

Herbicide options for cultivated wild rice (*Zizania palustris*) in California

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Research Article

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Carfentrazone; cyhalofop-butyl; florypyrauxifen-benzyl; penoxsulam; propanil; triclopyr; common spikerush; *Eleocharis palustris* (L.) Roem. & Schult; longleaf pondweed; *Potamogeton nodosus* Poir; ricefield bulrush; *Schoenoplectus mucronatus* (L.) Palla; wild rice; *Zizania palustris* L.

Keywords:

California; spikerush; waterplantain; wild rice; *Zizania palustris*

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Abstract

Wild rice is a high-value specialty crop in California. Weeds are an important pest issue in this crop, yet to date, only carfentrazone is registered for weed control in this crop. Herbicide field trials were conducted in 2022 and 2023 in Shasta and Yolo counties, California, in support of the IR-4 project's mission to register new pesticides for specialty crops. Herbicides tested for efficacy and crop safety included cyhalofop-butyl, florypyrauxifen-benzyl, penoxsulam, propanil, and triclopyr at two application rates each, as well as carfentrazone applied at the labeled rate. At all sites, weed control was acceptable with most treatments and comparable to that of carfentrazone. Generally, florypyrauxifen-benzyl, penoxsulam, and triclopyr provided the greatest broad-spectrum weed control. In particular, uncommon weeds such as common spikerush and longleaf pondweed (Shasta County sites in 2022 and 2023, respectively) were controlled well with these herbicides. Propanil was also very effective against these two species, yet it provided only up to 25% control of ricefield bulrush. Crop response to herbicides was variable. Carfentrazone, cyhalofop-butyl, florypyrauxifen-benzyl, and propanil all caused minor and transient injury to the wild rice, characterized by chlorosis, leaf burn, and stunting. Florypyrauxifen-benzyl and triclopyr also caused some leaf deformation, which the wild rice did not recover from. The most significant crop injury was caused by penoxsulam, resulting in severe or complete stand loss at the low and high rates, respectively, across all site-years. Triclopyr also caused unacceptable lodging at both rates at all sites, significantly reducing yield at the higher rate. Crop yields in noninjured plots were similar to those from the untreated control and carfentrazone-treated plots, although the higher rate of florypyrauxifen-benzyl did reduce yields somewhat. These data provide important crop-safety information for wild rice and will inform further herbicide program research toward potential registration for wild rice in California.

Introduction

Northern wild rice is an annual aquatic grass native to North America (Biesboer 2019; Cardwell et al. 1978; Porter 2019). It is naturally abundant in the western Great Lakes region of the United States and Canada, growing in shallow, slow-moving water (Pillsbury and McGuire 2009; VanZomerem et al. 2023). Wild rice has been an important forage food for local human populations for at least 2000 years and carries important cultural and spiritual significance to Native American and First Nations peoples (Bouayad 2020; Nabhan 2016). Breeding programs to develop wild rice as a commercial crop began in the mid-20th century, and modern varieties are grown as a specialty crop, primarily in Minnesota and California (Marcum 2007; McGilp et al. 2023). Wild rice has a sustained popularity as a nutrient-dense grain substitute and culinary ingredient throughout North America, and is also used as an ingredient in some premium pet foods (Peres et al. 2023; Surendiran et al. 2014).

Cultivation of wild rice in California began in the 1970s (CWRRIC 2025; Marcum 2007). Today, California wild rice is a high-value specialty crop grown on approximately 8,000 ha in three main regions: the Sacramento Valley, the Clearlake area, and the northeast of the state (CWRRIC 2025). In California, cultural management practices for wild rice are largely similar to those for conventional rice (*Oryza sativa* L.), including the need for permanent-flood irrigation (Hill et al. 2006). Because the growing conditions are similar between wild rice and conventional rice in California, growers of both crops face similar weed spectra. Although wild rice has been grown for close to 50 years in California, available literature evaluating herbicide options is limited. Previous research on herbicide options for wild rice focused on foliar applications of

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Table 1. Treatments in Shasta County in 2022, and Shasta and Yolo counties in 2023.^a

Herbicide treatment	Rate ^b	Application timing	Application dates		
			2022	2023	
			Shasta	Shasta	Yolo
	kg ai ha ⁻¹				
1 Untreated check	–	–	–	–	–
2 Cyhalofop-butyl + COC	0.31	1–2 LS	June 27	July 21	July 17
3 Cyhalofop-butyl + COC	0.63	1–2 LS	June 27	July 21	July 17
4 Florpyrauxifen-benzyl + MSO fb	0.04 fb 0.04	2 LS fb 14 DAA	June 27 fb	July 21 fb	July 17 fb
florpyrauxifen-benzyl + MSO			July 11	August 4	July 31
5 Florpyrauxifen-benzyl + MSO fb	0.08 fb 0.08	2 LS fb 14 DAA	June 27 fb	July 21 fb	July 17 fb
florpyrauxifen-benzyl + MSO			July 11	August 4	July 31
6 Penoxsulam + COC	0.05	1.5 LS	June 27	July 21	July 17
7 Penoxsulam + COC	0.1	1.5 LS	June 27	July 21	July 17
8 Triclopyr + COC fb triclopyr + COC	0.42 ^a fb 0.42	3–4 LS fb 20 DAA	July 11 fb July 29	August 4 fb August 11	July 31 fb August 8
9 Triclopyr + COC fb triclopyr + COC	0.84 fb 0.84	3–4 LS fb 20 DAA	July 11 fb July 29	August 4 b August 11	July 31 fb August 8
10 Propanil + COC	3.37	3.5 LS	July 11	July 21	July 17
11 Propanil + COC	6.73	3.5 LS	July 11	July 21	July 17
12 Carfentrazone	0.53	20 to 45 DAA	July 11	July 21	July 17

