stands typically have lower yields despite increased tillering, and uneven ripening due to nonsynchronous emergence may reduce milling quality (Dilday, Mgonja, Amonsilpa, Collins, & Wells, 1990; Gravois & Helms, 1994; Koger et al., 2006). Therefore, rice cultivars with greater vigor would be expected to have more rapid emergence and more even stands than lower-vigor cultivars when sown at greater depths (Dilday et al., 1990; Turner, Chen, & Bollich, 1982).

Elongating seedlings of cereal crops sown below the soil surface consist of a coleoptile, which covers and protects the first leaf during elongation towards the surface, and a mesocotyl, which is the first internode between the coleoptile and the seed (Moldenhauer, Gibbons, Smith, & Dilday, 2003). In dry-seeded cereals, mesocotyl elongation tends to cease once the coleoptile tip reaches the soil surface (Loercher, 1966; Takahashi, 1978; Vanderhoef, Quail, & Briggs, 1979), at which point the coleoptile opens and the seedling emerges. Semidwarf rice cultivars have historically been found to have lower emergence rates from deeper plantings than taller rice cultivars, primarily due to lower rates of mesocotyl elongation (Dilday et al., 1990; McKenzie, Rutger, & Peterson, 1980). However, semidwarf rice cultivars with higher rates of mesocotyl elongation have been produced in recent years (Alibu, Saito, Shiwachi, & Kenji, 2011; Ju et al., 2007). Though semidwarf California rice cultivars are bred primarily for water-seeding, these cultivars are known to have high germination rates and high vigor, which are essential for emerging through water depths of up to 20 cm (McKenzie et al., 2015). In this way, CA cultivars may be suitable for the increased elongation and emergence needs of drill seeding to depths exceeding 2 cm. The present study aims to evaluate above- and belowground physiological responses of common CA rice cultivars to planting at various soil depths in a controlled environment, and thus identify cultivars that may be suitable for field-level studies on the efficacy of a deep-seeded stale seedbed strategy for herbicide resistance management in California rice.

2.2. Materials and Methods

2.2.1 Cultivar selection

All rice cultivars used in the experiments are nonhybrid semidwarf medium-grain temperate *Japonica*, supplied from commercially available seedlots with tested germination of 96% or greater. The four cultivars selected are widely planted in California, with full-season durations of about 150 days. ‘M-105’ is a very-early heading cultivar, averaging 83 days to 50% heading, and is grown on approximately 12% of California rice land (UCCE, 2012). M-105’s earlier heading might compensate for delayed emergence under deep seeding conditions. ‘M-205’ and ‘M-209’ are sequential releases of higher yielding cultivars that have the latest average heading times of the tested cultivars, at 94 days and 92 days to 50% heading, respectively. M-205 and M-209 are grown on approximately 11% and 24% of California rice lands, respectively. M-205 and M-209 have higher susceptibility to low-temperature induced sterility (blanking) than M-105 and M-206. Thus, deeper planting may provide better temperature moderation and protection from blanking for M-205 and M-209. In addition, M-205 and M-209 are larger-seeded varieties than M-105 and M-206; this may provide increased reserves to push through soil when planted deeply. ‘M-206’ is the most widely planted rice cultivar in California, grown on roughly half of the region’s area, with an average time to 50% heading of 86 days. M-206 has the lowest lodging resistance of the tested cultivars; deeper planting should help anchor M-206’s roots better and reduce propensity to lodging.

2.2.2 Growing conditions

Experiments were conducted over 2017-2018 in glasshouses at the University of California, Davis (UCD), Davis, CA., USA, and at the Rice Experiment Station (RES), Biggs, CA., USA. Plastic tubs measuring 43 x 29 x 24 cm (Sterilite Corporation, Townsend, Ma., USA) were bottom-drilled with 1.5-cm diameter holes to facilitate slow drainage after irrigation events and simulate field drainage in flush-irrigated drill seeded systems. Tubs were pre-filled to set depths with ricefield soil from Biggs, Ca., a Yolo clay loam (fine-silty, mixed, nonacid, thermic Typic Xerorthents, 1.7% organic matter) which was carefully leveled. Ten seeds of each cultivar were randomly assigned to be placed in four regularly-spaced longitudinal rows atop the level bed, and subsequently covered with soil to provide a uniform planting depth for each tub. Tubs were irrigated to saturation after seeding, and allowed to drain. Subsequent irrigation flushes to 15 mm water depth occurred every eight days thereafter, and allowed to drain. Supplemental lighting was provided by 1000 w high-pressure sodium lamps (UCD) or 1000 w metal halide lamps (RES) providing 400 µmol m^{-2} sec^{-1} photosynthetic photon flux density, with a 16 h photoperiod. Average day / night temperature and relative humidity were 32 / 18 °C and 44 / 80%, respectively, in both experiments.

2.2.3 Germination and belowground elongation study

This study was conducted at UCD. Rice seed were planted as described above to 2.5, 5.1, and 7.6 cm depths. Seeds or seedlings of each cultivar were carefully excavated every two days after planting until 20 DAP, and carefully washed with water. Germination, emergence, coleoptile and mesocotyl length, and total length were recorded. Germination was determined by the presence of an emerged coleoptile of greater than 1 mm length. This experiment was conducted in a split-plot design, with factors of depth as main plot, and cultivar as sub-plot. Treatments were replicated six times, and the study was repeated once.

2.2.4 Emergence and early-season growth and development study

This study was conducted at RES. Rice seed were planted as described above to 0, 1.3, 2.5, 3.8, 5.1, 6.4, and 7.6 cm depths. Seedling emergence was noted on a daily basis, and plant height was recorded weekly, until 28 DAP. At 28 DAP, emerged rice plants were randomly thinned to two plants per cultivar per tub. Plant height and number of tillers were recorded weekly until eight weeks after planting (8 WAP), upon which the number of leaves and aboveground fresh weight per plant were recorded. Plants were dried at 50°C for one week, and weighed. This study was conducted in a split-plot design in the same manner as the germination and elongation study. Treatments were replicated four times, and the study was repeated once.

2.2.5 Statistical analysis

No significant run-by-factor effects were detected in either study; therefore, data for each measurement were pooled across runs. Germination data were highly skewed towards 100% and were analyzed by semiparametric one-inflated beta regression (Ferrari & Cribari-Neto, 2004) using the package "gamlss" in R software (R core team). An index of emergence potential was calculated by dividing the proportion of emerged seedlings by the proportion of germinated seedlings, and analyzed as described above. While specific to soil and environmental conditions (Wanjura & Buxton, 1977), this index is a reasonable indicator of vigor differences between cultivars (Ranal & Santana, 2006). Cumulative seedling emergence data were analyzed by time-to-event analysis using the package "DrcSeedGerm" in R, to account for observation interval censoring, and to account for un-germinated or un-emerged seeds at the time of the study's termination (Onofri, Benincasa, Mesgaran, & Ritz, 2018), and fit to a three-parameter log-logistic model. Total emergence data at 8 WAP were fit with quadratic regression. All other data were analyzed via standard linear regression and ANOVA, using R and JMP® 14Pro (SAS Institute

Inc., Cary, NC, 1989-2019), with means separated by Tukey honestly significant difference (HSD) at $\alpha = 0.05$, where applicable.

2.3. Results and Discussion

2.3.1 Germination and belowground elongation

Each cultivar achieved 94% or greater germination at all planting depths by 20DAP. The greatest germination was found with *cv.* M-209, with 97% germination at 2.5 cm planting depth, and the lowest was found with M-105 at 7.6 cm depth, with 95% germination. No significant differences in germination were found between cultivars at any depth (data not shown), however M-205 and M-209 tended to consistently greater germination at all depths. Germination rates decreased slightly with deeper plantings for all cultivars, however the negative trend was not statistically significant. Emergence potential indices (Fig. 2.1) showed marked differences in the proportion of germinated seeds that were able to emerge. M-209 exhibited a greater emergence potential than the other cultivars at each planting depth, and was the only cultivar to have an index greater than 0.95. In addition, the apparent rate of decline in potential with increasing depth was lowest for M-209. Given the high germination rates for all cultivars, the consistently greater index for M-209 reflects a greater degree of apparent vigor for that cultivar.

Greater than 75% of seedlings emerged from 2.5 cm, 5.1 cm, and 7.6 cm planting depths after 8 DAP, 10 DAP, and 14 DAP, respectively. Consequently, below-soil elongation data reported are for up to those dates only. Total below-soil elongation over time of each cultivar followed a similar pattern for each seeding depth: M-209 tended to the most rapid elongation, followed by M-205, M-206, and M-105, respectively, in decreasing relative elongation rates.

For each cultivar, total elongation by 8-10 DAP was no different regardless of planting depth (Fig. 2.2A), suggesting that total cultivar elongation ability was independent of effects of planting depth under the study conditions. Turner et al. (1982) similarly found that depth did not play a role in elongation rates of either coleoptiles or mesocotyls of semidwarf or conventional rice in well-watered soils. M-205 and M-209 total elongation rates were unchanged from 10-14 DAP at 7.6 cm depth, while M-105 and M-206 total elongation rates slowed by 69% and 71%, respectively.

Coleoptile elongation was also similar for each cultivar at 8 DAP for all planting depths, yet by 10 DAP at 7.6 cm depth, differences between cultivars became more apparent (Fig. 2.2B). Interestingly, coleoptile elongation slowed for all cultivars after 10 DAP at 7.6 cm depth, regardless of coleoptile length or the relative soil depth of coleoptile tips. M-205 coleoptile length at 7.6 cm planting depth only increased 2% from 10 to 14 DAP, yet its mesocotyl length increased more than threefold over the same period, resulting in a nearly linear total elongation.

Mesocotyl elongation rates increased for all cultivars after 8 DAP at the 5.1 cm and 7.6 cm planting depths (Fig. 2.2C). Irrigation occurred at 8 DAP, therefore it is possible that increased plant-available water enhanced cellular expansion after that date, however it is also possible that a decrease in available O_2 subsequent to soil saturation may also have contributed to the rapid increase in mesocotyl elongation.

Rice coleoptile elongation is well known to be enhanced by hypoxic or anoxic environments (Alpi & Beevers, 1983; Magneschi & Perata, 2008; Setter, Ella, & Valdez, 1994; Turner, Chen, & McCauley, 1981) due to heightened α-amylase activity and fermentative metabolism (Perata, Geshi, Yamaguchi, & Akazawa, 1993), yet research detailing mesocotyl elongation in response to hypoxia is less common. Raskin and Kende (1983) found that hypoxia increased elongation of both coleoptiles and mesocotyls, though Huang, Greenway, and Colmer (2003) only observed mesocotyl elongation enhancement under anoxia that was present at imbibition, as opposed to anoxia imposed several days afterward. In this study, mesocotyl lengths were far more variable than coleoptiles between cultivars at any depth, and between depths for a given cultivar and DAP. For example, observed mesocotyls were far shorter at 8 DAP for all cultivars at 5.1 cm and 7.6 cm depths, compared to the same DAP at 2.5 cm planting depth (Fig. 2.2C). However at 10 DAP mesocotyl elongation was similar for all cultivars at both 5.1 cm and 7.6 cm depths. Beyond 10 DAP, mesocotyl elongation for all cultivars at 7.6 cm depth proceeded relatively linearly, with M-205 having the most rapid elongation at 0.31 cm / day, and M-206 having the slowest at 0.05 cm / day. Final lengths for the cultivars at the deepest planting were telling. M-209 had significantly greater total and coleoptile lengths than the other cultivars, (Fig. 2.2A-B), yet M-205 and M-209 had no differences in final mesocotyl lengths (Fig. 2.2C), though both of those were significantly longer than the other cultivars' mesocotyls.

It has been previously reported that semidwarf rice cultivars do not establish well under deeper seeding, compared to conventional-stature cultivars. Earlier research demonstrated a correlation between mesocotyl length and vigor in semidwarf and taller cultivars (Dilday et al., 1990; Mgonja, Dilday, Skinner, & Collins, 1988; Turner et al., 1982). Semidwarf cultivars tended to have shorter mesocotyl length, as well as reduced stand establishment and reduced early-season growth rate when seeded at greater depths. However, McKenzie et al. (1980) found that crosses of a semidwarf line with a conventional line showed no difference in seedling length between semidwarf and taller descendants, but all seedlings were significantly longer than the semidwarf parent. More recently, Ju et al. (2007) found that several semidwarf cultivars had higher rates of mesocotyl elongation than conventional lines, and two long-mesocotyl semidwarf lines had the highest emergence percentages from up to 6 cm soil depth. In the present study the final mesocotyl lengths for all cultivars at the deepest planting were 1 cm or greater. The relative proportion of mesocotyl length to total length by 14 DAP at 7.6 cm depth was 0.19 - 0.2 for all cultivars except M-205, which had a mesocotyl - to - total length ratio of 0.25. It is unclear why M-205 had a greater proportional mesocotyl length, though the present results suggest that the increased mesocotyl elongation rate may provide some vigor advantage over M-105 and M-206.

