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California arrowhead is a weak competitor in water-seeded rice

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California arrowhead is a broadleaf weed widespread in water-seeded rice. Bensulfuron is the only herbicide currently available for use throughout the California rice growing region that provides complete control of California arrowhead; however, resistance to bensulfuron has been detected in California arrowhead and in several other weed species. Growers have herbicide alternatives for weed species other than California arrowhead but continue to use bensulfuron year after year for control because they believe California arrowhead reduces rice yields. However, damage thresholds have not been determined for this weed, and the crop may be able to tolerate relatively high California arrowhead densities. In this work, the damage thresholds for California arrowhead were determined in field and greenhouse experiments. Water-seeded rice was grown in mixture with California arrowhead in a 1992 greenhouse experiment and in field experiments in 1992 and 1998. Rice tiller density and grain yields were not affected by California arrowhead densities up to 200 plants m^{-2} in any year. Rice was taller than California arrowhead throughout the growing season in all experiments, and the weed senesced well before rice maturity. The ability of the crop to overtop the weed and grow weed-free during the latter part of the season may explain why California arrowhead is such a weak competitor with water-seeded rice. The results suggest that growers may be able to tolerate California arrowhead densities up to 200 plants m^{-2} without detectable yield losses. Implications for weed management are discussed.

Nomenclature: Bensulfuron, California arrowhead, *Sagittaria montevidensis* Cham. and Schlect SAGMO; rice, *Oryza sativa* L.

Key words: Herbicide resistance, yield loss, damage threshold.

Determining the weed density at which the benefit obtained equals the cost of control measures should be an integral component of weed management (Jordan 1992). In the absence of such information, growers may reduce their perceived risk by taking control actions below the true economic threshold (Coble and Mortensen 1992). California arrowhead is one of the most common broadleaf weeds in California rice production (Barrett and Seaman 1980) and has been cited as a problem in direct-seeded rice culture (Bayer and Hill 1993; Smith et al. 1977). However, the competitive effect of this species on water-seeded rice has not been studied, and its economic importance remains unknown. Of the herbicides currently registered for use in rice in California, only bensulfuron and propanil control this weed. Propanil is used primarily to control weedy grass species, and severe acreage restrictions have been imposed on it following drift damage to sensitive crops (Miller 1979), limiting its usefulness in controlling California arrowhead. Resistance to bensulfuron has been detected in several weed species, including California arrowhead (Hill and Hawkins 1996). Growers have herbicide options for other weeds but may continue to use bensulfuron year after year to control California arrowhead, thereby maintaining a strong selective pressure for resistance not only in California arrowhead but also in other weeds controlled by bensulfuron. Quantifying the damage threshold for California arrowhead could help growers avoid unnecessary bensulfuron use. For example, if California arrowhead densities were below the economic threshold in a particular field, a California grower might be able to use alternative herbicides such as triclopyr to control nongrass weed species. Rotating herbicides with different modes of action may reduce selective pressure for resistance (Holt and LeBaron 1990) and might help conserve the few herbicides available for use in California rice. The objective of this research was to quantify the relationship between water-seeded rice yield and California arrowhead density under field and greenhouse conditions.

Materials and Methods

Field Experiments

The field experiments were located in grower's fields near the Rice Experiment Station at Biggs, CA. Presoaked rice was aerially seeded at a rate of 168 kg ha^{-1} into disked, rolled, and flooded fields on May 2, 1992, and May 27, 1998. Nitrogen fertilizer was applied aerially to Stockton clay soil (fine, montmorillonite, thermic, Typic Pelloxerts) at 160 kg N ha^{-1} in 1992 and 110 kg N ha^{-1} in 1998 (rates determined by the growers) and incorporated by harrowing before flooding in each year. 'M-202' and 'M-204' early maturity medium-grain rice cultivars with very similar growth habits were used in 1992 and 1998, respectively.