^aAbbreviations: COC, crop oil concentrate; DAA, days after initial application; fb, followed by; LS, leaf stage of crop; MSO, methylated seed oil
^bThe triclopyr rate is in kilograms of acid equivalent per hectare (kg ae ha⁻¹). COC was applied at 25 ml L⁻¹; MSO was applied at 10 ml L⁻¹.

bentazon, propanil, and 2,4-D (Clay and Oelke 1990) or aquatic applications of diquat, endothall, fluridone, triclopyr, and 2,4-D (Madsen *et al.* 2008; Nelson *et al.* 2003). To date, the only herbicide registered for use on wild rice in California is carfentrazone (Brim-DeForest *et al.* 2025). Currently, deep flooding of up to 60 cm is the main cultural weed control method for wild rice. With limited herbicides available to allow for rotation of modes of action and given that herbicide resistance in conventional rice weeds is already widespread in California (Becerra-Alvarez *et al.* 2023; Hill *et al.* 1994), it is important to develop additional herbicidal tools for wild rice. The purpose of this study was to evaluate conventional rice herbicides for crop safety and efficacy when used in wild rice production to pursue registration via Interregional Research Project No. 4 (IR-4) (Baron *et al.* 2016).

Materials and Methods

The IR-4 Process

The concept of this study was submitted to the Integrated Solutions platform of IR-4 (IS00402, www.ir4project.org), then nominated and selected as a priority at the 2021 IR-4 Food Use Workshop. Results were used to determine appropriate materials for registration on wild rice and submitted to the Residue and Product Performance Platform of IR-4 to be considered for registration (PR13881, PR13886, PR08951). These requests were then nominated for the 2024 IR-4 Food Use Workshop for manufacturer consideration of registration.

Pilot Study

In 2020, wild rice was pre-screened in a greenhouse for phytotoxicity using all California-registered conventional rice herbicides; several of these were eliminated for use in field trials (Brim-DeForest 2022). Herbicides evaluated in the field were postemergent formulations and included cyhalofop-butyl, florpyrauxifen-benzyl, penoxsulam, propanil, and triclopyr. Carfentrazone, which is the sole currently registered herbicide for wild rice, was included as a positive control. To determine the best timing for applying these herbicides, guidelines from the IR-4 Project on wild rice were followed, as noted above.

Location Information

Three field trials were conducted in 2022 and 2023, in production fields in Shasta and Yolo counties. Shasta County locations were (41.068289°N, 121.384118°W) in 2022 and (40.940495°N, 121.709427°W) in 2023, and the Yolo County site was located at (38.558126°N, 121.620503°W) in 2023. Wild rice variety Tuber was applied by fertilizer spreader onto dry ground in the Shasta County fields at 100 kg ha⁻¹ on May 31, 2022, and 120 kg ha⁻¹ on June 2, 2023. In the 2023 Yolo County field, variety Tuber was applied by aircraft at 135 kg ha⁻¹ on June 9, onto dry ground. Fields were flooded shortly after seeding, and a flooding depth of 30 to 60 cm was maintained for the duration of the growing season.

Weeds present at the 2022 site included watergrass species (*Echinochloa* P. Beauv. spp.), sprangletop [*Leptochloa fusca* (L.) Kunth], ricefield bulrush [*Schoenoplectus mucronatus* (L.) Palla.], duck salad [*Heteranthera limosa* (Sw.) Willd.], waterhyssop (*Bacopa* Aubl. spp.), common spikerush [*Eleocharis palustris* (L.) Roem. & Schult], and common waterplantain (*Alisma plantago-aquatica* L.). Weeds present at the 2023 sites were waterhyssop, duck salad, California arrowhead (*Sagittaria montevicensis* Cham. & Schltdl.), longleaf pondweed (*Potamogeton nodosus* Poir.), and common waterplantain.

Experimental Design

In all trials, treatments were arranged in a randomized complete block design with four replications and a plot size of 3 m by 6 m. Treatments included cyhalofop-butyl (0.31 and 0.63 kg ai ha⁻¹), two sequential applications of florpyrauxifen-benzyl (0.04 and 0.08 kg ai ha⁻¹), penoxsulam (0.05 and 0.1 kg ai ha⁻¹), sequential applications of triclopyr (0.42 and 0.84 kg ae ha⁻¹), propanil (3.37 and 6.73 kg ai ha⁻¹), carfentrazone (0.53 kg ai ha⁻¹), and two untreated checks per block, which were combined for analysis. Full herbicide rate and application timing are shown in Table 1. Herbicides were applied using a CO₂-pressurized backpack sprayer with a 3-m boom and 8003 flat-fan nozzles (Tee-Jet Technologies, Glendale Heights, IL) calibrated to deliver 187 L ha⁻¹. Weather data were recorded for each application and are listed in Table 2. During 2022 and 2023 in Shasta County, weed control and crop phytotoxicity evaluations (stunting, stand loss, leaf burn, leaf

Table 2. Weather data recorded when each herbicide was applied in field trials.^a

	2022			2023					
	Shasta			Shasta			Yolo		
	June 27	July 11	July 29	July 21	August 4	August 11	July 17	July 31	August 8
Wind speed	0.53	0	0	1	0.23	0	0.21	1.18	9.7
Air temperature	26.1	36.0	33.2	33.0	25.7	43.0	29.6	35.7	27.0
Relative humidity	27.5	22.7	20.3	38.7	22.7	16.2	47.7	32.7	46.7

^aWind speed is measured in kilometers per hour (km h⁻¹); air temperature is measured in (°C); relative humidity is measured as a percent (%).

deformation such as cupping and twisting, chlorosis, and lodging) were carried out on a per-plot percentage basis at 7, 14, 21, 28, and 35 d after application (DAT), and percent-heading was evaluated at 39 DAT. During 2023 in Yolo County, weed control and crop phytotoxicity evaluations (stunting, stand loss, leaf burn, dead, chlorosis, and lodging) were carried out on a per-plot percentage basis at 7, 14, 21, and 28 DAT. Experimental plots in Shasta County were hand-harvested from 1-m by 3-m quadrats and were threshed using a powered portable thresher (Almaco, Nevada, IA). Plot yield was adjusted to 14% moisture. Yield data could not be collected for the 2023 Yolo County trial.