2.3.2 Emergence and early-season growth and development

Rice seedlings began to emerge by 4 DAP at 1.3 and 2.5 cm depth plantings, and by 5 DAP at all deeper plantings. However, at 7.6 cm depth only M-209 had any emergence until 8 DAP. M-205 and M-209 tended to emerge earlier and more rapidly than the other cultivars, across planting depths (Table 2.1). In 2.5 cm plantings, M-105 and M-206 had more rapid emergence rates (denoted by large "*b*" values) around T_{50}, although at deeper plantings, M-205 and M-209 generally had larger *b* and smaller T_{50} values, indicating early and rapid emergence from 3 cm or greater planting depth for those cultivars. Overall, M-205 and M-209 had the lowest time to 50% emergence *("e"*, or T_{50}) for all depths except surface plantings. Plotting the reciprocal of *e* against planting depth (Fig. 2.3) revealed consistently greater emergence rates for M-205 and M-209. These values decreased linearly with depth for all cultivars, however the slopes of M-205 and M-209 (b = -0.014) were less steep than for M-105 and M-206 (b = -0.018 and -0.019, respectively). Traits conveying higher seedling vigor would be expected to contribute to earlier and more rapid crop emergence (Dilday et al., 1990; Mgonja et al., 1988), thus contributing to synchronous stand emergence and development. By these measures, high vigor traits seen here in M-205 and M-209 should facilitate early-season crop and weed management (Gravois & Helms, 1994; Hadjichristodoulou, Della, & Photiades, 1977; Koger et al., 2006).

There were no significant differences in total emergence (*"d"*) between cultivars seeded on the soil surface, but differences in total emergence became apparent between cultivars when seeded at any below-surface depth (Table 2.1). Total emergence was greater than 95% for all cultivars at 1.3 cm and 2.5 cm planting depths, and all cultivars showed decreasing total emergence as burial depths increased (Fig. 2.4). Reductions in total emergence from 1.3 cm to 7.6 cm depths were greatest for M-105 and M-206 at 79% and 76% respectively, followed by M-205 and M-209 at 56% and 38%, respectively.

Relative growth rates of emerged seedlings were similar over time, however M-205 and M-209 were taller than the other cultivars at 0 cm, 6.4 cm, and 7.6 cm depths from 2 WAP onward (Table 2.2). Total 8 WAP height responses to seeding depth were varied. Between 5.1 cm and 7.6 cm M-105 and M-206 heights decreased 8.8%, and 4.9%, respectively. In contrast, M-205 and M-209 plant heights increased 5.2% and 5.7%, respectively, between 5.1 cm and 7.6 cm depths.

Seeding depth had no effects on the length of time to first tiller appearance for any cultivar, though M-205 and M-209 had somewhat higher tiller numbers at each depth over time. At all depths M-205 and M-209 increased tillers at greater rates than the other cultivars, yet tillering at 8 WAP was only significantly different at 6.4 cm and 7.6 cm depths (Table 2.2). It is interesting that tiller initiation and total tillers were largely unchanged across depths, and that M-205 and M-209 saw tillering increases at the greatest depths. Reductions in tillering and plant height with increased crown soil depth are well documented in other cereals. Hucl and Baker (1990) found slight but nonsignificant reductions in rate of tiller emergence and total tillers plant^{-1} with increasing crown depth from 3 cm to 6 cm in Canadian spring wheat, and studies on European wheat and barley cultivars saw decreases in full-season tillering and height at depths greater than 5 cm (Photiades & Hadjichristodoulou, 1984). In contrast, other studies found slight increases in wheat tiller number from 3 cm to 6 cm planting depths (Mahdi, Bell, & Ryan, 1998), and from 5 cm to 10 cm planting depths (Hadjichristodoulou et al., 1977), although tillering decreased with greater planting depths in both cited studies.

It is possible that the observed tillering and height accumulation advantages of M-205 and M-209 would be transient if this study progressed to heading or grain harvest. By way of example, cultivar-specific advantages in aboveground growth rate early in the season would be expected to be overcome by the time of heading, as final plant height is generally a fixed characteristic of a cultivar (Harlan, 1992). However, in this study we saw that M-205 and M-209 had greater rates of belowground elongation overall, as well as greater aboveground height and tiller number over time at the deepest plantings. This suggests that these cultivars, though able to mobilize seed reserves to elongate and emerge more quickly, did not suffer for their early vigor in comparison to the less-vigorous cultivars in the study. The data on height and tillering responses observed in this study are insufficient to predict whether these cultivars would respond similarly in the field; however, further studies on the effects of increasing crown soil depth on these cultivars' growth and development at a field scale should shed light on these characteristics, and their potential effects on yield.

Leaves per plant only differed where tiller number was significantly different. No differences were found in leaves per tiller across all cultivars and depths (data not shown). Dry weights at each depth were only significantly different between cultivars at 0 cm, 6.4 cm, and 7.6 cm depths (Table 2.2), and likely reflected the combined effects of final height and tiller number. Cultivar dry weights across were no different between 1.3 cm and 5.1 cm plantings. Between 5.1 cm and 7.6 cm planting depths, M-105 and M-206 dry weights were reduced by 45% and 50%, respectively, whereas M-205 and M-209 dry weights increased by 31% and 58%, respectively.

Direct comparisons between below-soil elongation and parameters of emergence and development were not possible in these studies. However, our observations of differences between cultivars in seedling organ elongation and early-season growth parameters generally agreed with previous research linking elongation to rates of emergence, height, or tillering (Alibu et al., 2011; Ju et al., 2007; McKenzie et al., 1980). As new cultivars are developed, seedling organ elongation rates might be used to by breeders to identify seedlines that are well-suited to the stresses of deep dry-seeding.

Our combined findings suggest that the observed vigorous characteristics of M-205 and M-209 seedlings should allow them to emerge rapidly and evenly several days after planting, if drilled to depths greater than 3 cm the field. This in turn would facilitate the usage of a stale seedbed technique without a delay of planting, and allow the application of nonselective herbicides to control early-emerging and resistant weeds without damaging emerging rice. In addition, if M-205 and M-209 demonstrate vigorous early growth and tillering in the field, that may hasten canopy closure, potentially conferring an additional competitive advantage over later-emerging weeds.

Conclusion

M-205 and M-209 were found to be more vigorous overall than the other cultivars evaluated. Breeding efforts in California have continued to produce high vigor cultivars for cold tolerance and rapid emergence from flooding depths up to 20 cm (McKenzie, Johnson, Tseng, Oster, & Brandon, 1994). Uniform stands and even emergence are primary concerns in drill seeded rice culture (Koger et al., 2006), and these traits would be critical for successful implementation of deep drilling as a strategy for herbicide resistance management. The observed characteristics of high vigor found in these CA cultivars, such as rapid elongation and even emergence, might be utilized successfully in such a system that integrates stale-seedbed with deep drilling. Although earlier emergence of high-vigor cultivars might shorten the window of application for weed burndown treatments, their higher total emergence would help to ensure strong stands that would be competitive with later emerging weeds. The observed levels of vigor in M-205 and M-209, as demonstrated by robust elongation and rapid rates of emergence from sowing depths up to 7.6 cm, suggest that vigor traits bred into CA cultivars for water seeding are also well suited for drill seeding at depths greater than 2 cm. Formal field studies comparing higher- and lower-vigor cultivars would be necessary to adequately evaluate them for suitability in a deep-seeded stale-seedbed rice system. If successful, such a system may be a valuable tool for fields beset by herbicide resistance.

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Tables and Figures

Table 2.1. Emergence parameter estimates for four rice cultivars seeded at various depths.

		Log-logistic regression parameters[†]					
Depth, cm	Cultivar	*b*	S.E.[‡]	*d*	S.E.	*e*	S.E.
0	M-105	-1.6a[§]	0.2	0.88a	0.17	13.0a	3.5
	M-205	-1.5a	0.2	0.86a	0.09	8.2a	2.8
	M-206	-2.0a	0.4	0.77a	0.05	7.2a	1.8
	M-209	-1.8a	0.2	0.81a	0.08	10.4a	2.3
1.3	M-105	-7.1a	0.6	0.96b	0.02	6.5a	0.2
	M-205	-6.1a	0.7	0.98a	0.01	6.4a	0.2
	M-206	-6.3a	0.9	0.98a	0.01	6.6a	0.3
	M-209	-6.5a	0.7	0.96b	0.02	6.1a	0.2
2.5	M-105	-20.6a	3.7	1.00a	0.002	7.6a	0.1
	M-205	-7.7b	0.7	0.96c	0.02	6.9b	0.2
	M-206	-15.7a	2.2	0.96c	0.02	7.6a	0.2
	M-209	-8.1b	0.8	0.98ab	0.01	6.9b	0.1
3.8	M-105	-12.2a	2.1	0.88c	0.03	8.5a	0.2
	M-205	-11.8a	2.3	0.91b	0.02	7.9b	0.2
	M-206	-14.8a	2.3	0.92b	0.03	8.0b	0.2
	M-209	-16.4a	1.8	0.95a	0.01	7.7b	0.1
5.1	M-105	-7.3b	0.8	0.76cb	0.06	10.1a	0.3
	M-205	-13.7a	4.1	0.80b	0.04	8.2c	0.2
	M-206	-10.9ab	2	0.79b	0.04	9.4b	0.2
	M-209	-15.3a	2.5	0.87a	0.05	8.3c	0.1
6.4	M-105	-5.7ab	1.4	0.47c	0.09	11.0ab	0.9
	M-205	-7.0a	1.9	0.63b	0.04	9.4b	0.4
	M-206	-3.6b	0.5	0.52bc	0.08	14.0a	1.4
	M-209	-9.6a	2.8	0.72a	0.04	9.4b	0.3
7.6	M-105	-3.9ab	0.5	0.20c	0.04	17.5a	1.2
	M-205	-4.8ab	1.1	0.43b	0.08	11.6a	1.2
	M-206	-3.3b	0.3	0.24c	0.05	16.9a	2.7
	M-209	-8.1a	1.4	0.60a	0.06	11.1a	0.4

[†] *Equation:* $Y = d / \{1 + \exp(b [\log x - \log e])\}$*, where b = the relative slope of the regression at [x = e], d = maximum value of the estimate (total % germination), and e =* T_{50} *(time to 50% emergence).*

[‡] *S.E. = Standard Error of estimate mean.*

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§*Means separations calculated from robust S.E.s generated using "drcSeedGerm" package in R. Values within a column for a given depth followed by the same letter are not significantly different at α = 0.05*

Table 2.2. Plant growth characteristics, measured 8 weeks after planting (WAP).