In 1992, natural populations of California arrowhead were hand-weeded 31 d after rice seeding (DAS) within 32, 2-m^2 plots to establish densities of 0, 50, 100, and 200 plants m^{-2}. Hand-weeding in 1992 and 1998 occurred as

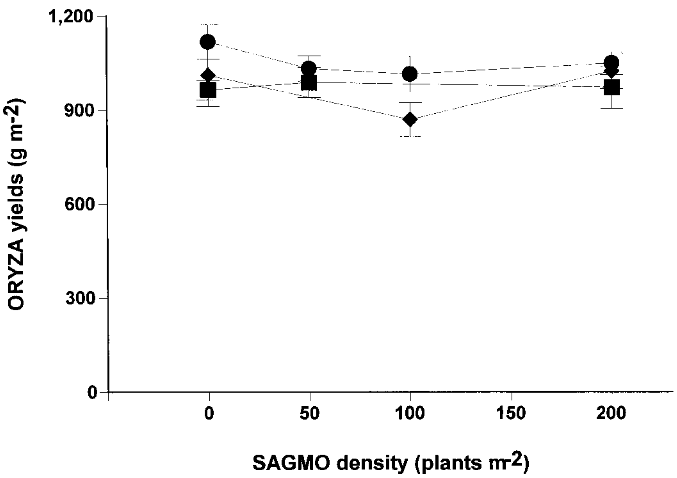

Figure 1. Effect of California arrowhead (*Sagittaria montevidensis*) density on rice (*Oryza sativa*) yield in the 1992 (●) and 1998 (■) field experiments and the 1992 (♦) greenhouse experiment. Data points are the means of four replicates, and vertical bars are standard errors of the mean. There was no significant ($P > 0.05$) linear or hyperbolic relationship between rice yields and weed density in field or greenhouse experiments.

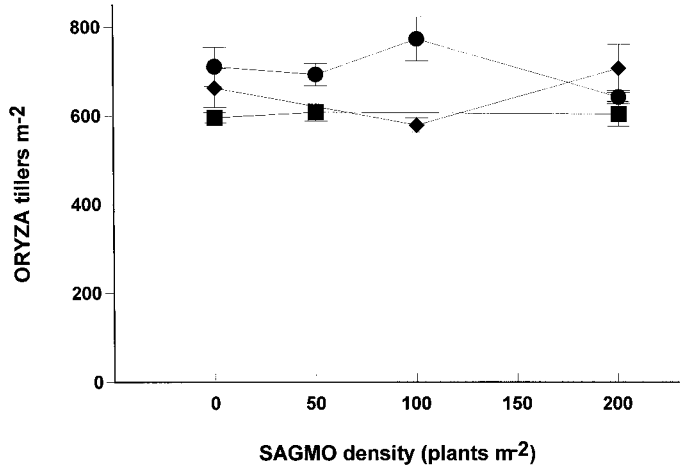

Figure 2. Effect of California arrowhead (*Sagittaria montevidensis*) density on rice (*Oryza sativa*) tillers at final harvest in the 1992 (●) and 1998 (■) field experiments and the 1992 (♦) greenhouse experiment. Data points are the means of four replicates, and vertical bars are standard errors of the mean. There was no significant ($P > 0.05$) linear or hyperbolic relationship between rice tillers and weed density in field or greenhouse experiments.

California arrowhead emerged from the water. Subsamples were harvested for each weed density using 1-m^2 quadrats 66 and 132 DAS. Sampled plots were not resampled at subsequent harvests. All weeds other than California arrowhead were removed with a combination of 4.5 kg ai ha^{-1} preplant granular molinate and 0.07 kg ai ha^{-1} bensulfuron foliar-applied at the two-leaf stage of rice. Molinate does not control California arrowhead. Bensulfuron had no visible effect on California arrowhead in 1992; the field population may have been resistant. In 1998, we hand-weeded naturally occurring populations of California arrowhead within 24, 2-m^2 plots to densities of 0, 50, and 200 plants m^{-2} 29 DAS. Grasses were controlled with 4 kg ai ha^{-1} propanil applied at the five-leaf stage of rice. Propanil was applied too early to control California arrowhead. All other weeds were removed by hand. Plots were sampled with 0.25-m^2 quadrats 36 DAS and again at rice maturity (135 DAS). Both experiments followed a complete randomized design with four replicates per harvest.