Data Analysis

Data for untreated control plots were pooled for each block at each site-year. Site-years were analyzed separately. All data were evaluated using JMP software (v.18; SAS Institute, Cary, NC), and means were separated with Tukey's HSD or chi-square tests at $\alpha = 0.05$.

Results and Discussion

Weed Evaluations 2022

The major weed species in the study area included ricefield bulrush, common spikerush, and duckweed, with lower populations of watergrasses, sprangletop, waterhyssop, and common waterplantain (Table 3). Weed species appeared or reached maximum coverage at different parts of the study period. For example, duckweed reached 28% coverage in control plots by 7 DAT, yet had completed its lifecycle by 39 DAT. Waterhyssop also had a maximum coverage of 16% in control plots at 7 DAT, but was no longer observed in untreated plots by 28 DAT.

The broadleaf weeds of duckweed, waterhyssop, and waterplantain were generally controlled with applications of florypyrauxifen-benzyl (treatments 4 and 5), triclopyr (treatments 8 and 9), and penoxsulam (treatments 6 and 7) at 21 DAT, particularly at the higher use rates. Common spikerush and ricefield bulrush were also well controlled by 39 DAT with applications of penoxsulam and triclopyr, even at lower use rates. Common spikerush was also controlled well by propanil, although the control was only 75% at the higher rate. Smith (1965) also found that propanil effectively controlled *Eleocharis* R. Br. species. Control of ricefield bulrush from propanil and carfentrazone was unusually low in our 2022 trial. Although propanil resistance is widespread for that species in California (Becerra-Alvarez et al. 2023; Pedrosa et al. 2016), ricefield bulrush tolerance to carfentrazone is not known to occur in California. Although grass species coverage was low overall, control of watergrass with cyhalofop-butyl (treatments 2 and 3), florypyrauxifen-benzyl, penoxsulam, and propanil (treatments 10

and 11), and control of sprangletop with cyhalofop-butyl were excellent, particularly at higher use rates.

Florypyrauxifen-benzyl, penoxsulam, and triclopyr provided the greatest overall weed control, with all three showing good to excellent weed control at the lower use rates. Florypyrauxifen-benzyl is a newer herbicide and has been demonstrated to control broadleaf and sedge weeds very well in conventional California rice fields (Inci and Al-Khatib 2024) at the same rates that were applied in the present study. The other tested herbicides have been registered in California for longer, and the control observed in this trial largely agrees with their known performance (Becerra-Alvarez et al. 2023). Carfentrazone delivered good to excellent control of waterhyssop, common waterplantain, and common spikerush, but poor control of duckweed and ricefield bulrush.

Weed Evaluations 2023

The major weed species in the Shasta field were duckweed, pondweed, and arrowhead. The major weed species in the Yolo field was waterhyssop (Table 4).

In the Shasta field, florypyrauxifen-benzyl and penoxsulam provided excellent control of arrowhead and duckweed, yet only fair control of pondweed. Yaghoubi et al. (2022) also found poor pondweed control from 35 g ai ha⁻¹ penoxsulam. Propanil at the higher rate controlled arrowhead and pondweed, yet its ability to control duckweed was poor. This is expected, as propanil is known to only provide suppression of duckweed (Smith 1965; Smith and Khodayari 1985). Carfentrazone provided excellent control of arrowhead only at the Shasta site. At the Yolo site, waterhyssop control was inconsistent. Florypyrauxifen-benzyl, triclopyr, and propanil provided somewhat greater control at the lower rates, yet overall control was good to excellent from each of these. Waterhyssop control from penoxsulam and carfentrazone was also excellent.

Phytotoxicity 2022

Foliar phytotoxicity in 2022 was largely transient (Figure 1), with penoxsulam (treatments 6 and 7) and triclopyr (treatments 8 and 9) causing the strongest foliar symptoms. Chlorosis (Figure 1A) reached 50% by 7 DAT after both rates of penoxsulam were applied, and peaked at 28 DAT with 51% and 86% after applications at the low and high rates of triclopyr, respectively. Similarly, leaf burn (Figure 1B) peaked under penoxsulam treatments at 7 DAT with 95% to 100% injury, and leaf deformation (Figure 1C) reached 53% to 83% by 39 DAT after triclopyr treatments. The high rates of cyhalofop-butyl (treatment 3) and florypyrauxifen-benzyl (treatment 5) also caused noticeable and significant leaf deformation by 7 DAT and 28 DAT, respectively ($P < 0.001$). Whole-plant symptoms were more severe. Stunting (Figure 1D) was pronounced at 7 DAT under the high rates of

Table 3. Evaluations of 2022 weed control at 39 d after final herbicide applications.^{a,b,c,d}