Depth, cm	Cultivar	Height, cm	S.E.[†]	Tillers plant^{-1}	S.E.	Dry mass, g	S.E.
0	M-105	60.3b[‡]	4.0	3.1a	0.4	0.9b	0.1
	M-205	60.4b	4.0	4.4a	0.5	1.3a	0.1
	M-206	63.3ab	4.0	3.4a	0.4	1.3ab	0.1
	M-209	64.6a	4.0	3.6a	0.4	1.3ab	0.1
1.3	M-105	63.8a	4.0	2.6a	0.3	0.9a	0.1
	M-205	62.9a	4.0	3.7a	0.4	1.1a	0.1
	M-206	65.3a	4.0	3.1a	0.4	1.2a	0.1
	M-209	62.7a	4.0	3.1a	0.4	1.1a	0.1
2.5	M-105	62.8a	4.0	3.0a	0.4	1.0a	0.1
	M-205	61.5a	4.0	3.6a	0.4	1.0a	0.1
	M-206	63.6a	4.0	2.9a	0.4	1.0a	0.1
	M-209	63.4a	4.0	3.4a	0.4	1.3a	0.1
3.8	M-105	62.5a	4.0	2.8a	0.4	1.1a	0.1
	M-205	63.2a	4.0	4.1a	0.5	1.1a	0.1
	M-206	63.3a	4.0	2.7a	0.4	1.0a	0.1
	M-209	64.3a	4.0	3.6a	0.4	1.3a	0.1
5.1	M-105	62.6a	4.0	2.8a	0.4	1.0a	0.1
	M-205	63.2a	4.0	3.8a	0.4	1.3a	0.1
	M-206	63.9a	4.0	3.1a	0.4	1.2a	0.1
	M-209	64.4a	4.0	3.5a	0.4	1.2a	0.1
6.4	M-105	57.6b	4.0	2.7b	0.4	0.7c	0.1
	M-205	66.9a	4.0	4.7a	0.5	1.5a	0.1
	M-206	63.4a	4.0	2.9ab	0.4	0.9b	0.1
	M-209	64.7a	4.0	3.3ab	0.4	1.1ab	0.1
7.6	M-105	57.1b	4.0	2.6b	0.4	0.6b	0.1
	M-205	66.5a	4.0	5.0a	0.6	1.7a	0.2
	M-206	60.8b	4.0	2.5b	0.4	0.6b	0.1
	M-209	68.1a	4.0	4.8a	0.5	1.9a	0.2

[†] *S.E. = Standard Error.*

[‡] *Values within a column for a given depth followed by the same letter are not significantly different according to Tukey HSD at α = 0.05.*

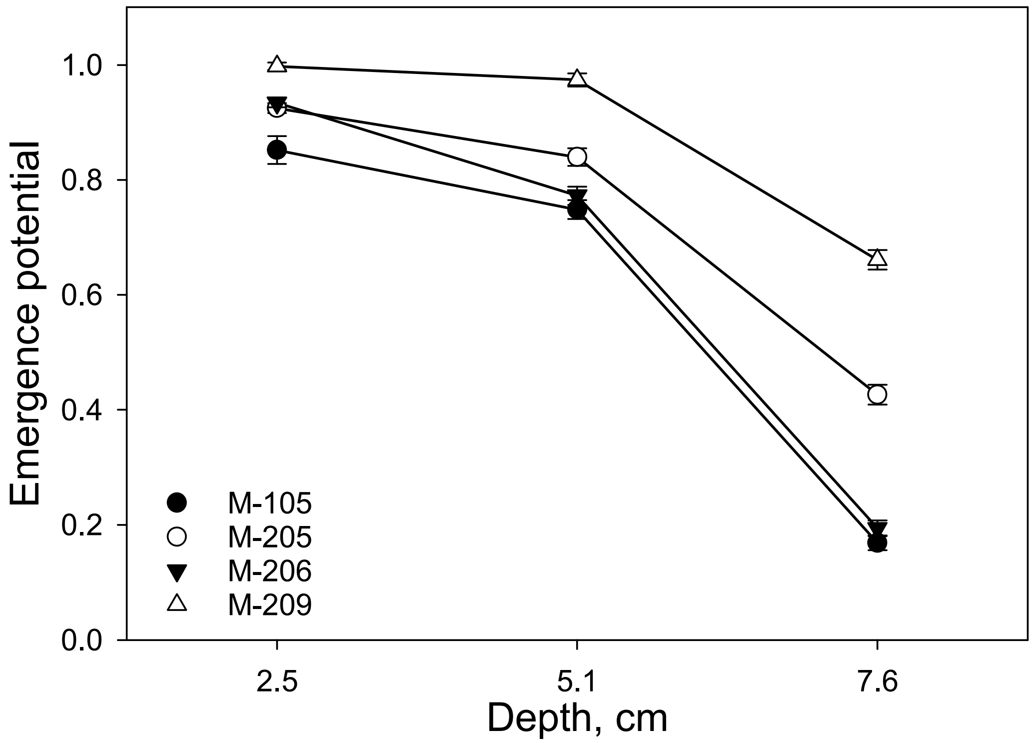

Figure 2.1. Emergence potential indices for four rice cultivars at three burial depths. Indices were calculated by dividing proportional emergence by germination. Error bars are +/- standard error.

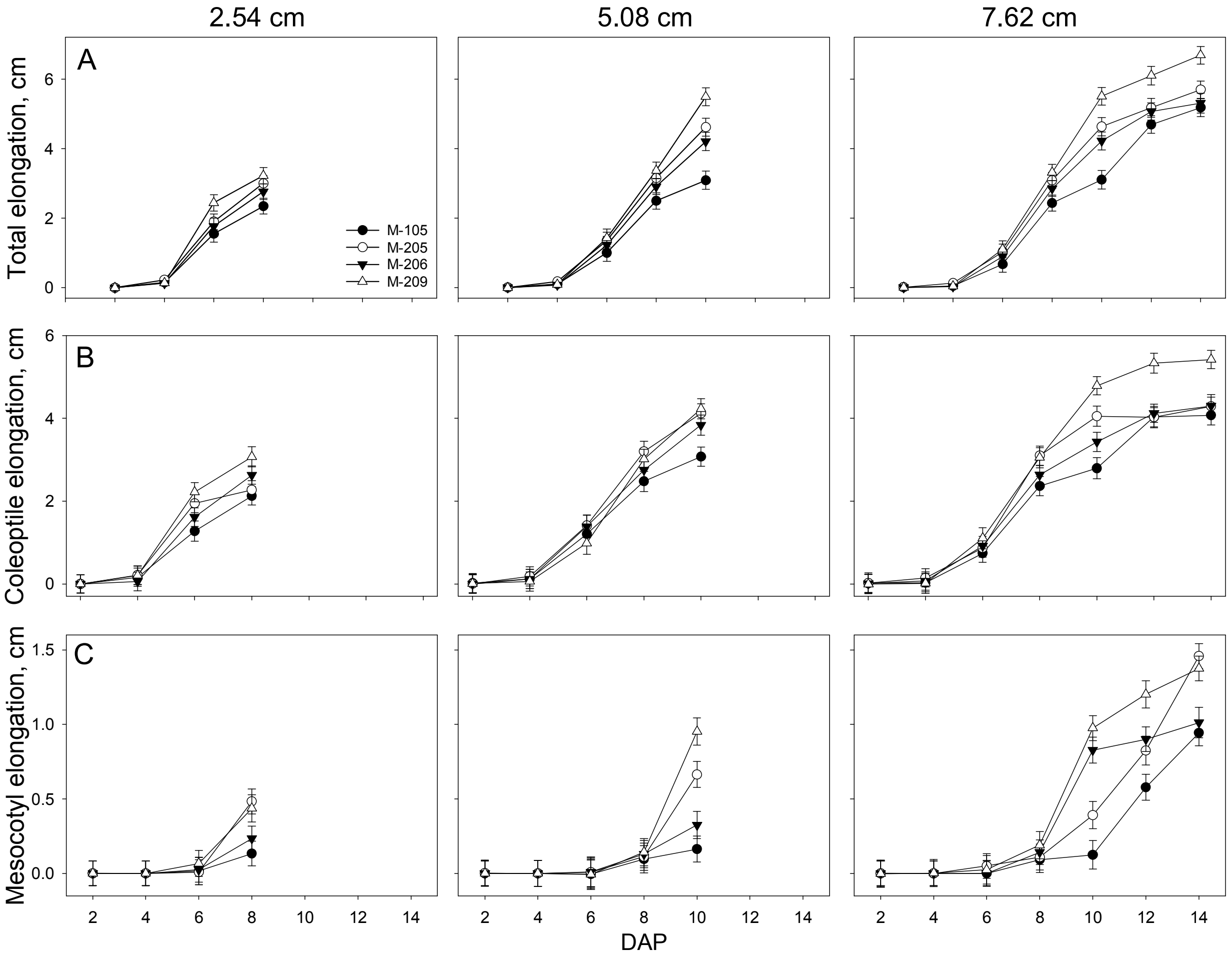

Figure 2.2. Below-soil elongation of four California rice cultivars at 2.5 cm, 5.1 cm, and 7.6 cm seeding depths. A: Total seedling elongation over time, B: Coleoptile elongation, C: Mesocotyl elongation. Error bars are +/- standard error. Note differences in scale of elongation rates (y - axis) of the different seedling organs.

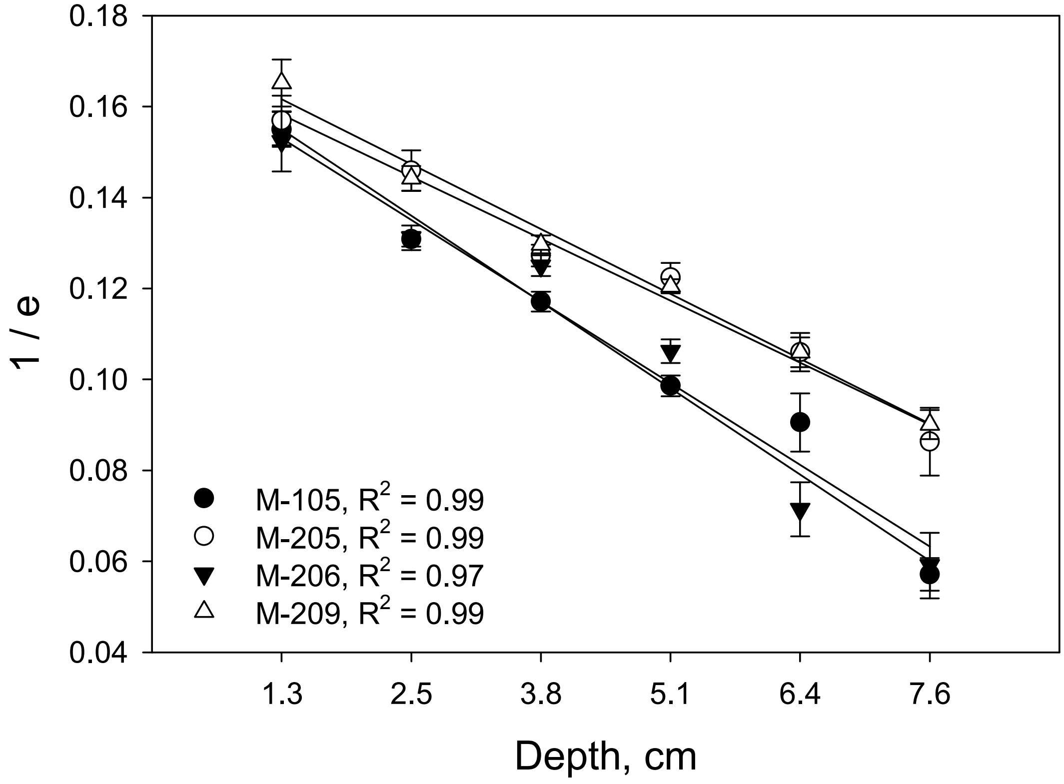

Figure 2.3. Linear relationships of the reciprocal of T_{50} (“1 / e”) with soil burial depth for four rice cultivars. Error bars are robust S.E.s generated with drcSeedGerm package in R.

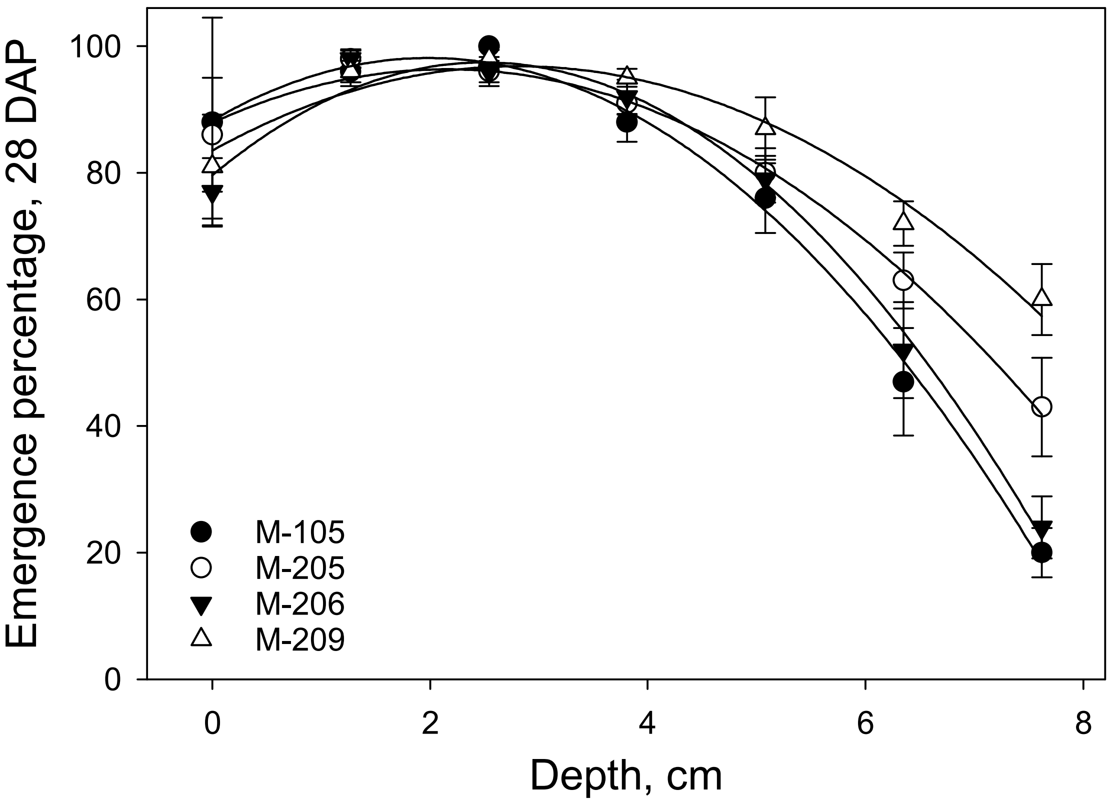

Figure 2.4. Total emergence of four rice cultivars at 28 days after planting (DAP) from seeding depths of 0 cm to 7.6 cm. Lines represent fitted quadratic regression for each cultivar; error bars are robust S.E.s generated with drcSeedGerm package in R.