In 1992 at 66 DAS, the height of 10 randomly selected California arrowhead individuals per quadrat were measured in the field. Rice and California arrowhead shoots were cut at soil level and transported to the laboratory, where rice tiller density and height from 10 tillers were measured before rice and weed shoots were dried at 70 C to a constant weight. In 1998, intact plants of both species were uprooted 36 DAS and transported to the laboratory. Plant densities, mean plant height of 10 individuals per sample, and shoot dry weight (DW) were determined for rice and California arrowhead. Tiller density was also determined for rice. At the final harvest in each year, rice grain was separated from panicles by hand, grain and shoots were dried to a constant weight at 70 C, and weights were determined.

Greenhouse Study

In 1992, California arrowhead seed was sown into wooden basins (0.8 m^2 by 0.3 m deep) located in a greenhouse at the University of California, Davis, CA. On the same day, rice (M-202) was sown at 200 plants m^{-2}. Basins were lined with plastic, filled with 18 cm of Capay silty clay (fine, smectic, thermic Typic Haploxerts), and flooded to a depth of 10 cm before plants were hand-seeded into the water. Ammonium sulfate was incorporated preflood at 110 kg N ha^{-1} into all basins. California arrowhead was hand-weeded 10 DAS to establish densities of 0, 100, and 200 plants m^{-2}. All weeds other than California arrowhead were removed by hand. A split plot design was used with harvest date as the main plot and weed density as the subplots. Plots were harvested 32, 58, and 100 DAS. Plant height, shoot DW, and rice tiller densities were determined for the first two harvests. Tiller density, shoot DW, and seed DW were determined for the last harvest that coincided with rice maturity.

Data Analysis

Linear regression analysis was performed on rice yield, tiller density, and shoot DW data from all experiments. Only three weed densities were used in the 1992 greenhouse and 1998 field experiments so nonlinear regression models were not evaluated. However, rice yield, tiller density, and shoot DW data from the 1992 field experiment were fitted with a rectangular hyperbolic regression model (Cousens 1985). Multiple regression was performed on height data in each experiment with species and weed density as the dependent variables.

Results and Discussion

Rice yields were not reduced by California arrowhead densities from 0 to 200 plants m^{-2} (Figure 1), and there was neither a significant linear nor a significant hyperbolic relationship ($P \geq 0.45$ for all regression models) between rice yields and California arrowhead densities in any year of the study. Rice tiller density at final harvest (Figure 2), which is highly correlated with rice yields, was also unaf-

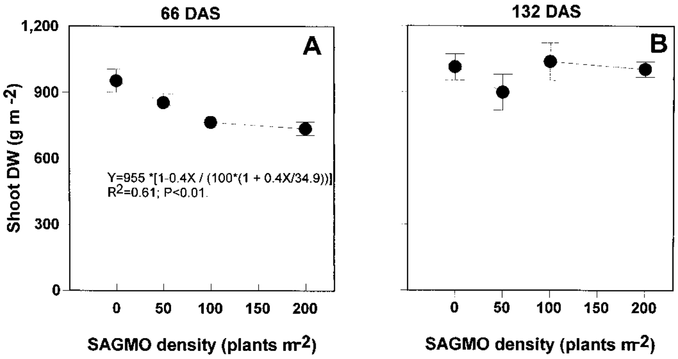

FIGURE 3. Effect of California arrowhead (*Sagittaria montevidensis*) on rice (*Oryza sativa*) shoot dry weight (DW) 66 DAS (A) and 132 DAS (B) in 1992. Data points are the means of four replicates and vertical bars are standard errors of the mean. There was no significant ($P > 0.05$) relationship between rice shoot DW 132 DAS and weed density.

