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Weed Community Dynamics and System Productivity in Alternative Irrigation Systems in California Rice

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Over the last 10 yr, California has experienced a series of ever-worsening droughts. Rice, traditionally a flooded crop, has come under increasing scrutiny with respect to its water use, leading to proposals to evaluate alternative irrigation systems. For growers, weed competition is one of the most limiting factors to maintaining high yields, so understanding the shifts among species in weed communities under the proposed alternative irrigation systems is vital. A field study was conducted from 2012 to 2014 to compare weed population and growth dynamics with three irrigation systems: (1) a conventional water-seeded control system (WS-Control), with a permanent flood of 10 to 15 cm from planting until 1 mo prior to harvest; (2) a water-seeded alternate wet and dry system (WS-AWD), with the field flooded from planting until canopy closure, after which floodwater was allowed to subside and the field was reflooded when the soil volumetric water content reached 35%; and (3) a drill-seeded alternate wet and dry system (DS-AWD), with rice drill seeded and then flush irrigated to establish the crop, after which the field was flooded until canopy closure and then underwent an alternate wet and dry (AWD) treatment similar to WS-AWD. In the AWD treatments, there were two drying periods, neither of which occurred after the heading stage. The dynamics of major weed species were evaluated using plant density counts (2012) and relative cover and biomass (2013 and 2014). Grasses (sprangletop and watergrass species) dominated the DS-AWD system; sedges, broadleaves, and grasses dominated both WS systems. The WS-AWD system increased smallflower umbrella sedge relative cover at canopy closure, relative dry weight at harvest, and percent frequency when compared with the WS-Control system. Yields did not differ across treatments when weeds were controlled ($P > 0.05$); in the absence of herbicides, yields in the WS-AWD were equivalent to the WS-Control (ranging from 40 to 65% of the herbicide-treated yields) and zero in the DS-AWD due to weed pressure.

Nomenclature: bearded sprangletop, *Leptochloa fusca* (L.) Kunth N. Snow; ducksalad, *Heteranthera rotundifolia* (Kunth) Griseb.; redstem, *Ammannia coccinea* Rottb.; ricefield bulrush, *Schoenoplectus mucronatus* (L.) Palla; smallflower umbrella sedge, *Cyperus difformis* L.; rice (*Oryza sativa* L.).

Key words: Irrigation, direct-seeded rice, water-seeded rice.

Introduction

Rice is one of the most important sources of human energy worldwide and is grown in a wide range of agroecosystems, though paddy (flooded) systems are the most prevalent (Global Rice Science Partnership 2013). In California, more than 200,000 ha of flooded rice are grown in a water-seeded, continuously flooded system that has successfully suppressed certain nonaquatic weed species such as barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] and bearded sprangletop (Adair and Engler 1955). Currently, rice growers in California flood fields at the beginning of the growing season and then direct seed pregerminated rice seed into the flooded fields from airplanes. A flood depth of 10 to 15 cm is maintained until approximately 1 mo before harvest, when the field is drained to allow rice harvesting.

Repeated use of flooded irrigation in the California rice agroecosystem has since selected for weed species such as late watergrass [*Echinochloa oryzicola* (Vasinger) Vasinger] (Barrett 1983) that are well adapted to the system. In recent years, California has experienced unprecedented drought, with the 2012 to 2014 period being the driest on record (Jones 2015). Accordingly, concerns about water usage have increased, particularly for crops like rice that have high water use. Due to the flood irrigation, rice is a visible water user, receiving attention from both the general public and policy makers, and there is increased pressure on rice growers to reduce water use. In California, the only alternative to water seeding currently in use is dry seeding followed by

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flooding after early postemergent herbicide applications. Recent research, however, indicates that drill seeding into dry soil as practiced in California rice systems does not necessarily reduce crop evapotranspiration, crop coefficient, or irrigation delivery (in millimeters) in comparison with the continuously flooded system (Linquist et al. 2015).

A number of alternatives to flood irrigation exist in other rice-growing regions of the world, including an alternate wet and dry system (AWD), which reduces water use over the crop growth period through alternating periods of flooding with periods of drying, and saturated soil culture (SSC), which reduces water use over the crop growth period by maintaining the soil at the saturation point (Bouman et al. 2007). Yields in aerobic (nonflooded, nonsaturated soil) systems are often lower due to the reduced ability of rice to compete with weeds (Bhagat et al. 1996), and this may be an obstacle to adoption of alternative irrigation systems by growers.

In addition to changing the competitive ability of rice with respect to weeds, alternative irrigation systems can shift weed species composition, selecting for some species over others. In California, differences in irrigation during the seedling recruitment period have been shown to shift the emergence of certain weed species when comparing wet- versus dry-seeded systems (Fischer et al. 2009; Linquist et al. 2008; Pittelkow et al. 2012). In these systems, water seeding favored sedges and broadleaves, whereas dry seeding favored grasses, particularly watergrass and sprangletop species (Pittelkow et al. 2012). Later in the season, sedges and grasses dominate over aquatic weeds in saturated, nonflooded soils (Bhagat et al. 1996). For continuously flooded systems, water depth also affects the presence of certain species. Grasses are suppressed by continuous flooding to a depth of at least 5 cm, whereas a deeper flood of about 15 cm suppresses most sedges (De Datta 1981). If growers are to adopt alternative irrigation systems, understanding potential shifts in weed species' composition will be critical to weed management.

It is well documented that weed community composition can affect yields. The critical period of watergrass competition for rice in California is the first 30 d after planting, and yields can be reduced by as much as 59% when watergrass is uncontrolled (Gibson et al. 2002). However, critical periods of competition for other weed species are not known, and differences in composition between early- and late-season weed communities and the impacts of late-season competition on rice yields remain to be seen. Using two alternative irrigation systems adapted for California rice, the primary objectives of this research were: (1) to determine weed community composition in rice under different irrigation systems; (2) to determine whether there are differences between early and late weed communities within a system; and (3) to quantify differences in yields between irrigation systems in both the presence and absence of weed competition.