CHAPTER 3

The Stale-Drill Method for Rice: Preliminary Findings of Weed Population Composition, Stand Development, and Yield Components in Two Vigorous *japonica* Cultivars

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Abstract

Rice grown in the Sacramento Valley of California is predominantly water seeded (WS), by direct-seeding rice into flooded basins. The effects of flooded rice monoculture and limited herbicides have led to weed populations which are difficult to control, and widespread herbicide resistance. A novel "stale-drill" rice cropping method has been under investigation in California, to assess its potential as an alternative option for rice stand establishment. Two high-vigor rice varieties ('M-206', 'M-209') were dry-drilled to 3 cm and 6 cm in 2018 and 2019, and fields were flush-irrigated to initiate weed germination prior to rice emergence. A postplant-burndown (PPB) application of glyphosate at 870 g a.e. ha^{-1} was applied 6-7 days after planting (DAP), at rice emergence, which controlled >50% of grass and sedge weeds. Glyphosate PPB caused rice first-leaf dieback, but no other symptoms developed. Neither planting depth nor cultivar affected the date of emergence in either year. Deeper seeding reduced M-206 and M-209 stand density by 15.4% and 5.2%, respectively, in 2018, but not in 2019. Increased tillering compensated for stand reductions in 2018. Panicle yield components were largely unaffected by planting depth in 2018, although florets panicle^{-1} and filled grains panicle^{-1} were slightly greater for both cultivars at 6 cm planting depth. In 2019 however, M-209 suffered reductions in florets per panicle and grain filling at 6 cm planting depth. Grain yields were not affected by planting depth in either study year. M-206 and M-209 grain yields were 10.2 T ha^{-1} and 12.2 T ha^{-1} respectively, in 2018, and 9.4 T ha^{-1} and 9.1 T ha^{-1} respectively, in 2019. The present study serves as a successful proof-of-concept for the "stale-drill" method as an alternative stand establishment method in mechanized rice production. Proper water management and scouting are essential to ensure that PPB treatments do not injure emerging rice to the extent that weak or reduced stands result. However, by way of introducing a novel mode

of action, this method may be a useful strategy in fields with difficult-to-control weeds, including herbicide-resistant populations.

3.1. Introduction

Mechanized direct-seeded cultivation of rice (*Oryza sativa* L.) is growing as a proportion of total area planted to rice around the world (Rao et al., 2017). Direct-seeded rice systems generally fall into the broad categories of dry-seeding or water-seeding. Dry-seeded rice can be broadcast onto dry soil by seed spreader or sown directly into soil by mechanical drill, whereas water-seeded (WS) rice can be broadcast into flooded fields by seed spreader or aircraft (Kumar and Ladha, 2011; Rao et al., 2017). Although direct-seeding of rice can significantly reduce time and labor investment in the planting stage, the various establishment methods described generally ensure that rice and weeds germinate and emerge synchronously (Chauhan, 2012; Brim-DeForest et al., 2017b), and weed management thus becomes largely dependent on chemical interventions (Rao et al., 2007). Herbicides can further reduce time and labor costs for weed management, however injudicious application techniques or overreliance on very few key active ingredients (AIs) often result in the development of herbicide-resistant weed biotypes (Hill et al., 2006). As mechanization continues to be adopted in the rice sphere, integrated approaches to weed management are becoming more and more crucial.

Rice grown in the Central Valley of California, USA comprises approximately 200 000 ha of irrigated fields. The region, which is among the highest-yielding in the world for rice production (USDA, 2021), is characterized by hot, dry, summers with abundant sunshine, and supports a single crop per year (Hill et al., 2006). California rice growers predominantly use a WS system, wherein pre-germinated seed is sown by aircraft into flooded fields. Rice seed sink to the soil surface and root down, emerging from the water after several days. Floodwaters are generally maintained at 10-20 cm for the entire season. California rice cultivars are temperate *japonica* inbred lines, with sufficient vigor to quickly elongate and escape deep floodwaters (McKenzie et al., 2015). Water seeding was adopted in the region in the 1920's to suppress competitive grass weeds (Adair and Engler, 1955), and has remained the preferred method of rice cultivation in California, even as herbicides have been widely available for decades (Hill et al., 1994; Hill et al., 2006).

Although the WS rice cropping system is optimized for the region, it is not without disadvantages. Water seeding encourages higher seeding rates that can incur higher production costs, because floating seedlings are subject to wind drift and predation, both of which may result in reduced or patchy stands at lower seeding rates. Surface-rooted rice is also prone to lodging. Irrigation water usage is also of concern (Hill et al., 2006; LaHue et al., 2016), as California is regularly beset by drought and irregular rainy seasons exacerbated by climate change. The near-exclusive use of permanently-flooded rice culture has also resulted in a small spectrum of well-adapted and competitive grass species (Hill et al., 1994), as well as aquatic broadleaves and sedges (Pittelkow et al., 2012).

As the permanently-flooded cropping system essentially precludes cultural weed management practices such as cultivation, and as large farm size and high labor costs discourage hand-weeding, herbicides are the sole means of weed control outside of water management for most California growers (Hill et al., 2006). Although effective herbicides have been available for California rice since the 1960's, the nearly exclusive use of water seeding has meant that the number of registered active ingredients remains low, amid pesticide contamination concerns and California's stringent regulatory structure (Hill et al., 1994). This limited herbicide palette restricts herbicide rotation. Since rice is largely grown year after year in the region, the combined effects of a water-seeded monoculture, and extensive use of limited available herbicides on a small weed spectrum, have resulted in widespread cases of herbicide resistance (Brim-DeForest et al., 2017a).

Cultural methods for weed and resistance management in California rice are generally limited to modifications of the dominant WS system (Hill et al., 1994). For example, with the "stale seedbed" method rice fields are prepared for planting as usual, but are flushed with water prior to seeding to promote weed germination (Harrell et al., 2011, Pittlekow et al., 2012). Nonselective herbicides are typically used as a burndown treatment on emerged weeds (Hill et al., 2006; Linquist et al., 2008), and fields are then flooded and air-seeded as usual. This method can be a useful strategy to manage weeds that are resistant to registered rice herbicides, by introducing novel nonselective herbicides without known local resistance (Rao et al., 2007). However, implementing a stale seedbed can delay rice planting and shorten the growing season, potentially depressing yields (Rao et al., 2007).

Stale-seedbed can be followed by drill seeding (DS) to shorten the delay between burndown treatment and rice planting. In DS systems, rice is dry-drilled to 1.25 - 2 cm, and fields are flush-irrigated intermittently as the stand develops and herbicides are applied, then flooded for the remainder of the season 30-40 days after seeding (Gravois and Helms, 1994; Harrell et al., 2011). This method discourages aquatic weeds and algae (Hill et al., 1994; Brim-DeForest et al., 2017b), however in this system the rice often emerges synchronously with grass weeds (Smith et al., 1977), reducing the stand's ability to compete with weeds. This also limits management of resistant weeds to the short preplant burndown window. However, if rice seed is sown to depths exceeding 2 cm, it might emerge later than early-germinating grasses (Koger et al., 2006), thus allowing cultural or chemical weed management practices to be used safely on emerged weeds without injuring the rice (Ceseski et al., 2021). This would lengthen the stale-seedbed burndown window, allowing more weeds to be managed by the burndown treatment. As California rice cultivars are bred for water seeding, they have suitable vigor to emerge through water depths of up to 20 cm (McKenzie et al., 2015). This high vigor may make California rice cultivars suitable for drill seeding to depths greater than 2 cm.

If planting vigorous rice deeply can permit delayed, but even rice stand emergence, it should be possible to combine drill seeding with a stale seedbed as an integrated approach to herbicide resistance management. This "stale-drill" method could permit the use of a novel mode of action in a postplant-burndown (PPB) treatment, which would safely manage key herbicide resistant weeds prior to stand emergence, without crop injury or delayed planting. Studies under controlled conditions comparing several California rice cultivars' responses to burial depth indicated varying levels of vigor between cultivars (Ceseski and Al-Khatib, 2021). The cultivar 'M-209' was found to have the greatest vigor of those tested, in terms of below-soil elongation, emergence, and early-season development. The purpose of this study was to compare stand establishment and yield components of M-209 and the most commonly planted cultivar, 'M-206', when seeded at two different depths. In addition, herbicide programs featuring a PPB application were evaluated for optimized late-season weed control.

3.2. Materials and Methods

3.2.1 Site characterization

Field experiments were conducted at the Rice Experiment Station (RES) in Biggs, CA, USA (39.45°N, 121.72°W) from May – October 2018, and June – October 2019. Soils at the site are classified as Esquon-Neerdobe (Vertisols: fine, smectitic, thermic, Xeric Epiaquerts or Duraquerts), with a composition of 24%, sand, 31% silt, and 45% clay. Soil average pH for the study years was 5.3, with 2.7% organic matter. The rice growing season in the Sacramento Valley is typically from April / May to September / October, while the rainy season is typically from October to May. Average minimum and maximum temperatures for the 2018 (28 May – 20 October) growing season were 13.5°C and 31.5°C, respectively, and for 2019 (17 June – 29 October) were 12.8°C and 30.6°C, respectively (CIMIS 2018-2019). Precipitation during both growing seasons was minimal, and concentrated in the latter weeks of the season. Seedbed preparation and cultural practices followed current University of California guidelines for water-seeded rice cultivation (UCANR 2018), with an added flat-roller operation to create a smooth seedbed for drillseeding.

3.2.2 Experimental design

Studies were conducted in a split-split-plot design, with planting depth as the main plots, cultivar as the subplots, and herbicide treatment as the sub-subplots, with three replicates each year (Fig. 3.1). Main plots were 16 x 18 meters, and were surrounded by 2.2-meter wide levees to allow independent flush-irrigation and flooding. Main plots were separated from each other by 6 m buffers to minimize lateral water movement. Planting depths in main plots were either 3 or 6 cm.

Within the main plots, cultivars ‘M-206’ and ‘M-209’ were planted on approximately half of the plot area each, separated by a 1.5 m unplanted buffer strip. M-206 is the most commonly planted cultivar in California (UCANR, 2018), grown on roughly half of the planted area, with a heading time of 86 days (UCCE, 2004). M-209 is a newer, higher-vigor cultivar that with a heading time of about 92 days (UCCE, 2017). Rice was dry-drilled at a rate of 121 kg ha^{-1}, using a mechanical seed drill (Great Plains Manufacturing Inc., Salina, Kansas, USA 67401) with 17.8 cm row spacing. Planting dates were 28 May 2018 and 19 June 2019 (Table 3.1).

Flush-irrigation for main plots was done by powered pumps. Main plots were flushed immediately after planting, and water was allowed to infiltrate the dry soil. Subsequent flushes were applied to each main plot independently, as the soil dried and cracks appeared. After final herbicides treatments were applied, the entire field was flooded to 10 cm average water depth for the remainder of the season. Harvest dates for 2018 and 2019 were 20 October and 29 October, respectively.

3.2.3 Herbicide programs

Herbicide programs were evaluated for PPB efficacy, and differences of control for later-emerging weeds. Sub-subplots of herbicide treatments were applied in 3 m x 6 m zones (hereinafter referred to as “plots”). Three herbicide treatments plus an untreated control (UTC) were used (Table 3.2). Herbicides were applied with a 6 m boom sprayer with six 8003XR flat-fan nozzles (TeeJet Technologies, Springfield, Illinois, USA 62703), CO_2-pressurized and calibrated for 187 L ha^{-1} carrier volume. At the date of first observed rice emergence, treated plots received a postplant-burndown (PPB) application of glyphosate (Roundup WeatherMAX®, Bayer CropScience, St Louis, MO, USA) at 870 g a.e. ha^{-1} + 2 % w/v ammonium sulfate (AMS) (Table 3.2).