Herbicide treatment ^e	kg ai ha ⁻¹	ECHCR	LEFFA ^f	SCPMU	ELOOB	HETLI	BAORO	ALSPA
1 Untreated	NA	0.0 (5.4) B	0.0	0.0 (7.1) B	0.0 (10.3) B	0.0 (4.8) E	0.0 (5.9) B	0.0 (2.8) B
2 Cyhalofop-butyl + COC	0.31	100.0 (8.9) A	100.0	NA	NA	NA	NA	NA
3 Cyhalofop-butyl + COC	0.63	100.0 (8.9) A	100.0	NA	NA	NA	NA	NA
4 Florpyrauxifen-benzyl + MSO	0.04 fb 0.04	100.0 (8.9) A	100.0	75 (9.9) A	68.7 (16.1) A	83.4 (7.9) ABC	NA	89.8 (5.9) A
5 Florpyrauxifen-benzyl + MSO	0.08 fb 0.08	100.0 (8.9) A	100.0	100.0 (9.9) A	52.8 (16.1) AB	100.0 (6.7) A	99.2 (12.7) A	100 (4.9) A
6 Penoxsulam + COC	0.05	100.0 (8.9) A	100.0	100 (9.9) A	77.3 (13.9) A	100.0 (7.9) A	99.2 (12.7) A	100.0 (5.9) A
7 Penoxsulam + COC	0.1	100.0 (8.9) A	100.0	100 (9.9) A	88.6 (13.9) A	95.5 (6.7) AB	99.2 (12.7) A	100.0 (5.9) A
8 Triclopyr + COC fb triclopyr + COC	0.42 fb 0.42	NA	NA	91.7 (9.9) A	79.0 (13.9) A	NA	99.2 (12.7) A	NA -
9 Triclopyr + COC fb triclopyr + COC	0.84 fb 0.84	NA	NA	100 (9.9) A	96.7 (13.9) A	NA	58.4 (13.1) A	NA -
10 Propanil + COC	3.37	57.8 (8.9) A	NA	25 (9.9) B	100 (16.1) A	42.6 (7.9) D	99.2 (12.7) A	79.2 (5.6) A
11 Propanil + COC	6.73	100.0 (8.9) A	NA	16.7 (9.9) B	75.5 (13.9) A	27.6 (14.5) CDE	99.9 (19.8) A	100.0 (5.9) A
12 Carfentrazone	0.53	NA	NA	14.6 (9.9) B	71.0 (13.9) A	55.1 (10) BCD	99.9 (19.8) A	99.2 (5.6) A

^aAbbreviations: ALSPA, common waterplantain (*Alisma plantago-aquatica*); BAORO, waterhyssop (*Bacopa* spp.); COC, crop oil concentrate; ECHCR, watergrass (*Echinochloa* spp.); ELOOB, common spikerush (*Eleocharis palustris*); fb, followed by; HETLI, duckweed (*Hydrothrix limosa*); LEFFA, sprangletop (*Leptochloa fusca*); MSO, methylated seed oil; NA, herbicide has no activity on target species; SCPMU, ricefield bulrush (*Schoenoplectus mucronatus*).

^bUntreated plot data are represented as the average of two untreated plots per block.

^cNumbers in parentheses following means are the estimated standard error (SE).

^dMeans followed by same letters in a column are not significantly different according to Tukey's HSD at $\alpha = 0.05$.

^eTreatments 2 to 12 are reported as plot-level percent weed control compared to untreated control plots.

^fSprangletop means were separated via chi-square estimation: $\chi^2 = 22.18$, $P < 0.001$.

cyhalofop-butyl and florpyrauxifen-benzyl, but the stands recovered by 14 d after both treatments. Stand loss (Figure 1E) was extreme from both rates of penoxsulam (treatments 6 and 7), reaching 100% loss by 14 DAT after both treatments. Stand loss was also significant with the high rate of cyhalofop-butyl, reaching 24% by 39 DAT ($P < 0.001$). Lodging (Figure 1F) was transient at the high rate of florpyrauxifen-benzyl, reaching 50% at 21 DAT but it recovered quickly. Lodging with triclopyr (treatments 8 and 9) caused more severe and permanent lodging, reaching 53% and 65% under the low and high rates, respectively.

Phytotoxicity 2023

Foliar phytotoxicity symptoms at the 2023 Shasta County site were slight and transient. High-rate propanil (treatments 10 and 11) caused chlorosis injury of 35% at 7 DAT (Figure 2A), but symptoms disappeared quickly. Likewise, leaf burn (Figure 2B) was significant only at high propanil rates at 14 DAT ($P < 0.001$), and stunting (Figure 2D) was significant only after penoxsulam applications (treatments 6 and 7) at 7 DAT ($P < 0.001$). Whole-plant symptoms were far more severe, exhibited in penoxsulam causing up to 100% mortality (Figure 2C) and thus stand loss (Figure 2E) by 14 DAT. Lodging (Figure 2F) was significant with triclopyr (treatments 8 and 9), reaching 75% at the higher rate by 21 DAT, although it decreased to 48% by 28 DAT.

Phytotoxicity was more evident at the Yolo County site in 2023, although foliar symptoms were short lived. Chlorosis (Figure 3A) reached 70% at 7 DAT with the high rate of propanil, and leaf burn (Figure 3B) reached 60% with the high rate of penoxsulam, also by 7 DAT. Cyhalofop (treatments 2 and 3), florpyrauxifen-benzyl treatments (Treatments 4 and 5) and propanil also caused mild but significant stunting (Figure 3D) at early ratings. Clay and Oelke (1990) also found that a foliar application of propanil at up to 4.5 kg ai ha⁻¹ resulted in moderate and transient injury to wild rice in Minnesota; however, in one site-year, yields were significantly reduced after the higher rate had been applied. Penoxsulam caused severe plant death (Figure 3C) and subsequent stand loss (Figure 3E). Lodging was more apparent at this site; most plots experienced some lodging by 21 DAT. Lodging was greatest after triclopyr was applied, although it was only significantly different from the other treatments under the higher rate at 21 DAT ($P < 0.001$) and 28 DAT ($P = 0.03$).