Materials and Methods

Site Characterization and Experimental Setup. The experiment was conducted from 2012 to 2014 at the California Rice Experiment Station in Biggs, CA (39.49°N, 121.62°W). Soils are classified as Esquon-Neerdobe (fine, smectitic, thermic Xeric Epiaquerts and Duraquerts). Soil characteristics in the 0 to 15 cm profile are: pH of 5.1, electrical conductivity of 0.35 dS m^{-1}, cation exchange capacity of 32.6 cmol kg^{-1}, and organic matter equaling 2.8%. The fractions of sand, silt, and clay are 28, 27, and 46%, respectively.

The climate is broadly classified as warm temperate, characterized by hot, dry summers and cold, wet winters. The majority of annual precipitation occurs between the months of October and May. The average maximum and minimum temperatures during the 2012 growing season (June 6 to November 7) were 30.0 and 12.3 C, respectively (California Irrigation Management Information System 2016: Durham location). For the 2013 growing season (May 23 to October 26), the maximum was again 30.0 C, but the minimum was 14.5 C. The 2014 growing season temperatures (May 21 to October 16) were slightly higher, with a maximum of 31.1 C and a minimum of 15.4 C. Average yearly temperature was highest in 2014. Average winter rainfall over the three winters (October to May) from 2012 to 2014 was 390.7 mm (SE 25.8). No major rain events occurred during the growing seasons from 2012 to 2014.

The total experimental area was 1.8 ha, divided into nine main irrigation treatment plots (0.2 ha each), with each main plot divided into two subplots: weedy versus weed-free (herbicide treated). The main plots were arranged as a randomized complete block design with three replications each. Each plot was separated from the others by two levees with a 3 m drainage ditch in between to prevent seepage between plots. The main irrigation treatments remained in the same plots over all 3 yr.

At the southern end of each main treatment plot was a weed-recruitment zone where no herbicides were applied. The weed-recruitment zones were 0.04 ha each and remained in the same location within each plot for all 3 yr. Weedy and weed-free zones were separated by a buffer zone of approximately 5 m where no measurements were recorded, in case of herbicide drift.

All weed assessments, including aboveground biomass, percent cover, emergence counts, and weedy biomass, were taken from within the weed-recruitment area. Weed-free yields were harvested from the remaining 0.16 ha area. Depending on the year and weed species present, the weed-free areas were treated with POST foliar herbicides cyhalofop-butyl (0.6 kg ai ha^{-1}), triclopyr (0.4 kg ai ha^{-1}), propanil (6.7 kg ai ha^{-1}), penoxsulam (0.04 kg ai ha^{-1}), and pendimethalin (1.1 kg ai ha^{-1}).

Rice Planting and Main Irrigation Treatments. Field preparation was standard for the California rice-growing region and consisted of chiseling twice, followed by disking twice, to prepare a level seedbed (Adair 1962). In the water-seeded alternate wet and dry (WS-AWD) and water-seeded control (WS-Control) conditions, fertilizer was banded in by drill in strips (approximately 15 cm apart) before seeding. Fertilizer applications in the drill-seeded alternate wet and dry (DS-AWD) treatment were broadcast approximately 1 mo after planting (Table 1). In all years, nitrogen was applied at a rate of 171 kg ha^{-1}. Drilled nitrogen was applied as urea (WS treatments), and broadcast N was applied as ammonium sulfate (DS-AWD). Phosphorous was applied as triple superphosphate at a rate of 86 kg ha^{-1} in 2012 and at a rate of 45 kg ha^{-1} in 2013 and 2014. Potassium was applied as potassium chloride at a rate of 25 kg ha^{-1} in 2013 and 2014 only. The WS-AWD and WS-Control fields were broadcast seeded onto dry soil at a seeding rate of 168 kg ha^{-1}. The DS-AWD field was seeded to a depth of 2 cm at a rate of 112 kg ha^{-1} into dry soil. Rice seed for all treatments was pretreated with a 1 h soak in 2.5% NaClO solution to prevent infection with Bakanae disease [*Gibberella fujikuroi* (Sawada) Wollenw.]. Plots in all irrigation treatments across all years were seeded with M-206, a Calrose medium-grain rice variety widely grown in the region.

The three main plot irrigation treatments were the DS-AWD, WS-AWD, and WS-Control. The DS-AWD treatment was initially flush irrigated for rice emergence and then flush irrigated once more when soil volumetric water content (VWC, measured in cm^{3} cm^{-3}) reached 35% (Table 1).

Table 1. Dates of irrigation events and crop management for three irrigation systems: water-seeded conventional (WS-Control), drill-seeded alternate wet and dry (DS-AWD), and water-seeded alternate wet and dry (WS-AWD) for rice planted at the California Rice Experiment Station in Biggs, CA from 2012 to 2014.