Follow-up early-postemergence (EPOST) and mid-postemergence treatments were applied at 3-leaf and 4-leaf rice stages, respectively. EPOST treatments consisted of bispyribac (Regiment CA®, Corteva Agriscience, Wilmington, DE, USA) at 37 g a.i. ha^{-1} + 0.4% v/v organosilicone surfactant (Dyne-amic®, Helena Agri, Collierville, TN USA), applied alone or with a tankmix partner of pendimethalin (Prowl® H_2O, BASF Corporation, Research Triangle Park, NC, USA) at 1070 g a.i. ha^{-1} or clomazone (Command 3ME®, FMC Corporation, Philadelphia, PA, USA) at

550 g a.i. ha^{-1}. MPOST treatments were cyhalofop (Clincher CA®, Corteva Agriscience) + 2.5% v/v crop oil concentrate.

3.2.4 Data collection

3.2.4.1 Weed control

The study site weed seedbank was previously described in Brim-DeForest et al. (2017a) and Brim-DeForest et al. (2017b). Weed control evaluations measured the early-season efficacy of PPB treatments in this program, as well as the contributions of PPB treatments to overall control. The potential for later applications of pre-emergent (PRE) herbicides to enhance control of later-emerging weeds was also investigated. Weed responses to herbicides (treatment) and treatment timing differences imposed by rice planting depth (depth) were measured. Weed density in each plot after PPB treatment was estimated 20 days after planting (DAP) by counting plants in 30 cm x 30 cm quadrat samples, with three averaged subsamples per plot. Follow-up weed density counts were performed at 45 and 70 DAP, following the same methodology. *Echinochloa* spp. and sedges were grouped in their respective genera for quadrat counts.

3.2.4.2 Rice growth and development

Rice growth and development in response to herbicide program 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 crop development and yield components. Date of rice emergence was determined by visual estimation, and defined as >10%

of rice plants visible at the soil surface, and was used to time PPB treatment. Rice stand density was recorded at 21 days after planting (DAP) by counting plants in 30 cm x 30 cm quadrats, with three subsamples averaged per plot. Due to different maturation rates of the cultivars used in this study, tiller density was recorded at 90 DAP (M-206) and 110 DAP (M-209) by counting tillers in 30 cm x 30 cm quadrats, with three samples per plot. Time to 50% heading was estimated visually, and plant heights were recorded with a meter-stick at 120 DAP.

Prior to field harvest, ten panicles per plot were randomly selected, hand-harvested, and dried for three days at 50°C. Grain yield per panicle and 1000-grain weight were measured, and adjusted to 14% moisture content. Filled and total florets per panicle were measured, and percentage of unfilled florets was calculated. Whole plots were harvested and yields measured with a small-plot combine (ALMACO, Nevada, Iowa, USA) with a swath width of 2.3 m, and were adjusted to 14% moisture content.

3.2.5 Statistical analysis

All data –with the exception of time-to-heading– were subjected to ANOVA and linear regression analyses using the *agricolae* and *emmeans* packages in R (R core team), and JMP® 14Pro (SAS Institute Inc., Cary, NC, USA), using planting depth, cultivar, and herbicide treatment as fixed effects, and replicates as random effects. Significant year-by-depth and year-by-treatment and interactions for all data were observed; therefore, data were re-analyzed separately by year, using the same fixed and random effects as described above. In both years, no differences were observed between rice planting depths, cultivars planted, or among applied herbicide treatments for weed count data, therefore data for planting depth, cultivar, and treated plots were pooled and re-analyzed as treatment (n = 36) versus UTC (n = 12). Similarly, in both years, no differences were observed between herbicide treatments for rice stand and yield components, therefore treated-plot data were pooled and re-analyzed as treatment (n = 9) versus UTC (n = 3). Pooled data met assumptions of homogeneity and normality of variance, and were untransformed for analysis.

Rice time-to-heading data timepoints were analyzed with ANOVA, and cumulative heading data were fit with four-parameter logistic regression:

$$y = a + \frac{a - c}{\left[1 + \left(\frac{x}{x_0}\right)^b\right]}$$

Where a and c = maximum and minimum observed heading percentages, x_0 = time to 50% heading (T_{50}), and b = slope of the regression at x_0. Component cluster analysis of rice stand and yield parameters in response to planting depth and cultivar was performed using JMP® 14Pro. Means separations for analyzed data were performed using Tukey HSD at $\alpha = 0.05$, where appropriate.

3.3. Results

3.3.1 Weed control

Echinochloa spp. (*Echinochloa*) and *Leptochloa fusca* (L.) Kunth ssp. *fascicularis* (Lam.) N. Snow (*L. fusca*) were the major weeds in both years. Sedges were present in smaller numbers both years. No broadleaf weeds were present in either year. In addition, algae growth was inhibited until after the establishment of flood, at which time rice stands were tall enough to shade and suppress algae. In 2018, *Echinochloa* grasses were dominant in untreated (UTC) plots (Fig. 3.2), outcompeting other weeds and reducing sedge density to zero by 45 DAP ($p < 0.001$). *Echinochloa* densities in UTC plots eventually declined 27% between 20 DAP and 70 DAP ($p = 0.003$); however, combined weed density remained greater than 900 plants m^{-2} at 70 DAP. In 2019, combined weed density in UTC plots was approximately half of 2018 density throughout the season. *L. fusca* was the dominant species in 2019, however *L. fusca* self-thinning was not apparent by 70 DAP. *L. fusca* densities increased roughly linearly over time, increasing 57% between 20 DAP to 70 DAP ($p < 0.001$). *Echinochloa* and sedge densities decreased by 73% ($p < 0.001$) and 88% ($p < 0.001$) respectively, by 45 DAP. Rice and weeds in UTC plots were 100% lodged by 50-60 DAP in 2018, but rice lodging was reduced in 2019 due to lower weed densities.

PPB treatments were applied at 7 DAP in 2018, and 6 DAP in 2019. Glyphosate PPB reduced weed densities at 20 DAP in both years (Table 3.3). There were no differences in PPB effects between cultivars or planting depths. In 2018, PPB reduced *Echinochloa* spp., *L. fusca*, and sedge density by 60% ($p < 0.001$), 45% ($p = 0.045$), and 32% ($p = 0.064$), respectively. In 2019, PPB treatment reduced *Echinochloa* spp., *L. fusca*, and sedges by 52%, 95%, and 93%, respectively (all $p < 0.001$). By 45 DAP all treated plots, irrespective of planting depth or cultivar, were weed-free and remained so for the remainder of the season.

3.3.2 Rice growth and development

3.3.2.1 Rice stand

Rice became visible at the soil surface by 7 DAP in 2018, and 6 DAP in 2019, by which time grass and sedge seedlings were very dense in all plots. At date of emergence (DOE) either year, M-209 had slightly greater emergence than M-206 at both planting depths. Likewise, rice planted to 3 cm was slightly taller than rice planted to 6 cm, regardless of cultivar. Nevertheless, at DOE there were no differences in emerged seedling heights between cultivars or planting depths either year, and stands in all plots were even. In both years, glyphosate PPB was applied at DOE. Rice first-leaf tips exposed to the PPB treatment died off within a few days, however plants developed normally and exhibited no stunting, chlorosis, or other injury symptoms (data not shown).

Comparing pooled herbicide treatments with UTC plots, rice stand reductions were observed by 21 DAP in 2018 (Table 3.4). Averaged across planting depths and cultivars, rice plants m^{-2} were reduced by 46% in UTC plots in 2018 ($p < 0.001$), and were eventually reduced to zero. In 2019, no stand reductions were observed in UTC at 21 DAP, however significant reductions in all other growth and yield components were observed in UTC plots.

Rice stand development in treated (weed-free) plots was affected by cultivar and planting depth both years. In 2018 stand density for M-206 and M-209 planted at a 6 cm depth was reduced by 15.4% ($p < 0.001$) and 5.2% ($p = 0.34$), respectively, relative to the 3 cm planting depth. However, stand density was not affected by cultivar or planting depth in 2019. Increased tillering in M-206 compensated for stand reductions in the 6 cm planting depth in 2018; M-206 tillering decreased only 3.2 % ($p = 0.82$) between the 3 cm and 6 cm planting depths. For either cultivar, tiller density decreased slightly at 6 cm planting depth in 2018, and increased slightly in 2019. Cultivar differences in tillers $plant^{-1}$ were only observed in 2018, averaging 2.3 and 1.9 tillers for M-206 and M-209, respectively.

Time to heading was affected by cultivar in 2018, and by both cultivar and planting depth in 2019 (Fig. 3.3). Time to 50% heading (T_{50}) in 2018 was 75 DAP and 83 DAP for M-206 and M-209, respectively. In 2019, T_{50} for M-206 was 76 DAP for both plating depths. M-209 T_{50} was affected by planting depth in 2019, at 79 DAP and 80 DAP for 3 cm and 6 cm planting depths, respectively

($p < 0.001$). Full-season plant heights were not affected by PPB treatment, cultivar or planting depth either year (data not shown).

3.3.2.2 Yield components

In 2018 there were no harvestable panicles or yield component analysis in UTC plots. Rice yield components in weed-free plots were significantly affected by cultivar in 2018 (Table 3.5); all measured yield components were greater for M-209 at either planting depth. M-209 averaged 26 more florets per panicle ($p < 0.001$), and 19 more filled grains ($p < 0.001$) than M-206 in 2018. Percent unfilled grains (blanking %) was 1.6-fold greater in M-209 ($p < 0.001$). Although not significant, panicle yield, 1000-grain weight, total florets per panicle, and filled florets per panicle were generally greater for rice seeded at the 6 cm planting depth for both cultivars in 2018.

In 2019 yield components were significantly reduced in UTC plots. Averaged across planting depth and cultivar, panicle grain yield, florets per panicle, filled grains per panicle, and 1000-grain weight decreased 47%, 31%, 37%, and 15%, respectively (all $p < 0.001$). M-209 planted at the 6 cm depth had the greatest reductions in yield components in 2019 UTC plots, with nearly 30% lower 1000-grain weight and 50% blanking when seeded to that depth. In 2019 weed-free plots, cultivar differences in yield components varied. Averaged across planting depths, M-206 had greater panicle grain yield ($p = 0.028$) and 1000-grain weight ($p = 0.004$), while M-209 had greater florets per panicle ($p = 0.005$). M-209 blanking percentage averaged 1.7-fold greater than M-206 ($p < 0.001$) in 2019.

No harvestable field grain yields were available in UTC plots in either year. In weed-free plots, yields were affected by cultivar, but not planting depth in 2018 (Fig. 3.4), averaging 10.2 T ha^{-1} and 12.2 T ha^{-1} for M-206 and M-209, respectively. M-206 and M-209 yields were 5.2% and 25.8% greater, respectively than typical local water-seeded rice yields of 9.7 T ha^{-1} in 2018 (USDA, 2021). In 2019 M-206 averaged 9.4 T ha^{-1} across planting depths, while M-209 average yields were 9.1 T ha^{-1}. M-206 and M-209 yields were 1.1% and 4.2% lower, respectively, than local average yields of 9.5 T ha^{-1} in 2019 (USDA, 2021).

Separate-year cluster analysis did not reveal any determinable effects of cultivar or planting depth (data not shown). Combined-year cluster analysis revealed that cultivar type was critical to response differences of stand and yield components (Fig. 3.5), whereas planting depth did not appear to have any influence. Analyzing the biplot with the smallest Bayes information criterion (BIC) value, cluster A corresponded to 92% of M-209 data, and cluster B corresponded to 100% of M-206 data, with 8% of M-209 data as outliers. Both clusters generally corresponded to principle components (PCs). Clusters A and B explained 33.2% and 24.1% of total variance, respectively, whereas PC 1 and PC 2 explained 38.1% and 25.4% of total variance.

3.4. Discussion

3.4.1 Weed control

3.4.1.1 Weed composition in untreated plots

Weed group composition in untreated (UTC) plots did not vary between years, however weed group densities varied greatly. Aquatic broadleaves and algae were not observed in either year, which is in agreement with previous research on DS rice using early-season flush irrigation, or full-season alternate wetting and drying (Pittelkow et al., 2012; Brim-DeForest et al., 2017b). As aquatic weeds and algae can inhibit rice growth via shading and physical barrier in water-seeded (WS) systems, the potential suppressive benefit of early-season flushing in DS rice is clear. This can be a useful component of the stale-drill method as a measure for herbicide resistance management, as algae and broadleaf suppression can occur without any additional resistance selection pressure.