Yield

Plot-level yields were variable in both Shasta County site-years (Table 5). Although yields were lower overall in 2023, yields from plots that received experimental herbicides were generally greater at the lower use rates in both years. The greatest yields were found with carfentrazone (Treatment 12) in 2022, and the lower rate of florpyrauxifen-benzyl (Treatment 4) in 2023, at 3,343 kg ha⁻¹ and 1,409 kg ha⁻¹, respectively, although these were not significantly different from control plot yields. In addition to those two treatments, the higher rate of propanil (Treatment 11) also provided numerically greater yields than the untreated control in both years. Penoxsulam (Treatments 6 and 7) and the higher rate of triclopyr (Treatment 9) were the only treatments that resulted in significantly different yields from untreated plots. Yields from penoxsulam-treated plots fell to zero at the higher use rate in both site-years, and fell by 73% and 56% by the high rate of triclopyr in 2022 and 2023, respectively.

Table 4. Evaluations of 2023 weed control at 28 d after final herbicide applications.^{a,b,c,d}

			SAGMO ^f	HETLI	PTMNO	BAORO
Herbicide treatment ^e			Rate	Shasta County		Yolo County
			kg ai ha ⁻¹	% Control (SE)		
1	Untreated		NA	0.0	0.0 (7.9) C	0 (10.4) B
2	Cyhalofop-butyl + COC		0.31	NA	NA	NA
3	Cyhalofop-butyl + COC		0.63	NA	NA	NA
4	Florpyrauxifen-benzyl + MSO fb florpyrauxifen-benzyl + MSO	0.04 fb 0.04	100.0	84.1 (11.0) AB	40.0 (17.5) AB	100.0 (9.4) A
5	Florpyrauxifen-benzyl + MSO fb florpyrauxifen-benzyl + MSO	0.08 fb 0.08	100.0	100.0 (11.0) A	86.7 (17.5) A	75.2 (9.4) A
6	Penoxsulam + COC	0.05	100.0	100.0 (11.0) A	63.3 (14.7) A	85.8 (10.9) A
7	Penoxsulam + COC	0.1	100.0	100.0 (11.0) A	71.7 (14.7) A	99.1 (10.9) A
8	Triclopyr + COC fb triclopyr + COC	0.42 fb 0.42	NA	NA	NA	83.9 (10.9) A
9	Triclopyr + COC fb triclopyr + COC	0.84 fb 0.84	NA	NA	NA	74.3 (13.5) A
10	Propanil + COC	3.37	100.0	55.8 (11) AB	79.9 (22.1) AB	99.5 (10.9) A
11	Propanil + COC	6.73	100.0	45.9 (11) B	99.9 (22.1) A	83.2 (9.4) A
12	Carfentrazone	0.53	100.0	79.2 (11) AB	52.7 (17.5) AB	96.0 (9.4) A

^aAbbreviations: BAORO, waterhyssop (*Bacopa* spp.); COC, crop oil concentrate; fb, followed by; HETLI, ducksalad (*Heteranthera limosa*); MSO, methylated seed oil; NA, herbicide has no activity on target species; PTMNO, longleaf pondweed (*Potamogeton nodosus*); SE, estimate standard error; SAGMO, California arrowhead (*Sagittaria montevidensis*).

^bUntreated plot data are represented as the average of two untreated plots per block.

^cNumbers in parentheses following means are the estimate standard error (SE).

^dMeans followed by same letters in a column are not significantly different according to Tukey's HSD at $\alpha = 0.05$.

^eTreatments 2 to 12 are reported as plot-level percent weed control (compared to untreated control plots).

^fArrowhead means separated via chi-square estimation: $\chi^2 = 38.14$, $P < 0.001$