Year	System	Seeding	Fertilizer	Flood	Drain	Irrigation flushes	Drain	Harvest
2012	WS-Control	June 6	June 1	June 7	—	—	September 30	November 7
	DS-AWD	June 6	July 2	July 20	July 23	June 8 June 20 August 13 August 27 September 14	October 1	November 7
	WS-AWD	June 6	June 1	June 7	July 23	August 14 August 28 September 15	October 1	November 7
2013	WS-Control	May 23	May 21	May 25	—	—	September 14	October 11
	DS-AWD	May 23	June 20	June 20	July 11	May 25 June 6 July 23 August 15	September 14	October 11
	WS-AWD	May 23	May 21	May 25	July 11	July 23 August 15	September 14	October 11
2014	WS-Control	May 21	May 19	May 25	—	—	September 7	October 1
	DS-AWD	May 21	June 16	June 16	July 14	May 25 June 6 July 21 August 13	September 16	October 9
	WS-AWD	May 21	May 19	May 25	July 14	July 22 August 13	September 7	October1

Immediately after the N fertilizer application at approximately 1 mo after planting, the DS-AWD was flooded to 10 cm above the soil surface, and water was held at that level to allow for N uptake. The WS-AWD and WS-Control plots were flooded to 10 cm above the soil surface within 24 h of broadcast seeding. The WS-AWD plot remained flooded until canopy closure of the rice, at which point water flowing into the system was shut off, and the standing water was allowed to recede into the soil. Canopy closure of the rice was determined to be when photosynthetic photon flux density (PPFD) reached or fell below 800 μmol m^{-2} s^{-1}, which is approximately where subcanopy PPFD stabilized. PPFD was measured every other day using a line quantum sensor (LI-191SA, Li-Cor, Lincoln, NE) at 15.2 cm above the soil surface, which was below the rice canopy. Canopy closure was determined to be at 47, 49, and 54 d after seeding (DAS) in 2012, 2013, and 2014, respectively.

After being drained at canopy closure, both the WS-AWD and the DS-AWD treatment plots were flush irrigated again when soil VWC reached 35% (done once and then repeated). The WS-Control plot remained flooded until 1 mo before harvest, when it was drained to allow harvesting equipment onto the field (Table 1). Soil VWC for irrigation purposes was measured at hourly intervals in each plot using EM5B data loggers and 10HS soil moisture sensors (Decagon Devices, Pullman, WA). The 35% VWC was determined using the average of the three replicates for each treatment. Further management details can be found in LaHue et al. (2016).

Germinable Seedbank Assessment. In spring 2012, immediately before rice seeding and irrigation, four soil samples were collected from each main irrigation plot from the top 6 cm of soil. Each sample was mixed for uniform aggregate size and seed distribution and then split between four 26 by 26 by 5.5 cm nursery flats, with an average soil weight of 251.2 ± 4.3 g (mean ± SE) per flat. Flats were filled to a depth of 5 cm, where the germinable seed bank resides (Forcella et al. 2000), and placed in a greenhouse at 22.0 ± 0.2 C. Two flats from each sample were watered daily with 0.5 L of water, and two flats from each sample were flooded to 10 cm above the soil surface. Emerged plants were counted and removed every other day for 51 d. Plants were considered emerged when one to two leaves were visible. Species counted were watergrass, smallflower umbrella sedge, bearded sprangletop, ricefield bulrush, ducksalad, and redstem. At this growth stage, watergrass could not be identified to species, so early and late watergrass, as well as barnyardgrass, were all classified as *Echinochloa* spp. Total counts for all species were summed at the conclusion of the experiment, and data from all four flats were averaged.

Weed Community Dynamics. In 2012 plant density counts were taken at 20, 40, and 60 DAS. Nondestructive counts were taken in three 25 by 25 cm quadrats from the weed-recruitment sections of each treatment. Counts were taken in the same quadrats at each point in time. In 2013 and 2014 visual weed cover assessments at canopy closure and aboveground biomass at harvest were assessed in each plot. At canopy closure of the rice, visual weed cover assessments of all major weed species were taken in nine 25 by 25 cm quadrats from the weed-recruitment sections in each treatment (Hamill et al. 1977). At rice physiological maturity, the same quadrats were harvested for fresh aboveground biomass, and biomass was separated on a per species basis. The fresh biomass was weighed immediately after harvest, dried to a constant weight at 65 C, and weighed.

On the same day, rice was harvested from two 3 by 6.1 m areas from both the weed-recruitment zones and from the main irrigation plots, using a plot combine. The rough rice yields were adjusted to 14% moisture.

Experimental Design and Data Analysis

Germinable Seedbank. The germinable seedbank data were analyzed using SAS Statistical Software (version 9.4, SAS Institute, Cary, NC). Two-way analysis of variance (ANOVA) was conducted for each weed species using PROC GLM, with main irrigation treatment as a fixed factor and block as a random factor. Data were transformed using an inverse transformation when data failed to meet normality or homogeneity of variance. For data that were transformed, detransformed means are reported along with detransformed confidence intervals.

Weed Community Dynamics

Density counts. The 2012 plant density counts were analyzed using repeated-measures two-way ANOVA with PROC GLM for each weed species. DAS was the repeated factor, whereas irrigation treatment was the fixed factor, and field block was random. Data for smallflower umbrella sedge, watergrass species, sprangletop, and ricefield bulrush met all assumptions of normality and homogeneity of variance. Despite the use of various transformations to stabilize heteroscedasticity, data for redstem and ducksalad failed to meet assumptions of normality and homogeneity of variance. Therefore, data were analyzed using PROC GLIMMIX in SAS/STAT with DAS and block as the random factors and irrigation treatment as the fixed factor (Stroup 2015). The Satterthwaite method was used to approximate degrees of freedom to reduce the probability of a type I error (Satterthwaite 1946). Interactions between time (DAS) and treatment (field irrigation) were significant for redstem, so Fisher's protected LSD was run at 20, 40, and 60 DAS. Significant main effects of time and treatment are presented for each species.

Relative cover and relative dry biomass. Species-specific contributions to canopy cover were calculated by dividing the weed leaf area for each species by the weed plus crop leaf area per quadrat (Ngouajio et al. 1999a, 1999b, 1999c). Species-specific contributions to percent aboveground biomass (relative dry biomass per species) were calculated by dividing the dry aboveground biomass of each species by the total weed and rice biomass per quadrat (Bhagat et al. 1999).