Grass densities were high in both study years, however *Echinochloa* densities were lower in 2019, allowing *L. fusca* and sedges to become more competitive. It is interesting that all three major weed groups were present in roughly equal numbers early in 2019 (Fig. 3.2), yet *Echinochloa* and sedge densities decreased dramatically by 45 DAP, while *L. fusca* densities increased. In 2018, extreme relative density allowed *Echinochloa* grasses to easily out-compete other weeds and rice in UTC plots, whereas in 2019 reduced *Echinochloa* density allowed *L. fusca* to out-compete other weeds. Emergence of *L. fusca* is discontinuous throughout the season (Brim-DeForest et al., 2017b; Driver, 2019), and the lack of suppressive competition -particularly from *Echinochloa* spp.- appeared to allow later-emerging *L. fusca* to freely establish.

3.4.1.2 Weed control in treated plots

Drilling rice seed at 3cm and 6 cm depths delayed rice emergence and successfully permitted the use of a postplant burndown (PPB) herbicide treatment just as rice was beginning to emerge. Using flush-irrigation to prime weed seed resulted in timed emergence of the majority of observed grasses, and glyphosate use alone reduced combined grasses by more than 50% in both study years (Table 3.3). Although *L. fusca* emergence appeared to continue after PPB treatment, this was not observed with *Echinochloa* or sedges. *Echinochloa* spp. emergence is also known to be discontinuous in rice systems (Chauhan and Johnson, 2011; Boddy et al., 2012; Brim-DeForest et al., 2017b; Driver, 2019), however our results suggest that shallow flushing may have inhibited *Echinochloa* emergence from heavy soil as it dried and crusted over.

Previous research showed a weed control benefit to applying pendimethalin at rice emergence, as a part of a PPB treatment (Ceseski et al., 2021). As there were no differences in further weed control between the subsequent treatments in the present study (Table 3.2), it appears that there were no added late-season benefits of applying pendimethalin (T2) or clomazone (T3) at the 3-leaf stage. Using the stale-drill method with PPB can achieve the dual cultural-chemical effects suppressing aquatic species and shifting the weed spectrum, as well as allowing novel modes of action to be used to control grasses and sedges. Both of these effects could reduce the spread of herbicide resistance, if stale-drill is used in rotation with other rice establishment methods.

3.4.2 Rice growth and development

3.4.2.1 Rice response to planting depth

Previous research found that M-206 emergence in the field was delayed by up to three extra days by planting to 5.1 cm, compared to 1.3 cm (Ceseski et al., 2021). However, emergence in that study was likely slowed by unseasonably cool temperatures immediately following planting. A related greenhouse study comparing the relative vigor four California cultivars found that M-206 planted to 5.1 cm and 6.4 cm had time to 50% emergence (T_{50}) of 9.4 and 14.0 days, respectively. In contrast, M-209 had T_{50} of 8.3 and 9.4 days at the same respective planting depths (Chpater 2: Ceseski and Al-Khatib, 2021). Based on these prior findings, we expected shallower-sown rice to emerge earlier, and expected M-209 to emerge before M-206. However, although there were minor differences in emerged seedling length, we found no differences in emergence date between cultivars or planting depths. The soil at the study site is a Vertisol, characterized by shrinking and cracking as it dries (USDA-NRCS, 2021). We observed that soil cracking in hot weather after the initial flushing event followed the lines of furrows left by the seeding drill. This cracking likely exposed elongating seedlings to light and oxygen, hastening emergence (Taki et al., 2006). Taken together, our findings support the hypothesis that California cultivars have sufficient vigor to emerge rapidly and evenly from these depths, however the increased vigor of M-209 may provide an emergence advantage if planted in cooler than normal conditions.

The stand reductions at 6 cm planting depth observed in 2018 were not repeated in 2019. It is possible that physical or allelopathic effects of the much higher weed density that year inhibited some rice from establishing. The relative competitiveness of rice and *Echinochloa* spp. is well documented, and recent research suggests that root exudates from *E. crus-galli* (Zhang et al., 2018) and *E. colona* (Sitthinoi et al., 2017) may have inhibitory effects on rice germination and emergence. Alternatively, growing degree day (GDD) accumulation was more rapid in 2019 due to the later planting date, which may have minimized stand reductions due to deeper seeding. Nevertheless, increased tillering in M-206 compensated for stand reductions in 2018. In a related study we found increased tillering with increasing soil crown depth in these cultivars (Ceseski and Al-Khatib, 2021), although the opposite has been observed previously in small-seeded cereals (Hadjichristodoulou et al., 1977). In addition, M-209 planted at a depth of 6 cm reached heading later than the more shallow seeding in 2019, which resulted in fewer filled grains at time of harvest.

3.4.2.2 Rice response to PPB treatment

Applying glyphosate to just-emerged rice resulted in tip die-back, but no other symptoms developed. Glyphosate is a systemic herbicide, and needs to be translocated to the crown of a graminid species in order to fatally inhibit the 5-enolpyruvlyshikimate-3-phosphate synthase (EPSPS) enzyme (Sikorski and Gruys, 1997). Although the emerged rice seedlings were green at the time of PPB application, the lack of secondary symptoms could be evidence that seedlings were not yet translocating, and therefore still using seed reserves for growth. In addition, glyphosate in solution is anionic, and readily binds to clay soil particles, especially in lower pH soils such as found in rice systems (Miles and Moye, 1988). It is also possible that soil particles attached to the coleoptile below the emerged leaf may have protected the rice somehwat by binding glyphosate molecules. Al-Khatib et al. (1992) found that foliar uptake of glyphosate bound to particles of silt loam with 6.6 pH was less than 1% each in alfalfa (*Medicago sativa* L.) and pea (*Pisum sativum* L.), and 3% in grape (*Vitis vinifera* L.), compared to roughly 50% uptake of aqueous glyphosate in the same species.

Grains with starchy reserves such as rice tend to tolerate anaerobic environments well (Alpi and Beevers, 1983; Perata et al., 1993; Magneschi and Perata, 2008), and this fact is certainly a major factor in the ability of rice organs to elongate vigorously through heavy soils or floodwaters. Alpi and Beevers (1983) found that a vigorous *japonica* cultivar was able to continue coleoptile elongation for up to two weeks before exhausting seed reserves. The cellular machinery in rice that is optimized for fermentative anaerobiosis also appears to provide an emergence benefit for rice grown aerobically in deep soil. Rapid and even stand emergence is key to timing a PPB treatment in deep-sown rice, and good field scouting is essential to determining emergence. Although application of a nonselective herbicide directly to emerged rice seedlings would not be recommended, the continued reliance of just-emerged seedlings on seed reserves can provide a fail-safe against application of a normally-lethal herbicide as a burndown treatment.

3.*4.2.3 Rice response to seasonal variability*

Differential cultivar responses to seasonal variability were apparent in this study. Trials were planted later in 2019, for a 129-day growing season versus 139 days in 2018. Although both cultivars have nominal season durations of about 140 days (Hill et al., 2006), M-209 is slower to mature than M-206, reaching 50% heading about six days later in traditional WS rice culture. M-209 reached 50% heading eight days later than M-206 in 2018, but only 3-4 days later in 2019, reflecting a T_{50} shift of 3-4 DAP in 2019 (Fig. 3.3). As the rice was planted later in the summer, growing degree day (GDD) accumulation would be expected to be greater early in the season, resulting in panicle initiation occurring earlier than expected in M-209. This possibility, along with the shortened season duration, may explain why M-209 appeared to have higher sensitivity to seasonal fluctuations than M-206.

Conclusions

We find that the present study serves as a successful proof-of-concept for the stale-drill method as a new strategy for rice production and weed management. This work agrees with previous studies that suggested that California semidwarf rice cultivars possessed suitable vigor to emerge evenly from seeding depths up to 6 cm, and that a PPB application of a nonselective herbicide could be safely administered to emerging rice without causing sustained crop injury. Aquatic weeds were suppressed by water management, and the PPB treatment reduced overall weed density by more than 50% in both years, regardless of planting depth or cultivar used. Variability in observed effects of deeper planting on rice growth and development do not support planting rice deeper than 3 cm, however. Although the two cultivars used in this study have varying levels of observed responses to seasonal variability, adequate field preparation, irrigation management, variety selection, and scouting can help to ensure healthy and economically competitive stands. In order to validate our confidence in this method, field-scale trials analyzing the logistical and economic parameters of implementing this program across soil and climate types are necessary. In addition, further refinements to herbicide programs emphasizing reduced input costs, and the potential of reducing seedbanks of weedy (red) rice and herbicide-resistant weeds, would help to more adequately assess the flexibility and potential utility of this method.

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Tables and Figures

Table 3.1. Timing of crop operations, irrigation events, and herbicide treatments for rice cultivars M-206 and M-209, planted to 3 cm and 6 cm in 2018 and 2019.

Year	Planting date	Rice emergence	Irrigation flushes	Herbicide applications[a]	Flooding	Harvest
2018	28 May	04 June	28 May 05 June 12 June (3 cm) 13 June (6 cm) 20 June	PPB: 04 June EPOST: 18 June Cleanup: 22 June	25 June	20 October
2019	17 June	23 June	17 June 24 June 02 July 10 July	PPB: 23 June EPOST: 09 July Cleanup: 16 July	17 July	29 October

[a] PPB, postplant-burndown; EPOST, early post-emergence; MPOST, mid post-emergence.

Table 3.2. Herbicide treatments applied to M-206 and M-209 rice drilled to 3 and 6 cm seeding depths in 2018 and 2019. All herbicides were applied with manufacturer-recommended adjuvants.

Treatment	Herbicide[a]	Application rate g a.i.[b] or a.e. ha^{-1}	Crop timing	Treatment timing[d]
UTC	---	---	---	
T1	glyphosate-potassium	870	Emergence	PPB
	bispyribac-sodium	37	3 LS[c]	EPOST
	cyhalofop-ethyl	315	4 LS	MPOST
T2	glyphosate-potassium	870	Emergence	PPB
	bispyribac-sodium	37	3 LS	EPOST
	pendimethalin	1070	3 LS	EPOST
	cyhalofop-ethyl	315	4 LS	MPOST
T3	glyphosate-potassium	870	Emergence	PPB
	bispyribac-sodium	37	3 LS	EPOST
	clomazone	550	3 LS	EPOST
	cyhalofop-ethyl	315	4 LS	MPOST

[a] Herbicides were applied with manufacturer recommended or required adjuvants, where applicable.

[b] a.i., active ingredient; a.e., acid equivalent.

[c] LS, rice leaf stage.

[d] PPB, postplant-burndown; EPOST, early post-emergence; MPOST, mid post-emergence.

Table 3.3. Efficacy of glyphosate postplant burndown (PPB) application on weed density. Weed densities were recorded 20 days after planting (DAP) in 2018 and 2019. Values for a given year within a column are estimate means followed by ± values for 95% Tukey-Kramer confidence limits for paired comparisons.

Year	PPB / UTC[a,b]	*Echinochloa* spp.		*L. fusca* ssp. *fascicularis*		Sedges	
		Plants m^{-2}					
2018	PPB	487 ± 77		32 ± 13		125 ± 30	
	UTC	1225 ± 133	$p < 0.001$	58 ± 22	$p = 0.023$	181 ± 52	$p = 0.058$
2019	PPB	161 ± 22		15 ± 11		19 ± 18	
	UTC	333 ± 53	$p < 0.001$	287 ± 19	$p < 0.001$	269 ± 30	$p < 0.001$

[a] Glyphosate was applied at 870 g a.e. ha^{-1} just as rice was emerging.

[b] Values for PPB (n = 36) and untreated control (UTC, n = 12) are pooled across cultivars and planting depths for each year.

Table 3.4. Rice stand components in 2018 and 2019. Rice stand was measured 21-22 days after planting (DAP). Tillering was measured at 90 DAP (M-206) or 110 DAP (M-209). Values for a given year within a column are parameter means followed by ± values for 95% Tukey-Kramer confidence limits for multiple comparisons.

