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Herbicide-resistant *Echinochloa oryzoides* and *E. phyllopogon* in California *Oryza sativa* fields

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Echinochloa oryzoides and *E. phyllopogon* have become the most serious weeds in California *Oryza sativa* since continuous flooding was used to suppress *E. crus-galli.* Continuous use of a limited number of available graminicides and an increasing number of control failures led to the investigation of herbicide resistance in *E. oryzoides* and *E. phyllopogon.* Greenhouse dose-response studies with postemergence (POST) applications of molinate, thiobencarb, fenoxaprop-ethyl, and bispyribac-sodium estimating GR_{50} (herbicide dose to inhibit growth by 50%) values suggested resistance to all herbicides in two *E. phyllopogon* accessions and to molinate and thiobencarb in one *E. oryzoides* accession when compared with susceptible *E. phyllopogon* and *E. oryzoides* controls, respectively. No resistance was detected in dose-response studies with propanil. Minimum and maximum ratios (R/S) of the GR_{50} values of resistant to susceptible *E. phyllopogon* plants (in two experiments involving two resistant accessions) were 7.8 and > 13.3 for thiobencarb, 2.2 and 4.3 for molinate, 16.5 and 428.7 for fenoxaprop-ethyl, and 2.0 and 12.0 for bispyribac-sodium. Minimum and maximum *E. oryzoides* R/S ratios (average of two experiments) were 21.9 and 4.6 for thiobencarb and molinate, respectively. A resistant *E. phyllopogon* (one accession tested) and the susceptible control were killed by POST applications of glyphosate, glufosinate, and clomazone, and by a preemergence application of pendimethalin. Thus, the repeated use of the few available grass herbicides in the predominantly monocultured *O. sativa* of California has selected for herbicide resistance in *E. oryzoides* and *E. phyllopogon.* The introduction of herbicides with new mechanisms of action will be useful to manage herbicide-resistant *E. oryzoides* and *E. phyllopogon.* However, cross- and multiple resistance emphasize the need to integrate herbicide use with nonchemical means of weed management.

Nomenclature: Bispyribac-sodium, sodium 2,6-bis[(4,6-dimethoxypyrimidin-2-yl)oxy]benzoate; clomazone; fenoxaprop-ethyl; glyphosate; glufosinate; molinate; pendimethalin; propanil; thiobencarb; *Echinochloa oryzoides* (Ard.) Fritsch ECHOR, early watergrass; *Echinochloa phyllopogon* (Stapf) Koss ECHPH, late watergrass; *Echinochloa crus-galli* (L.) Beauv. var. crus-galli ECHCG, barnyardgrass; *Oryza sativa* L., rice.

Key words: Dose-response bioassay, graminicides, herbicide resistance, cross-resistance, multiple resistance, ECHOR, ECHPH, ECHCG.

Weed control has been a major concern of growers since the beginning of *Oryza sativa* production in California (Bayer et al. 1985). Water-seeding *O. sativa* in continuously flooded fields began in the 1920s in California as a method to control severe infestations of *Echinochloa crus-galli* (Adair and Engler 1955) and other weedy grasses (Dunshee 1923). Since the adoption of water-seeded *O. sativa* culture, *E. crus-galli* has been replaced by *E. oryzoides* (also mentioned in the literature as *E. macrocarpa* Vasing), *E. hostii* (Bieb.) Boros ex Holub, *E. crus-galli* (L.) Beauv. sp. *Oryzoides* de Bolos et Mascl., and by *E. phyllopogon* (also known in the literature as *E. crus-galli* (L.) Beauv. var. *oryzicola* Ohwi), *E. oryzicola* (Vasing) Vasing, *E. oryzoides* (Ard.) Fritsch ssp. *phyllopogon* (Stapf) Tzvel, and *Panicum oryzicola* Vasing (Michael 1983). The morphological characteristics of *E. phyllopogon* (Gould et al. 1972) and *E. oryzoides* (Vickery 1975) cannot be easily applied to identify these two species in the field during early vegetative stages. Cytological relationships have been used to clarify their taxonomy: 2n = 36 for *E. phyllopogon* and 2n = 54 for *E. oryzoides* (Yabuno 1984). In California, *E. phyllopogon* flowers late in the season at the same time as *O. sativa,* while *E. oryzoides* flowers about 40 d after *O. sativa* emergence.