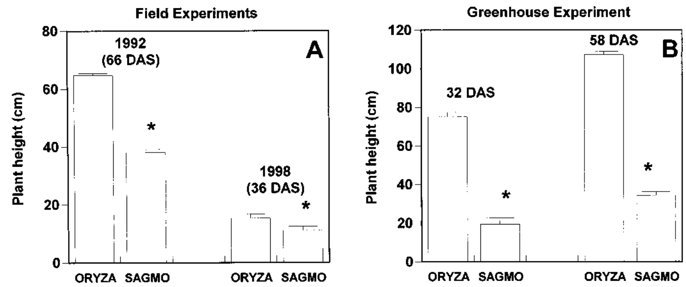

FIGURE 4. California arrowhead (*Sagittaria montevidensis*) and rice (*Oryza sativa*) height in field (A) and greenhouse (B) experiments. Columns are the means of four replicates, and vertical bars are standard errors of the mean. Asterisks indicate significant ($P < 0.05$) differences between species according to analysis of variance.

fected by weed density. In contrast, studies have shown substantial yield losses within a similar range of densities for other weeds common to water-seeded rice. For example, 200 plants m^{-2} early watergrass [*Echinochloa oryzoides* (Ard) Fritsch] and late watergrass [*E. phyllopogon* (Stapf) Koss] in a mixed infestation reduced M-202 yields 99% (Gibson et al. 2001). In recent field experiments, 330 panicles m^{-2} bearded sprangletop [*Leptochloa fasicularis* (Lam.) Gray] (plant density was not measured) reduced water-seeded rice yields 48 to 50% (J. Williams, personal communication). Caton et al. (1997) reported a 39% yield loss when rice was grown with a mixed infestation (110 plants m^{-2}) of purple ammannia (*Ammannia coccinea* Rottb.) and redstem (*A. auriculata* Willd). Relative to these weeds, California arrowhead is clearly a weak competitor with water-seeded rice.

The inability of California arrowhead to affect rice yields significantly may be explained by two factors. First, California arrowhead matures and senesces well before the crop when grown in a dense rice stand. No California arrowhead individuals were present in field plots 90 DAS in 1992 or 1998. In the 1992 field experiment, rice shoot DW had a hyperbolic response to weed density when plants were harvested 66 DAS (Figure 3a). However, there was no significant relationship (linear or hyperbolic) between rice shoot DW and weed density at final harvest (Figure 3b), suggesting that the crop recovered from competition with the weed. Weed density did not affect shoot DW at any harvest time in the other experiments (data not shown). Second, regression analysis revealed no relationship between weed density and weed or rice height and data were reanalyzed using analysis of variance with species as the single factor. The crop was significantly taller than the weed in both field and greenhouse experiments (Figure 4). The inability of the weed to grow taller than rice and the absence of the weed during rice grain-filling (approximately 90 to 120 DAS) may explain why rice was so tolerant of California arrowhead.

Our results suggest that rice can tolerate relatively high infestations of California arrowhead without yield losses. Therefore, control may not be needed to maintain rice yields, at least with California arrowhead densities below 200 plants m^{-2}. There is thus an opportunity for reducing the frequency of bensulfuron applications, which should ease selection pressure toward resistance. However, in the absence of any chemical control, soil seed bank enrichment might cause California arrowhead populations to increase over time to levels at which yield losses do occur. Limiting the use of bensulfuron to fields with rapidly increasing California arrowhead populations might prevent the buildup of California arrowhead densities while reducing selection pressure for resistance to this herbicide. However, because the population dynamics of California arrowhead are unknown, it will be difficult to predict the rate at which field populations might increase. In addition to herbicides, California rice growers use tillage, crop seedbed preparation, crop competition, and flooding to reduce weed establishment and growth. The effect of these practices on California arrowhead is largely unknown but they could provide alternative means for controlling the weed and limiting the buildup of California arrowhead densities in the absence of herbicide use.

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