Planting depth, cm	Cultivar	TRT / UTC[a]	Stand m^{-2}	Tillers m^{-2}	Tillers $plant^{-1}$
				2018	
3	M-206	TRT	356 ± 16	756 ± 41	2.2 ± 0.2
		UTC	206 ± 29	0 ± 0	-
	M-209	TRT	402 ± 16	780 ± 41.0	1.9 ± 0.2
		UTC	216 ± 29	0 ± 0	-
6	M-206	TRT	301 ± 16	732 ± 41.0	2.4 ± 0.2
		UTC	154 ± 29	0 ± 0	-
	M-209	TRT	381 ± 16	736 ± 41.0	1.9 ± 0.2
		UTC	201 ± 29	0 ± 0	-
				2019	
3	M-206	TRT	366 ± 20	669 ± 46	1.8 ± 0.1
		UTC	367 ± 35	311 ± 80	0.8 ± 0.2
	M-209	TRT	388 ± 20	702 ± 46	1.8 ± 0.1
		UTC	377 ± 35	319 ± 80	0.8 ± 0.2
6	M-206	TRT	379 ± 20	732 ± 46	1.9 ± 0.1
		UTC	347 ± 35	266 ± 80	0.8 ± 0.2
	M-209	TRT	387 ± 20	764 ± 46	2 ± 0.1
		UTC	390 ± 35	319 ± 80	0.8 ± 0.2

[a] Treated (TRT, n = 9) plot values are pooled across cultivars and planting depths for each year.

Table 3.5. Rice yield components in 2018 and 2019. Values for a given year within a column are parameter means followed by ± values for 95% Tukey-Kramer confidence limits for multiple comparisons.

Planting depth, cm	Cultivar	TRT / UTC[a]	Panicle yield, g	1000-grain weight, g	Florets panicle^{-1}	Filled grains panicle^{-1}	Blanking %
					2018		
3	M-206	TRT	3.1 ± 0.2	29.2 ± 0.8	112 ± 9	106 ± 9	5.9 ± 2.3
		UTC	-	-	-	-	-
	M-209	TRT	3.8 ± 0.2	29.9 ± 0.8	140 ± 9	126 ± 9	9.6 ± 2.3
		UTC	-	-	-	-	-
6	M-206	TRT	3.4 ± 0.2	29.7 ± 0.8	121 ± 9	114 ± 9	5.9 ± 2.3
		UTC	-	-	-	-	-
	M-209	TRT	4 ± 0.2	31 ± 0.8	144 ± 9	131 ± 9	9.5 ± 2.3
		UTC	-	-	-	-	-
					2019		
3	M-206	TRT	2.9 ± 0.2	30.4 ± 1.2	115 ± 10	97 ± 6	15.9 ± 5.0
		UTC	1.7 ± 0.4	25.9 ± 2.0	85 ± 16	65 ± 11	23.8 ± 8.6
	M-209	TRT	2.8 ± 0.2	29 ± 1.2	127 ± 10	96 ± 6	24.4 ± 5.0
		UTC	1.6 ± 0.4	25.2 ± 2.0	82 ± 16	64 ± 11	20.9 ± 8.6
6	M-206	TRT	2.9 ± 0.2	30.5 ± 1.2	110 ± 10	94 ± 6	14.7 ± 5.0
		UTC	1.9 ± 0.4	27.3 ± 2.0	84 ± 16	70 ± 11	16.3 ± 8.6
	M-209	TRT	2.5 ± 0.2	28.3 ± 1.2	119 ± 10	87 ± 6	26.3 ± 5.0
		UTC	0.7 ± 0.4	19.4 ± 2.0	73 ± 16	36 ± 11	49.6 ± 8.6

[a] Treated (TRT, n = 9) plot values are pooled across cultivars and planting depths for each year.

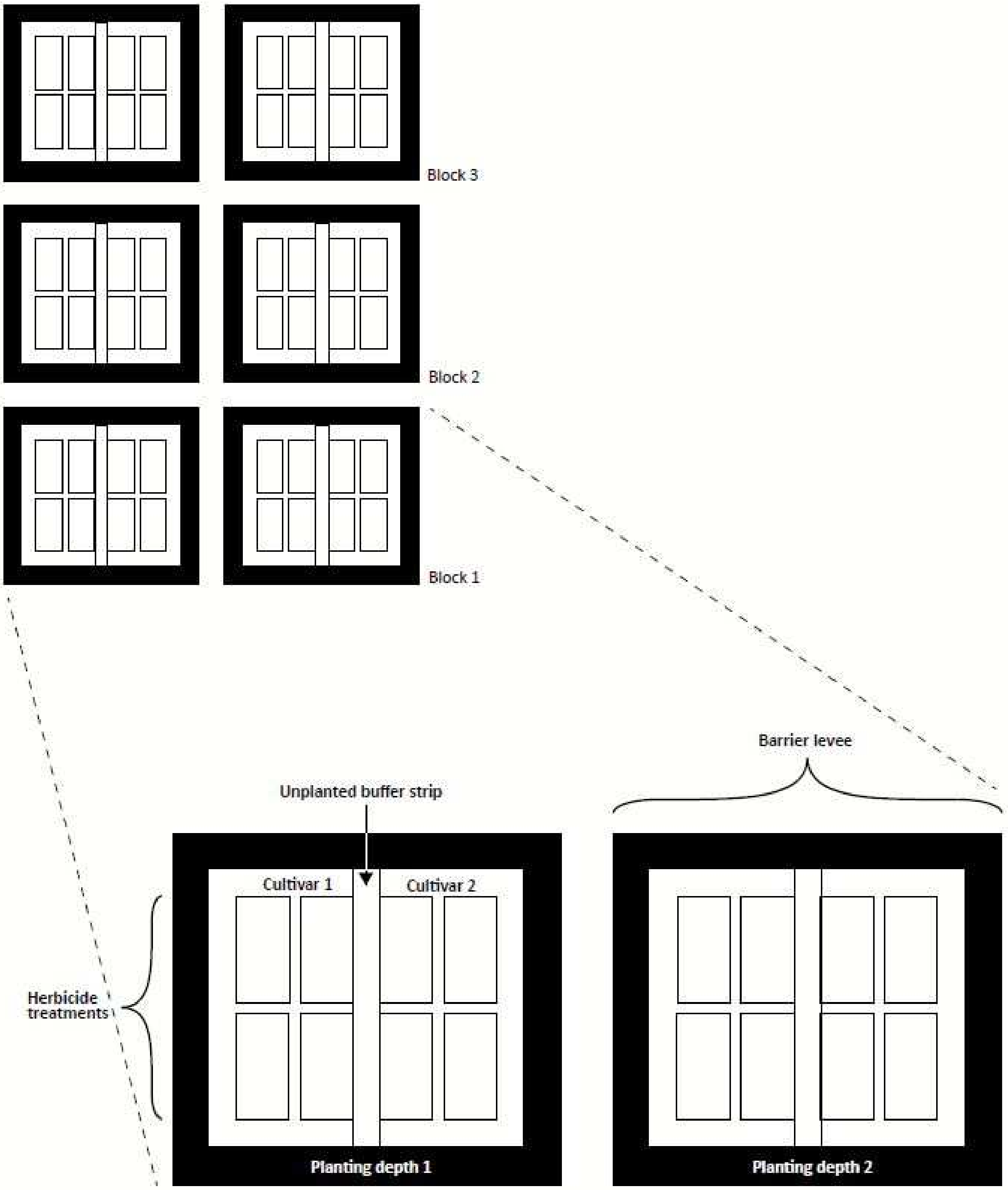

Figure 3.1. Field layout in 2018 and 2019. Planting depths (main plots) were encased by 2.2m levees, and cultivars (subplots) planted to each depth were separated by 2.5 m unplanted strips. Herbicide treatments (sub-subplots) were in 3m x 6m plots. Plots, subplots, and sub-subplots were randomized each study year.

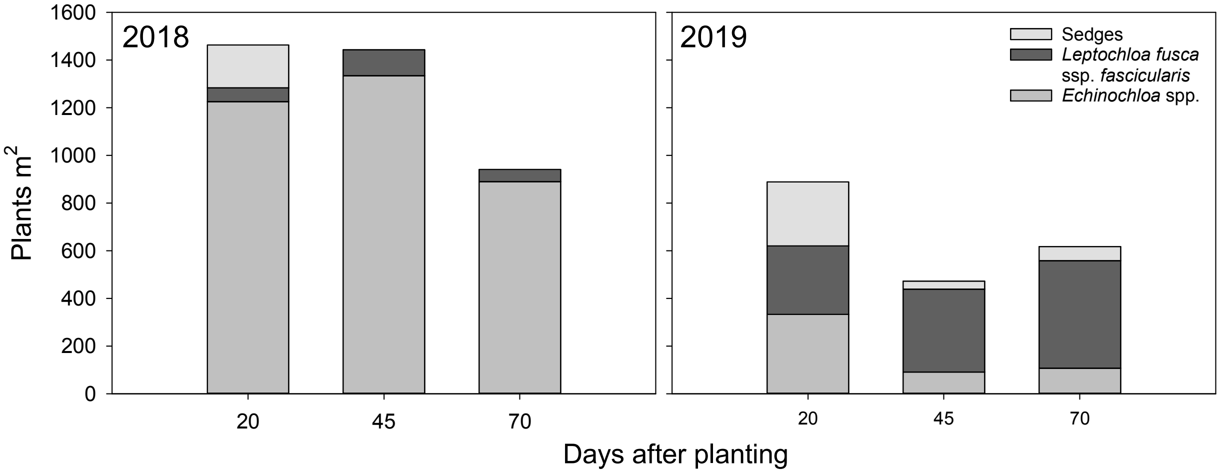

Figure 3.2. Relative weed density in untreated control (UTC) plots 20, 45, and 70 days after planting (DAP), in 2018 (left panel) and 2019 (right panel).

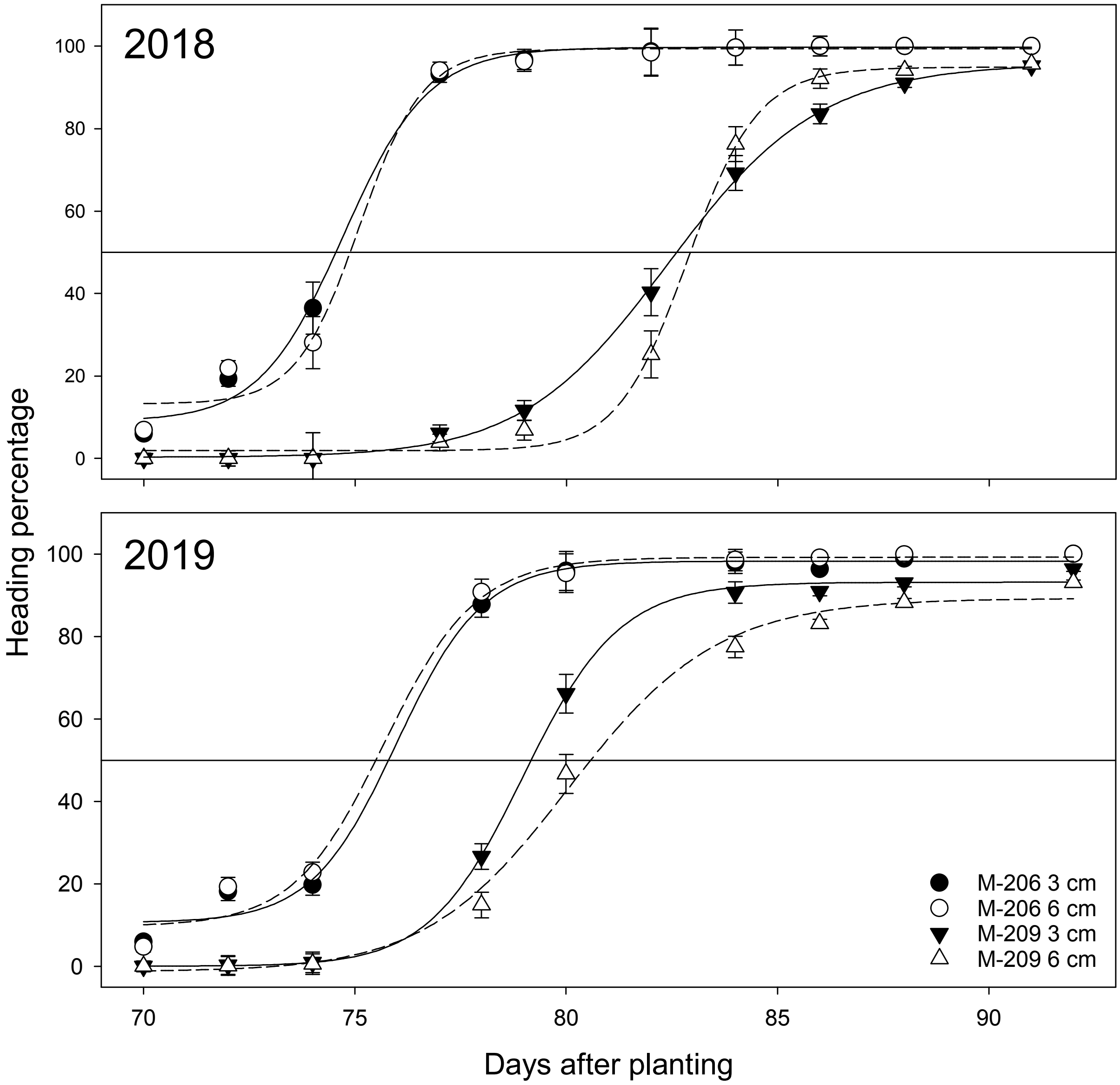

Figure 3.3. Time to heading for *cv.* M-206 and M-209 planted to 3 cm and 6 cm in 2018 and 2019. Curves represent four-parameter logistic regression. Equation: $Y = a + (a - d) / [1 + (x / x_0)^b]$, where a and d = the maximum and minimum estimated values, b = the relative slope of the regression about x_0, and x_0 = time to 50% heading (T_{50}). Horizontal line represents 50% of theoretical maximum heading. Error bars are ± estimate standard error.