Species frequency (F_i) at canopy closure and harvest were determined by the following equation (Nkoa et al. 2015):

$$F_i = \frac{\sum z_i}{n} \qquad [1]$$

where F_i is the frequency of species i, $\sum Z_i$ is the number of 25 cm^2 quadrats with species i present, and n is total number of quadrats surveyed ($n = 9$).

Relative cover (RC) and relative dry weight (RDW) were analyzed by univariate statistical analysis. PROC GLM was used to conduct ANOVA per species with year and block as random factors and irrigation treatment as a fixed factor. Only main effects of irrigation treatment and year are reported due to no year by treatment interaction. The Tukey-Kramer means comparison test was run to determine whether there were differences between species in each irrigation treatment. Multivariate statistics (Clarke 1993) were run on frequency data using Past Version 3.10 (Hammer et al., 2001). Two-way analysis of similarity using Sorenson (Bray-Curtis) distance was calculated using irrigation and years as crossed factors to determine whether there were significant differences between years and irrigation treatments (unpublished data). Since there were significant differences for both years and irrigation treatments, a similarity percentage analysis (SIMPER) using Sorenson (Bray-Curtis) distance was calculated to determine which species contributed most to the dissimilarity between irrigation treatments. A value of 0% indicates that the species-specific contribution to cover or biomass was the same in each irrigation treatment, whereas a value of 100% indicates that the species did not occur in one of the treatments. Only differences between WS-AWD and WS-Control are reported. PROC GLIMMIX in SAS/STAT was used to analyze frequency data for all weed species, comparing frequency at canopy closure and harvest from both 2013 and 2014. Time and block were random factors, and irrigation method was a fixed factor. Since relationships were similar to those found in RC and RDW data, only frequency data on smallflower umbrella sedge are reported.

Rice Yield. All rice yield data met assumptions of normality and homogeneity of variance. Analysis of variance was performed separately on yields from the weed-recruitment area and yields from the weed-free area using SAS/STAT. ANOVA was conducted using PROC GLM with year and block as random factors and irrigation treatment as a fixed factor. The Tukey-Kramer means comparison test was used to determine whether there were differences in yields between irrigation treatments.

Results and Discussion

Seedbank. The seedbank assessment in 2012 established a baseline germinable population of each species in the seedbank for each irrigation treatment. Only one species, redstem, was found to have significantly different initial germinable populations across the experimental site. Redstem germinable populations were greater on average in the DS-AWD plots (1300 ± 188 plants m^{-2}) (mean ± SE) than in the WS-AWD plots (528 ± 176 plants m^{-2}) and WS-Control plots (256 ± 40 plants m^{-2}). Smallflower umbrella sedge germinable populations ranged from a low of 5828 ± 880 plants m^{-2} in the DS-AWD plots to a high of 6484 ± 388 plants m^{-2} in the WS-Control plots. Watergrass species germinable populations ranged from 16 ± 8 plants m^{-2} in the WS-Control plots to 28 ± 8 plants m^{-2} in both the DS-AWD plots and the WS-AWD plots. Ducksalad germinable populations ranged from a low of 128 ± 20 plants m^{-2} in the DS-AWD to a high of 236 ± 64 plants m^{-2} in the WS-Control.

Sprangletop germinable populations ranged from a low of 68 ± 12 plants m^{-2} in the WS-AWD plots to a high of 164 ± 76 plants m^{-2} in the DS-AWD plots. Ricefield bulrush germinable populations ranged from a low of 148 [104, 264] plants m^{-2} (mean [95% CI]) in the DS-AWD plots to a high of 248 [192, 340] plants m^{-2} in the WS-Control plots.

Weed Community Dynamics

Density Counts. In 2012 there were only minor differences between irrigation systems in the weed counts taken at 20, 40, and 60 DAS. There were no significant differences in population densities of watergrass species, smallflower umbrella sedge, and ricefield bulrush between irrigation systems across all counts. Our results confirm previous research that showed watergrass plasticity and ability to germinate and emerge under both aerobic and anaerobic soil environments (Boddy et al. 2012).

There were three weed species with differences among irrigation treatments: redstem, ducksalad, and sprangletop. For redstem, there was an interaction between irrigation systems and count timing ($P < 0.0001$). Redstem was not present in any system at 20 DAS, but at both 40 and 60 DAS, the redstem density was greater in the WS-AWD than in the other two irrigation systems (Table 2). Density was greater in the WS-Control system than in the DS-AWD system. The high redstem population in the water-seeded systems is consistent with earlier research showing redstem emergence under water-seeded but not under dry-seeded systems (Pittelkow et al. 2012).

Ducksalad density was greatest in the WS-Control and WS-AWD systems, irrespective of count timing (20, 40, or 60 DAS) (Table 2). Sprangletop density was greatest in the DS-AWD system across all counts (20, 40, and 60 DAS), though the difference was only significantly greater than the density in the

Table 2. Redstem (AMMAU), smallflower umbrella sedge (CYPDI), watergrass species (ECHOR), sprangletop (LEFFA), and ricefield bulrush (SCPMU) density at 20, 40, and 60 days after rice seeding in water-seeded conventional (WS-Control), drill-seeded alternate wet and dry (DS-AWD), and water-seeded alternate wet and dry (WS-AWD) irrigation systems in 2012.