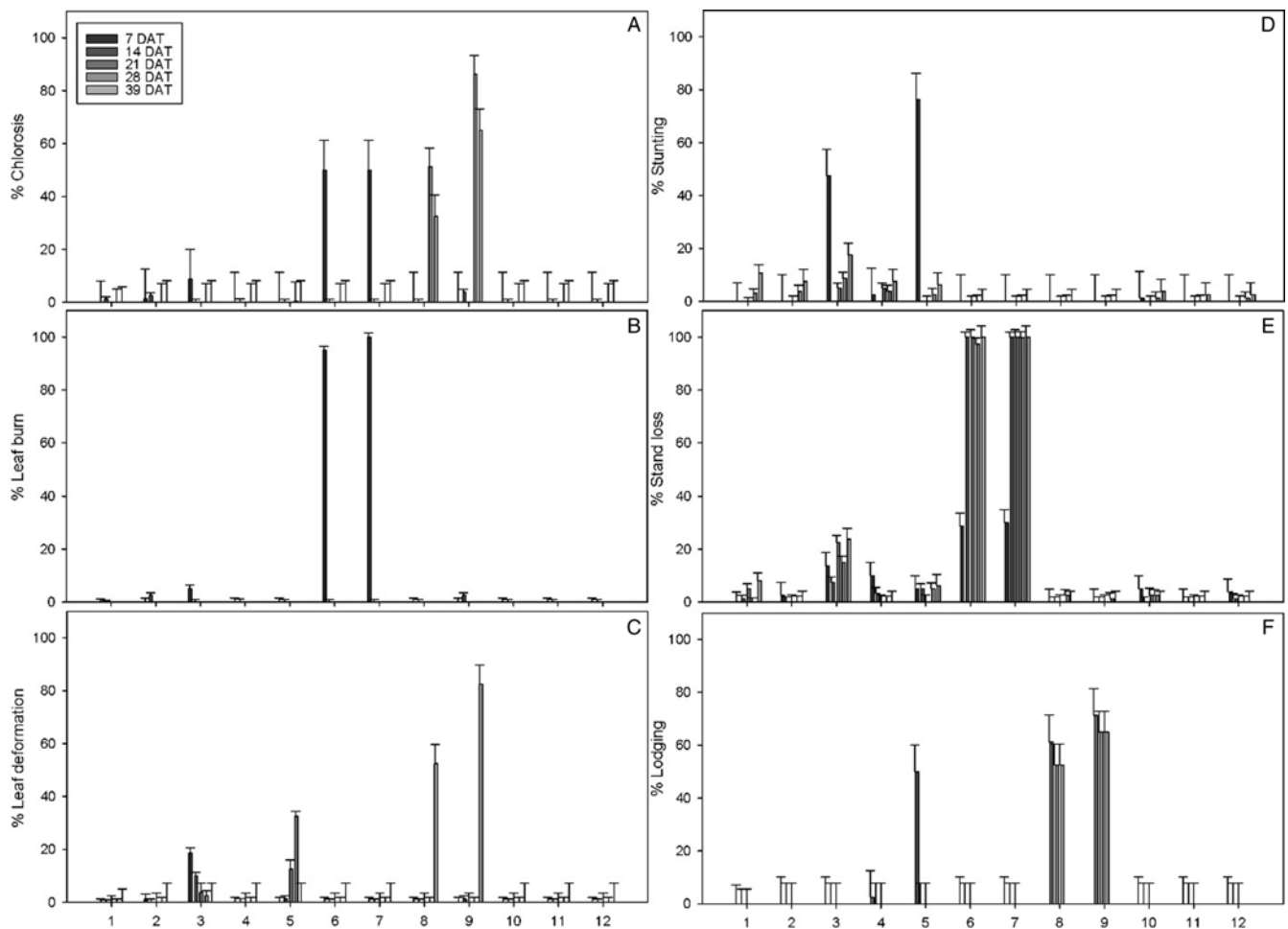


Figure 1. Wild rice response to herbicide treatments administered in 2022 in Shasta County, California. Ratings are presented as plot-level percent injury taken at 7, 14, 21, 28, and 39 d after treatment (DAT) (A–E) or 21, 28, and 39 DAT (F). Treatments are as follows: (1) untreated control; low (2) and high (3) rates of cyhalofop-butyl; low (4) and high (5) rates of florpyrauxifen-benzyl applied twice; low (6) and high (7) rates of penoxsulam; low (8) and high (9) rates of triclopyr applied twice; low (10) and high (11) rates of propanil; and (12) carfentrazone. Full herbicide rate and timing information are provided in the text and in Table 1. A: general chlorosis; B: leaf burn; C: leaf deformation (cupping, twisting, curling, etc.); D: stunting; E: stand loss; F: lodging. Error bars are standard errors generated from standard least-squares linear modeling.