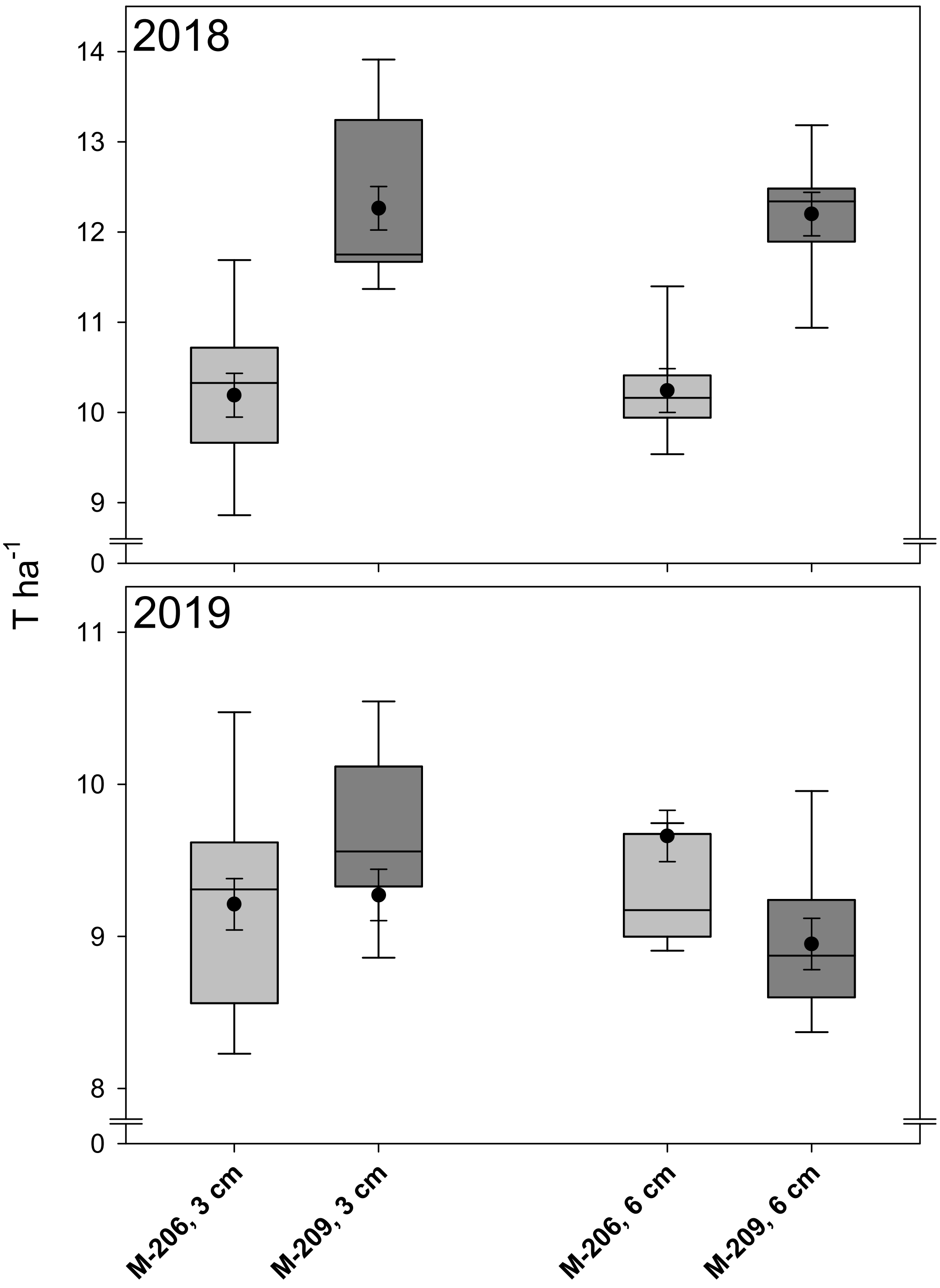

Figure 3.4. Rice grain yield of *cv.* M-206 (light grey) and M-209 (dark grey) seeded to 3 cm and 6 cm depths. Note differences in Y-axis scaling. No harvestable yields were recorded for untreated plots either year. Box whiskers represent 5th and 95th percentiles. Dots represent category means, and error bars are ± estimate standard error.

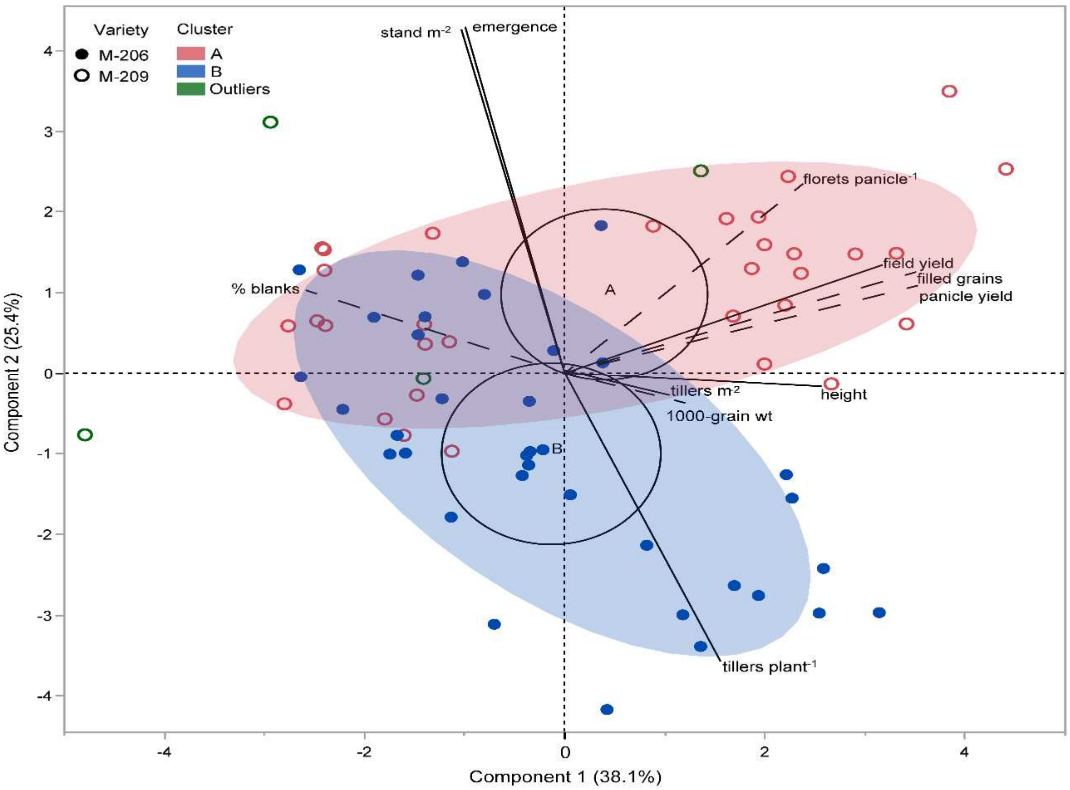

Figure 3.5. Combined-year cluster and PCA analyses of stand and yield components for *cv.* M-206 and M-209. PC 1 and PC 2 explain 38.1% and 25.4% of total variance, respectively. Cluster A (red) contains 92% of M-209 data and explains 33.2% of total variance. Cluster B (blue) contains 100% of M-206 data and explains 24.2% of total variance.

CONCLUSIONS

The overall purpose of this body of research was to demonstrate the potential for the “stale-drill” cropping method to provide good weed control and robust yields in California rice.

Our results identified high-vigor California rice cultivars that emerge evenly from planting depths of up to 6 cm. In doing so, we identified critical rice vigor traits that may aid breeders in selection for lines that can rapidly escape deep seeding. We also found that cultivar responses to environmental effects in the field were inconsistent. M-206 emergence was both delayed and reduced at greater seeding depths in 2016 and 2017, yet it emerged evenly and provided stable stands and yields in 2018 and 2019. In particular, cool and wet weather immediately after planting, and subsequent effects on field soil conditions, are suspected to be responsible for low M-206 emergence and poor stands in 2017. In contrast, hot, dry weather in 2018 and 2019 appeared to encourage both M-206 and M-209 to emerge from 3 cm and 6 cm planting depths simultaneously, as soil dried and cracks formed along furrows created by the planting drill. However, a late planting date in 2019 resulted in M-209 heading earlier than expected, which reduced grain filling and subsequently yield. Overall, the four years’ field data suggest that M-206 emergence is sensitive to cooler weather that may impede soil drying and cracking in the field, yet is less sensitive than M-209 to later planting date in years when temperatures are favorable for emergence and development. Although results from greenhouse studies conducted with damp soil that was free of cracks suggested that M-209 seedlings have better emergence than M-206 seedlings from greater soil depths, we were not able to compare M-206 and M-209 emergence under similar conditions in the field, to validate the greenhouse results. As soil cracking appeared to hasten emergence from any observed planting depth in warmer weather, there did not appear to be any benefit to planting either cultivar deeper than 3 cm, as deeper seeding did not result in greater delays in rice emergence, nor did it result in greater weed control with postplant-burndown (PPB) treatments.

We found PPB treatments to have mixed effects on grass and sedge weed control in these studies. We expected greater delays of rice emergence to result in concomitantly greater weed control with PPB, as that treatment was applied at date of rice emergence each year. However, increased delays in rice emergence were only observed with M-206 in 2016 and 2017, and PPB effects on weed control were not consistent in those years. Interestingly we found that PPB efficacy was greatest in 2018 and 2019, when favorable weather may have resulted in higher rates of grass and sedge weed emergence after the initial flushing event.

Full-season herbicide programs were more effective in 2018 and 2019 than previous years, and resulted in weed-free plots. However, using PPB as a means to manage herbicide-resistant grass and sedge populations, or to control weedy rice in fields, would only be effective as long as resistance does not develop to the mode of action in use. Additionally, as this method only controls weeds that are emerged in the first few days after planting, it cannot be used to manage resistant weeds that emerge later. The stale-drill method -and in particular the PPB treatment- are not intended to supplant the current water-seeded system in California. Rather, it is intended as a rotational option for growers, particularly those with heavy aquatic weed or algae pressure, herbicide-resistant grass and sedge populations, or weedy rice biotypes. As with any herbicidal intervention, using PPB to control early-season weeds carries the risk of selecting for herbicide resistance, or later germination and emergence.

Glyphosate PPB treatments visibly injured emerged rice immediately after planting in 2018 and 2019, yet did not result in later season rice stunting or apparent reduced yields. It would be premature to advocate applying a systemic herbicide such as glyphosate over the tops of emerged rice, based on the observations contained herein, however the observed rice injury and recovery are curious and worthy of further investigation. It would be useful to determine how long after emergence is safe to apply PPB before sustained injury is observed in rice seedlings, as they begin to shift from seed reserves to translocation. It may also be worthwhile to compare cultivar responses to glyphosate applications at increasing intervals post emergence. Finally, similar studies comparing glyphosate with nonselective contact herbicides such as glufosinate or paraquat may shed light on differences in injury with later applications.

Holistically, we have observed that water management and weather conditions appeared to have the greatest impact on rice emergence and weed control in these studies, as both factors influenced soil moisture and soil cracking behavior. As soils vary widely across the Sacramento Valley where rice is grown, soil behavior would also be expected to vary geographically, under similar weather conditions. In addition, since PPB treatment timing in stale-drill is based upon determining rice emergence, diligent field scouting would be essential for growers to adopt this program successfully. We suggest that larger field-scale studies conducted across a range of local soil and microclimate types would be the most effective means for evaluating the real-world viability of the stale-drill method in California. Besides adapting scouting and water management to local soil and weather conditions, comparative production costs with water-seeded rice should be assessed in order to properly evaluate the geographic and temporal range where stale-drill rice production may be best put to use.