		Days after seeding[a,b]		
Species	Irrigation	20	40	60
			Plants m^{-2}	
AMMAU	WS-Control	0Aa	64 ± 16Ab	52 ± 16Ac
	DS-AWD	0Ba	16 ± 16Bb	0Bc
	WS-AWD	0Ca	188 ± 16Cb	96 ± 16Cc
CYPDI	WS-Control	1320 ± 388Aa	88 ± 44Ab	124 ± 28Ab
	DS-AWD	440 ± 264Aa	0Ab	0Ab
	WS-AWD	1092 ± 268Aa	288 ± 108Ab	328 ± 112Ab
	WS-Control	48 ± 40Aa	16 ± 0Aa	32 ± 8Aa
ECHOR[c]	DS-AWD	492 ± 272Aa	108 ± 28Aa	72 ± 72Aa
	WS-AWD	224 ± 104Aa	64 ± 32Aa	72 ± 36Aa
HETLI	WS-Control	480 ± 76Aa	380 ± 76Aa	124 ± 76Ab
	DS-AWD	0Ba	64 ± 76Ba	0Bb
	WS-AWD	276 ± 76ABa	220 ± 76ABa	120 ± 76ABb
LEFFA	WS-Control	0ABa	164 ± 120ABb	88 ± 60ABb
	DS-AWD	64 ± 36Ab	288 ± 128Ab	272 ± 36Ab
	WS-AWD	0Ba	56 ± 20Bb	80 ± 24Ba
SCPMU	WS-Control	216 ± 212Aa	0Aa	40 ± 12Aa
	DS-AWD	28 ± 16Aa	0Aa	0Aa
	WS-AWD	76 ± 24Aa	24 ± 12Aa	36 ± 16Aa

[a] Different lowercase letters (a, b, c) indicate significant differences between 20, 40, and 60 DAS counts ($P < 0.05$) within irrigation treatment for each weed species.

[b] Different uppercase letters (A, B, C) indicate significant differences between irrigation treatments ($P < 0.05$) within weed species.

[c] ECHOR, *Echinochloa* spp.

WS-AWD system. These results are not surprising, since sprangletop emergence is reported to occur only under aerobic conditions in California (Bayer et al. 1989; Flint 1993). Since it emerged in both the WS-AWD and WS-Control systems, further investigation of the species is warranted to elucidate whether water depth may affect emergence under flooded conditions, allowing the species to emerge under a shallow flood. Both species of sprangletop found in California, bearded sprangletop and Mexican sprangletop [*Leptochloa fusca* (L.) Kunth ssp. *uninervia* (J. Presl) N. Snow], emerged from rice flooded to depths of 5 cm in Valencia, Spain (Osca 2013). In Turkey, bearded sprangletop emerges at greater numbers and at a faster rate under flooded conditions than under dry conditions (Altop et al. 2015).

Differences between weed counts at 20, 40, and 60 DAS indicate that certain species are emerging at different timings throughout the rice-growing season. Redstem did not emerge until 40 DAS across all irrigation systems. Sprangletop emerged by 20 DAS in the DS-AWD system, but did not emerge in the two water-seeded systems until 40 DAS. All other weed species emerged in significant numbers by 20 DAS, and then plant density was reduced by 40 and 60 DAS, presumably through competition for light as the canopy closed (White and Harper 1970; Yoda et al. 1963).

RC and RDW. There were no significant interactions between irrigation system and years for either RC at canopy closure or RDW at harvest for all weed species and rice; therefore, only main effects are presented (Figures 1 and 2). RC of smallflower umbrella sedge, watergrass species, and ricefield bulrush increased across systems from 2013 to 2014 (Figure 2), though the increase in ricefield bulrush was not highly significant ($P = 0.06$). The RC of rice also increased across all systems from 2013 to 2014. This increase may be due to the decrease in RC of ducksalad in 2014, since all other weed species increased in RC in 2014. In water-seeded Arkansas rice, ducksalad decreased yields by about 21% when germinating with rice (Smith 1968). The decrease in RC of ducksalad in 2014 may be due to competition with other weed species, particularly watergrass, which had the greatest increase in RC of all weed species. There was a negative correlation between watergrass RC and ducksalad RC in 2013, but the relationship did not hold in 2014 (unpublished data). Thus, it is difficult to say with certainty why ducksalad cover decreased in 2014. Redstem and sprangletop RC were the same across years.

At canopy closure the WS-Control and WS-AWD were dominated primarily by ducksalad and watergrass species, but both sedges were also present in small quantities (Figure 1). Sprangletop and redstem were present, but differences between systems were not significant (unpublished data). The only difference in weed composition between the two water-seeded systems at canopy closure was in the smallflower umbrella sedge cover, which was significantly greater in the WS-AWD compared with the WS-Control. The weed species composition of the DS-AWD at canopy closure was significantly different from the composition of the water-seeded systems. It was dominated by watergrass species, and the only other species present was sprangletop (8%, unpublished data). Rice RC was significantly greater in the WS-Control and WS-AWD than in the DS-AWD system.

RDW of all weed species did not vary across years. There were only two species that were significantly different across irrigation systems: smallflower umbrella sedge and watergrass species (Figure 1). The RDW of smallflower umbrella sedge was greatest in the WS-AWD, which was consistent with its RC at canopy closure. Ducksalad was not present at harvest, presumably because it had completed its life cycle and decomposed, although no information on longevity of this species is recorded in the literature. In Arkansas wet-seeded rice, Smith (1968) found that ducksalad matured by approximately 8 wk after seeding. In the DS-AWD system at harvest, the RDW of rice was 3% (Figure 1). In comparison, the WS-Control and WS-AWD systems had rice RDW measures of 72 and 77%, respectively.

The differences in frequencies of weed species in the DS-AWD and the water-seeded systems corresponded to the differences in RC and RDW (unpublished data). Frequency of smallflower umbrella sedge varied between WS-AWD and WS-Control (Table 3). The percentage contribution of smallflower umbrella sedge to the dissimilarity between the irrigation systems was the greatest of all weed species at every measurement point, except at canopy closure assessment in 2013. Analysis of the two systems over time showed that although the frequency of smallflower umbrella sedge was similar in the WS-AWD and WS-Control at canopy closure in 2013, the frequency of the species was consistently greater in the WS-AWD at all other assessment points (Figure 3).