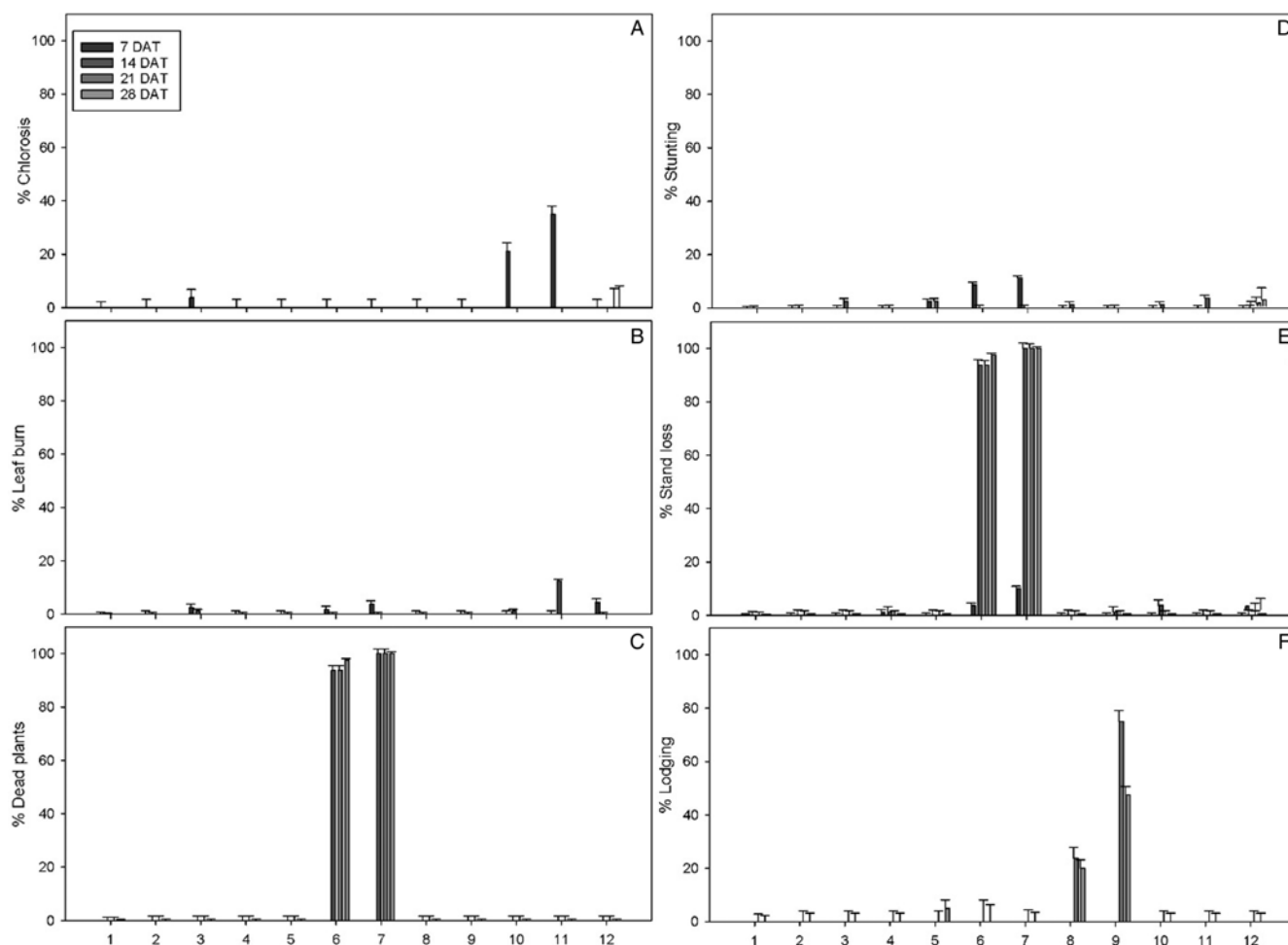


Figure 2. Wild rice response to herbicide treatments administered in 2023 in Shasta County, California. Ratings are presented as plot-level percent injury taken at 7, 14, 21, and 28 d after treatment (DAT). Treatments are as follows: (1) untreated control; low (2) and high (3) rates of cyhalofop-butyl; low (4) and high (5) rates of florypyrauxifen-benzyl applied twice; low (6) and high (7) rates of penoxsulam; low (8) and high (9) rates of triclopyr applied twice; low (10) and high (11) rates of propanil; and (12) carfentrazone. Full herbicide rate and timing information can be found in the text and in Table 1. A: general chlorosis; B: leaf burn; C: dead plants; D: stunting; E: stand loss; F: lodging. Error bars are standard errors generated from standard least-squares linear modeling.

Practical Implications

The major aim of these field trials was to evaluate common herbicides for weed control and their safety when applied to rice, with the aim of seeking registration to use them on wild rice. For most of the evaluated herbicides, phytotoxicity was minor and short lived, and comparable to that of carfentrazone. However, penoxsulam was highly phytotoxic to wild rice, causing complete stand loss at the higher use rate. Triclopyr also caused significant wild rice lodging at both use rates, reducing yields to unacceptable levels at the higher rate. Similarly, Madsen *et al.* (2008) also found increasing injury to wild rice at higher rates (2.5 mg L⁻¹) of aqueous triclopyr, particularly to seedlings and young plants. In the present study, triclopyr was administered at the 3.5-leaf stage, and again 20 d later. It may be useful to determine the crop safety of the 0.84 kg ai ha⁻¹ rate applied only once, later in the season. Yields from treatments that did not cause lasting crop injury at the Shasta County sites were also comparable to those of untreated control plots or that that received carfentrazone treatment. In a full-season setting with several registered herbicides, growers would likely implement a comprehensive weed management program. For instance, cyhalofop-butyl, which is used to control grass weeds, might be tank-mixed with carfentrazone for an early application,

and then followed up with florypyrauxifen-benzyl or propanil for a cleanup treatment. This is a similar strategy to herbicide programs used for conventional rice production in California, where these herbicides are all registered. These treatments provide good to excellent weed control in a conventional rice system and would be expected to perform similarly in wild rice production. Propanil, in particular, provided excellent control of spikerush, an uncommon weed of conventional rice in the Sacramento Valley. Further herbicide efficacy evaluations of spikerush conducted in controlled and field environments would provide valuable data to support adding this species to herbicide labels.

These trials demonstrated that cyhalofop-butyl, florypyrauxifen-benzyl, and propanil all provided satisfactory weed control and were safe to wild rice when applied alone. Further studies of these herbicides applied together in an integrated weed management program would also help determine which treatment combinations are the safest and most effective for full-season weed control in wild rice. Pesticide manufacturers review efficacy and crop safety data developed in IR-4 IS00402 studies, such as those in these trials, and the data generated may influence manufacturers' objectives in registering their use on specialty crops such as wild rice.

Table 5. Plot-level harvest data for 2022 and 2023 Shasta County studies.^{a,b,c,d,e}

Herbicide treatment		Rate	Yield	
			2022	2023
		kg ai ha ⁻¹	kg ha ⁻¹ (SE)	
1	Untreated	NA	2,647 (243) AB	1,156 (123) A
2	Cyhalofop-butyl + COC	0.31	2,884 (366) AB	1,127 (148) A
3	Cyhalofop-butyl + COC	0.63	2,023 (320) ABC	934 (148) AB
4	Florpyrauxifen-benzyl + MSO fb florpyrauxifen-benzyl + MSO	0.04 fb 0.04	3,000 (320) AB	1,409 (148) A
5	Florpyrauxifen-benzyl + MSO fb florpyrauxifen-benzyl + MSO	0.08 fb 0.08	1,835 (320) BC	1,272 (148) A
6	Penoxsulam + COC	0.05	243 (320) D	114 (148) C
7	Penoxsulam + COC	0.1	0 (320) D	0 (148) C
8	Triclopyr + COC fb triclopyr + COC	0.42 fb 0.42	2,110 (320) ABC	1,112 (148) A
9	Triclopyr + COC fb triclopyr + COC	0.84 fb 0.84	750 (320) CD	512 (148) BC
10	Propanil + COC	3.37	2,589 (366) AB	1,261 (148) A
11	Propanil + COC	6.73	2,927 (320) AB	1,325 (148) A
12	Carfentrazone	0.53	3,343 (320) A	1,359 (148) A

^aAbbreviations: fb, followed by; COC, crop oil concentrate; MSO, methylated seed oil; SE, estimated standard error.