Dense infestations of *E. oryzoides* and *E. phyllopogon* can cause more than 50% *O. sativa* yield loss if not controlled (Hill et al. 1985). These weedy grasses are only partially controlled by continuous flooding, thus California *O. sativa* farmers must complement this practice with the use of herbicides such as molinate, thiobencarb, propanil, and fenoxaprop to protect the crop from *E. phyllopogon* and *E. oryzoides* competition. Propanil was introduced in the 1960s and was followed by molinate, which replaced propanil in regions where its use was restricted because of injury to nontarget crops (Hill et al. 1985). Propanil is an amide herbicide that inhibits electron transport at photosystem II and can also reduce anthocyanin content, inhibit RNA and protein synthesis, and affect plasmalemma function (Devine et al. 1993). Thiobencarb is a thiocarbamate that was introduced in the early 1980s (Hill et al. 1985). Thiocarbamate herbicides affect lipid (very long-chain fatty acids) biosynthesis (Gronwald 1991). Fenoxaprop is an aryloxyphenoxypropionate that inhibits acetyl CoA carboxylase (Gronwald

1991) and was introduced in the early 1990s in California *O. sativa* to control *E. crus-galli*, *E. phyllopogon*, and *E. oryzoides* that had escaped previous treatments.

Continuous use of a herbicide or herbicides with the same mechanism of action leads to the development of herbicide resistance in weed populations (Holt et al. 1993). *O. sativa* is seldom rotated with other crops in the Sacramento Valley of California, and the few available grass herbicides have been used continuously to control *E. phyllopogon* and *E. oryzoides*. Recently, farmers have complained of unacceptable control of *E. phyllopogon* and *E. oryzoides* in *O. sativa* by herbicides that previously controlled them. In response to these complaints, *E. phyllopogon* and *E. oryzoides* accessions were collected from fields where conventional herbicides failed and tested against recommended field rates of available herbicides. Herbicide resistance was detected in *E. phyllopogon* and *E. oryzoides* (Fischer and Hill 1998). Herbicide resistance in *E. phyllopogon* and *E. oryzoides* had not been reported previously to the best of our knowledge. However, resistance to propanil has been found in the related species *E. colona* (L.) Link in Central and South America following repeated use of this herbicide (Fischer et al.1993; Garita et al. 1995; Garro et al. 1991; Riches et al. 1996). Propanil resistance also has occurred in *E. crus-galli* in Greece (Giannopolitis and Vassiliou 1989) and in Arkansas (Smith et al. 1992).

A key approach to delay the development of herbicide resistance in weeds is to use herbicides with different modes of action and contrasting chemistry in mixture or in sequence (Jutsum and Graham 1995). Herbicides with new and different mechanisms of action may soon be available in California. Clomazone is being tested as a preemergence herbicide in *O. sativa*, while glyphosate and glufosinate may be used postemergence with genetically engineered herbicide-resistant *O. sativa* (Fischer and Hill 1998). Pendimethalin, which is effective on *E. crus-galli* in Arkansas (Baltazar and Smith 1994), could be used in dry-seeded *O. sativa* in California. Registration is also being pursued for bispyribac-sodium, an acetolactate synthase (ALS) inhibitor.

In this study, *E. phyllopogon* and *E. oryzoides* accessions were evaluated to characterize their response to fenoxaprop-ethyl, thiobencarb, propanil, molinate, and bispyribac-sodium, and to detect possible cross- and multiple resistance involving two or more of these herbicides. In addition, response of a herbicide-resistant *E. phyllopogon* accession to clomazone, glyphosate, glufosinate, and pendimethalin was evaluated.