Smallflower umbrella sedge cover was greatest in the WS-AWD treatment (Figure 1), and the relative

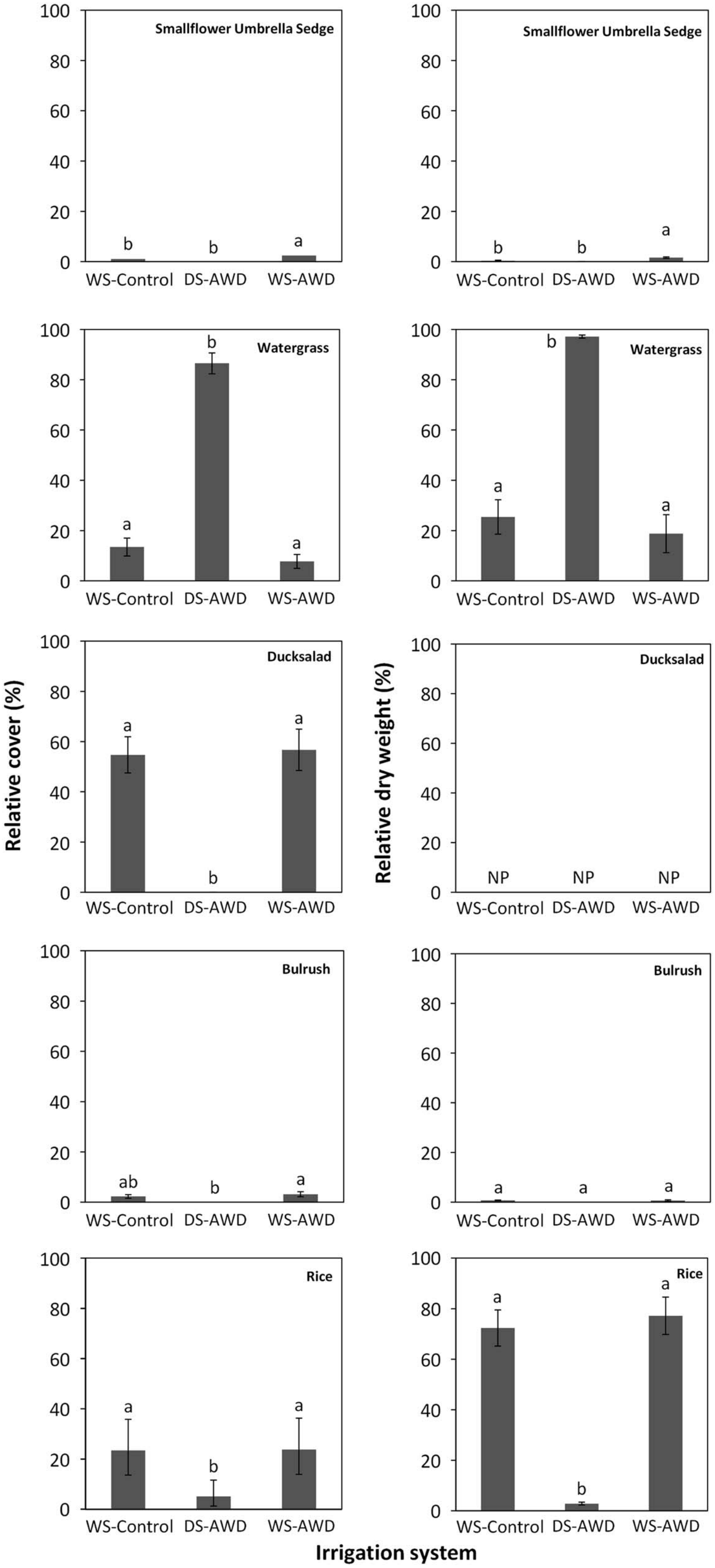

Figure 1. Smallflower umbrella sedge, watergrass, ducksalad, ricefield bulrush, and rice relative cover (RC) and relative dry weight (RDW) as affected by different irrigation systems: water-seeded conventional (WS-Control), drill-seeded alternate wet and dry (DS-AWD), and water-seeded alternate wet and dry (WS-AWD). Since there was no interaction between irrigation and years, data were pooled over years for each system. Both RC at canopy closure (left) and RDW at harvest (right) are included. Within each species, columns with the same letter are not significantly different ($P > 0.05$). NP (not present) indicates that a species was not present at sampling. Bars represent ± 1 SE.