^bStudies in 2022 and 2023 were conducted at different locations in Shasta County California. GPS locations are listed in the text.

^cPlots were hand-harvested from 1-m × 3-m quadrats, data is adjusted to 14% moisture.

^dNumbers in parentheses following means are the estimated SE.

^eMeans followed by same letters in a column are not significantly different according to Tukey's HSD at $\alpha = 0.05$.

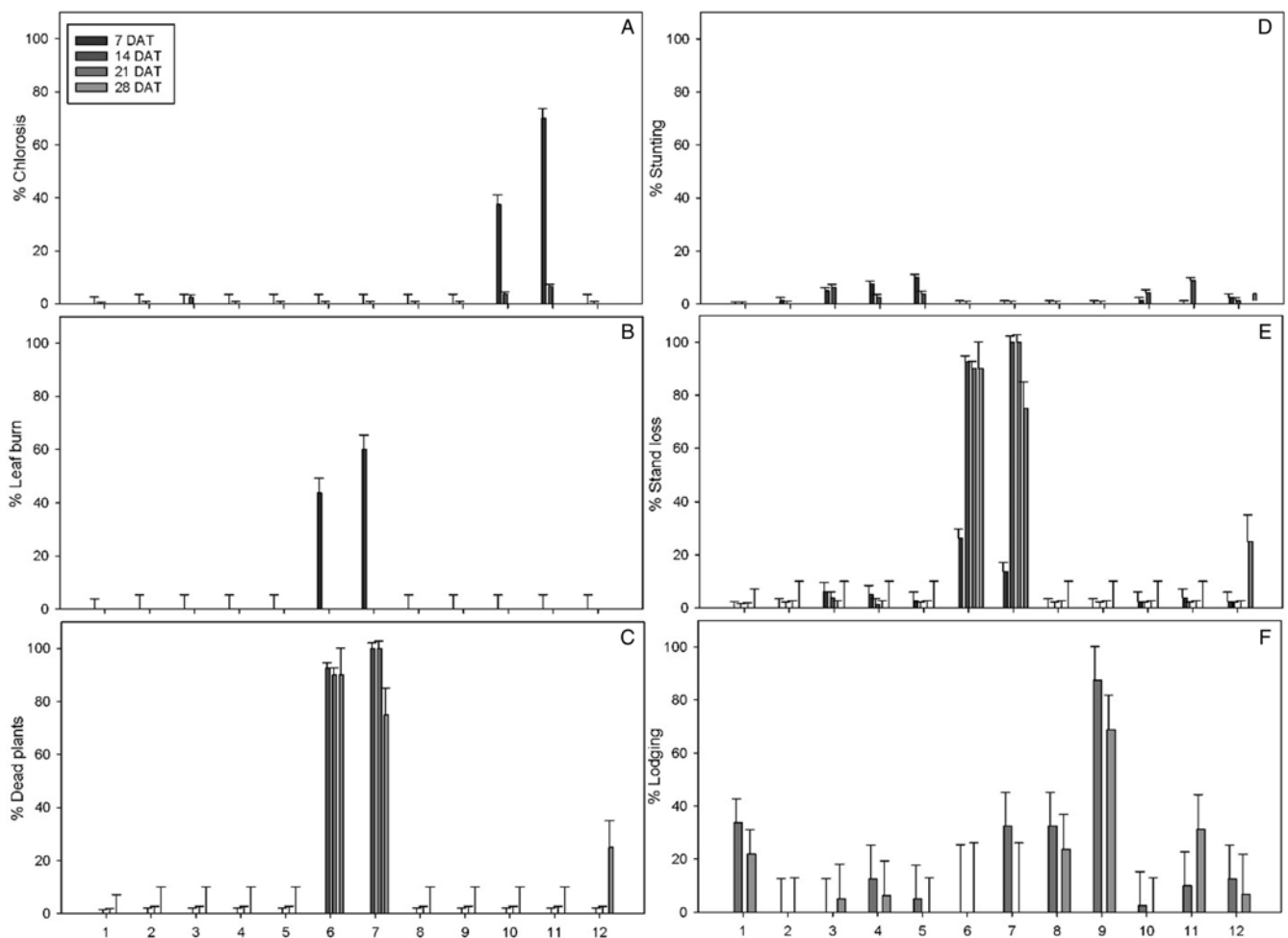


Figure 3. Wild rice response to herbicide treatments administered in 2023 in Yolo County, California. Ratings are presented as plot-level percent injury taken at 7, 14, 21, and 28 d after treatment (DAT) (A–E) or 21 and 28 DAT (F). Treatments are as follows: (1) untreated control; low (2) and high (3) rates of cyhalofop-butyl; low (4) and high (5) rates of florpyrauxifen-benzyl applied twice; low (6) and high (7) rates of penoxsulam; low (8) and high (9) rates of triclopyr applied twice; low (10) and high (11) rates of propanil; and (12) carfentrazone. Full herbicide rate and timing information can be found in the text and in Table 1. A: general chlorosis; B: leaf burn; C: dead plants; D: stunting; E: stand loss; F: lodging. Error bars are standard error generated from standard least-squares linear modeling.

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Competing Interests. The authors declare they have no competing interests.

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