Materials and Methods

Greenhouse experiments for whole-plant bioassays were conducted in 1998 at the University of California in Davis to confirm herbicide resistance in *E. phyllopogon* and *E. oryzoides* and to determine the levels of resistance to currently available herbicides.

In 1997, 14 *E. oryzoides* and 26 *E. phyllopogon* seed samples (accessions) had been collected in the Sacramento Valley of California from farmers' fields including areas where control problems had been detected, areas with satisfactory control, and from organic farms where herbicides were not being used. Approximately ½ kg of bulked seed was collected from each field and, in certain cases, from areas within fields. These accessions were tested for resistance to molinate, thiobencarb, fenoxaprop-ethyl (racemate), propanil, and bispyribac-sodium (Fischer and Hill 1998). The first four herbicides are currently available for use in *O. sativa*, and bispyribac-sodium is expected to be released soon. Original seeds from the 1997 collection were stored. An *E. oryzoides* (ECHOR-R) and two *E. phyllopogon* (ECHPH-R1 and ECHPH-R2) accessions that exhibited the highest survival to treatment with field rates of molinate and thiobencarb (ECHOR-R) or with molinate, thiobencarb, and fenoxaprop-ethyl (ECHPH-R1 and ECHPH-R2) were selected for further characterization of herbicide resistance. From the same collection, a susceptible *E. oryzoides* population (ECHOR-S) and a susceptible *E. phyllopogon* population (ECHPH-S), which had been killed by field rates of all herbicides, were used as standards to determine the level of herbicide resistance. All five populations had been collected from different farms, and the *E. phyllopogon* accessions are the same as reported by Fischer et al. (1999). In each experiment the respective susceptible control was compared with a resistant population. The experiments were conducted from August 10 through December 22, 1998, and the average daily temperature in the greenhouse during this period declined from 31 C to 28 C. The photoperiod was 16 h, and natural sunlight was supplemented by high-pressure sodium lamps yielding an illumination of about 400 μmol m^{-2} sec^{-1} photosynthetic photon flux.

Germinated seeds were planted in 16-cm^2 pots filled with a Yolo clay loam (fine-silty, mixed, nonacid, thermic Typic Xerorthents, 1.7% organic matter). After emergence, seedlings were thinned to 4 or 6 equidistantly-spaced uniform plants per pot. Pots were flooded and fertilized shortly after thinning with a complete fertilizer as required. The following treatments were applied individually to each of the five *Echinochloa* accessions using a cabinet track sprayer delivering a spray volume of 140 L ha^{-1} at 276 kPa with an 8001 flat fan nozzle[1]: thiobencarb (0, 1.01, 2.02, 4.04, 8.08, and 16.16 kg ai ha^{-1}), molinate (0, 1.21, 2.42, 4.84, 9.68, and 19.36 kg ai ha^{-1}), fenoxaprop-ethyl (0, 0.045, 0.09, 0.18, 0.36, and 0.72 kg ai ha^{-1} of the ester), bispyribac-sodium (0, 0.0062, 0.0123, 0.0247, 0.0494, and 0.0988 kg ai ha^{-1}), propanil (0, 1.09, 2.18, 4.36, 8.72, and 17.44 kg ai ha^{-1}). Using the same application technique, the following treatments were applied to ECHPH-R2 and ECHPH-S: glufosinate (0, 0.175, 0.35, 0.7, 1.4, and 2.8 kg ai ha^{-1}), glyphosate (0, 0.14, 0.28, 0.56, 1.12, and 2.24 kg ae ha^{-1}), pendimethalin (0, 0.28, 0.56, 1.12, 2.24, and 4.48 kg ai ha^{-1}), and clomazone (0, 0.224, 0.448, 0.896, 1.792, and 3.584 kg ai ha^{-1}). Herbicide rates correspond to approximately 0, 0.25, 0.5, 1, 2, and 4 times the recommended field rate of each herbicide in California. A silicon-based surfactant (silicone-polyether copolymer)[2] was added to bispyribac-sodium at 0.25% v/v. The herbicides were applied at the following *E. phyllopogon* and *E. oryzoides* growth stages (number of leaves): thiobencarb, 1.5 to 2; molinate, 1 to 1.5; fenoxaprop-ethyl, propanil, glyphosate, and glufosinate, 4 to 5; bispyribac-sodium, 3; clomazone, 1; and pendimethalin, preemergence (pots were sprayed 1 d after germinated seeds were planted and covered with 5 mm of soil). Treatments were arranged in a completely randomized design, replicated four or six times, and each experiment was repeated once. Within 72 h after spraying, pots were