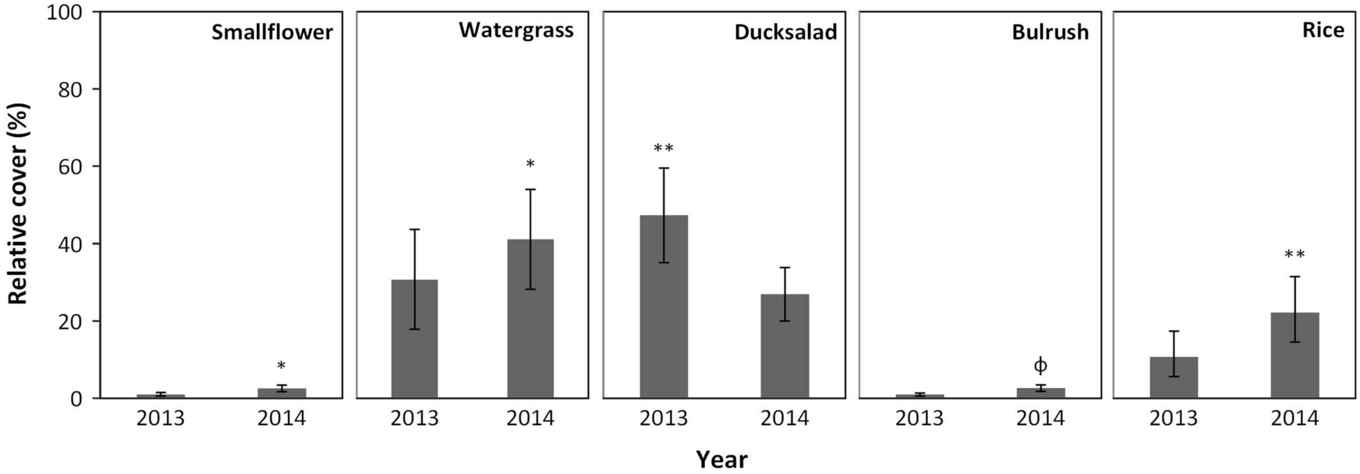

Figure 2. Relative cover (RC) of smallflower umbrella sedge, watergrass species, ducksalad, ricefield bulrush, and rice planted in 2013 and 2014. RC was averaged across irrigation systems. Within each species, differences are notated between years (ϕ $P < 0.10$; * $P < 0.05$; ** $P < 0.01$). Bars represent ± 1 SE.

Table 3. SIMPER analysis of dissimilarity between frequency of redstem (AMMAU), smallflower umbrella sedge (CYPDI), watergrass species (ECHOR), sprangletop (LEFFA), and ricefield bulrush (SCPMU) at canopy closure and harvest for water-seeded conventional (WS-Control) and water-seeded alternate wet and dry (WS-AWD) irrigation systems in 2013 and 2014. A value of 0% indicates that the frequency of each species in the two irrigation treatments was the same, whereas 100% indicates that the species was not present in one of the treatments.

	Canopy closure		Harvest	
	Dissimilarity contribution		Dissimilarity contribution	
Species	2013	2014	2013	2014
	%		%	
AMMAU	20.7	19.7	11.7	3.1
CYPDI	21.8	31.9	33.5	38.3
ECHOR[a]	26.6	13.5	21.6	18.7
HETLI	0.0	0.0	NP[b]	NP
LEFFA	16.2	14.8	14.4	16.1
SCPMU	14.7	20.1	18.9	23.8

[a] ECHOR, *Echinochloa* spp.
[b] NP, species not present.

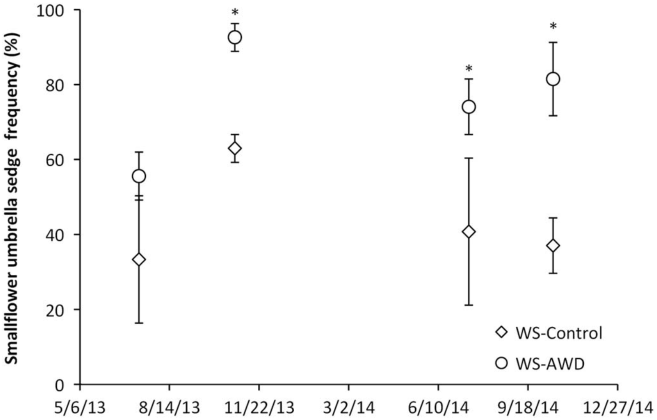

Figure 3. Differences in smallflower umbrella sedge frequency in water-seeded conventional (WS-Control) and water-seeded alternate wet and dry (WS-AWD) irrigation systems in rice planted in 2013 and 2014 (* $P < 0.05$, at each time point). Bars represent ± 1 SE.

cover of smallflower increased in 2014 over 2013 (Figure 2). The relative dry weight of smallflower umbrella sedge was greater in the WS-AWD than in the other treatments in both 2013 and 2014. Both the initial germinable seedbank assessment in 2012 and the plant density counts at 20 DAS in 2012 indicate similar germinable populations of smallflower umbrella sedge in the WS-Control and WS-AWD irrigation systems. The increased density in the WS-AWD system at 40 and 60 DAS and the increased cover and biomass in both 2013 and 2014 may indicate that the drain at canopy closure affects smallflower umbrella sedge germination or competitive ability. Smallflower umbrella sedge germination is best under flooded conditions, though it appears to germinate well under saturated soil conditions as well (Pedroso 2011). Preliminary evidence suggests that smallflower umbrella sedge has a biphasic emergence pattern (WB Brim-DeForest, unpublished data), and the relative growth rate of plants emerging under the second germination flush may be greater under the drier conditions of the WS-AWD.

The irrigation system was shut off and the water was allowed to recede into the soil beginning at 47 DAS in the WS-AWD system in 2012. In 2013 and 2014 this occurred at 49 DAS and 54 DAS, respectively. Weed density counts were taken 1 wk before the irrigation shutoff in 2012, and weed relative cover ratings were taken 1 d before irrigation shutoff in both 2013 and 2014. Thus, it is possible that the increase in smallflower umbrella sedge in the WS-AWD system may be unrelated to the irrigation system and was an artifact of greater population density in 2012. This could be related to the lower ducksalad density in the WS-AWD system that same year. Ducksalad may have a suppressive effect on smallflower umbrella sedge, given that it quickly covers the canopy, blocking out light, which smallflower umbrella sedge requires for germination (Sanders 1994). The two weeds had a similar density at the beginning of the experiment but smallflower increased as the experiment continued (Figure 3).

Rice Yields. Rice relative cover increased from 2013 to 2014 over all treatments, yet the increase in 2014 at canopy closure did not correlate with an increase in rice biomass at harvest in 2014. This response confirms earlier research in California that showed competition with late watergrass after the critical period of competition (30 DAS) further decreased rice yields (Gibson et al. 2002). It is significant to note that despite statistically similar initial populations of watergrass species in all fields (unpublished data), rice cover and biomass were lowest in the DS-AWD compared with the water-seeded treatments, either indicating that the watergrass species are more competitive against rice under anaerobic conditions or confirming that rice is less competitive with weeds under anaerobic environments (Bhagat et al. 1996).

Rice yields in weed-free plots were the same across all three irrigation systems in both 2013 and 2014 (Figure 4). Since there was no year by irrigation system interaction, data were pooled and analyzed over years. There was a significant decrease in yield in 2014, but this was found across all three irrigation systems, and may be due to the higher temperatures in 2014 (Krishnan et al. 2011). Research in the southern United States showed that rice yields are reduced by daytime maximum temperatures above 28 C (Baker 2004; Baker and Allen 1993). Rice yields from the weed-recruitment areas were significantly less in the DS-AWD system than in the WS-AWD and WS-Control systems across both years. In spite of a small amount of rice still present at canopy closure, yield losses were 100% in both 2013 and 2014 in the DS-AWD system. The few surviving rice plants did not produce panicles. Percent yield loss was greater in 2013 in the WS-Control system than in the WS-AWD, though the difference was not significant (unpublished data). In 2014 percent yield loss was greater in the WS-AWD than in the WS-Control. Yield reductions in the weedy plots do not correspond to a clear difference in weed species composition between the two water-seeded treatments, since there was no interaction between irrigation and year. Species-specific relationships to yield loss still remain to be elucidated.

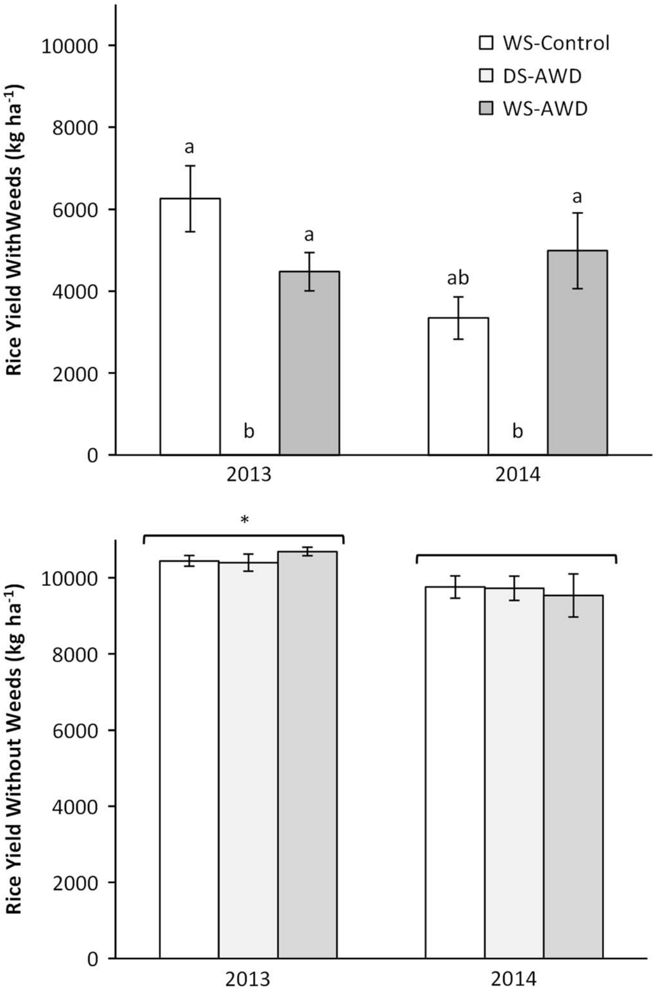

Figure 4. Grain rice yield of rice with weeds (top) and rice yield without weeds (bottom) at Biggs, CA, in 2013 and 2014. In the rice yield without weeds, there was no interaction between year and irrigation, so yield was averaged across different irrigation systems: water-seeded conventional (WS-Control), drill-seeded alternate wet and dry (DS-AWD), and water-seeded alternate wet and dry (WS-AWD). Within years, columns with the same letter are not significantly different ($P > 0.05$). Bars represent ± 1 SE.

The WS-AWD system, with its shortened flooding duration, may be a viable option in reducing water use in rice over the growing season. Yields are equivalent to yields in the WS-Control, if weed control is excellent and soil fertility is maintained. There are few differences in weed species composition between the WS-AWD and WS-Control. There is evidence from this study, however, that the early drainage and subsequent flushing events in the WS-AWD may increase smallflower umbrella sedge frequency and density. Since there are smallflower umbrella sedge populations in California that are resistant to both photosystem II and ACCase inhibitors (Osuna et al. 2002; Pedroso et al. 2013), the increased biomass and frequency of the weed under the WS-AWD system may increase the proportion of resistant plants in fields that have resistant populations. For smallflower umbrella sedge plants that escape early herbicide applications, the shift to an aerobic environment when the field is drained may have a positive effect on growth rate and seed production. The DS-AWD system is only viable with consistent and complete weed control, due to the reduced ability of rice to compete under dry conditions and the 100% reduction in yield under heavy weed pressure. Furthermore, since the DS-AWD system is overwhelmed by watergrass, the presence of multiple-herbicide-resistant watergrass (Fischer et al. 2000) may reduce some growers' ability to use the system in California.

Alternative irrigation systems may prove to be useful to reduce water use over the growing season, but potential water savings need to be balanced against shifts in weed species. Dry seeding favors watergrass species. and early drainage may favor late-germinating smallflower umbrella sedge. Since herbicide resistance in these species is spread throughout the rice-growing region, any changes to growing practices must incorporate methods for dealing with the added pressure of increased populations in growers' fields.

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