Table 1. Herbicide rates required for 50% reduction of aboveground biomass (GR_{50}) of susceptible and resistant accessions of *E. oryzoides* and *E. phyllopogon*, and ratios (R/S) of the GR_{50} values of resistant to susceptible plants.

Herbicide	Accession[a]	Experiment one		Experiment two	
		GR_{50}	R/S	GR_{50}	R/S
		kg ha^{-1}		kg ha^{-1}	
Thiobencarb	ECHPH-S	0.870		1.462	
	ECHPH-R1	8.400	9.7	> 16.160[b]	> 10.9
	ECHPH-S	1.220		1.273	
	ECHPH-R2	9.482	7.8	> 16.160	> 13.3
	ECHOR-S	0.390		—[c]	
	ECHOR-R	8.550	21.9	—	—
Molinate	ECHPH-S	1.250		1.380	
	ECHPH-R1	2.740	2.2	5.770	4.2
	ECHPH-S	2.942		1.120	
	ECHPH-R2	11.540	3.9	4.861	4.3
	ECHOR-S	1.370		—	
	ECHOR-R	6.268	4.6	—	—
Fenoxaprop-ethyl	ECHPH-S	0.001		0.040	
	ECHPH-R1	0.539	428.7	0.661	16.5
	ECHPH-S	0.030		0.020	
	ECHPH-R2	> 0.720	> 24	0.391	19.6
	ECHOR-S	0.001		—	
	ECHOR-R	0.001	1.0	—	—
Bispyribac-sodium	ECHPH-S	0.005		0.008	
	ECHPH-R1	0.010	2.0	0.040	5.0
	ECHPH-S	0.005		0.008	
	ECHPH-R2	0.060	12.0	0.030	3.8
	ECHOR-S	0.001		—	
	ECHOR-R	0.002	2.0	—	—
Propanil	ECHPH-S	0.610		1.420	
	ECHPH-R1	0.960	1.6	2.099	1.5
	ECHPH-S	0.502		1.590	
	ECHPH-R2	0.810	1.6	2.260	1.4
	ECHOR-S	0.810		—	
	ECHOR-R	0.640	0.8	—	—
Glyphosate	ECHPH-S	0.160		—	
	ECHPH-R2	0.260	1.6	—	—
Glufosinate	ECHPH-S	0.190		—	
	ECHPH-R2	0.140	0.7	—	—
Pendimethalin	ECHPH-S	—[d]		—	
	ECHPH-R2	—	—	—	—
Clomazone	ECHPH-S	—		—	
	ECHPH-R2	—	—	—	—

[a] Name of resistant accessions of *E. oryzoides* (ECHOR-R) and *E. phyllopogon* (ECHPH-R1 and ECHPH-R2) that were tested against the corresponding susceptible *E. oryzoides* (ECHOR-S) and *E. phyllopogon* (ECHPH-S) controls.

[b] Calculated GR_{50} is at a rate higher than the highest rate applied.

[c] Experiments one and two pooled for *E. oryzoides*.

[d] The susceptible and resistant accessions were killed at the lowest herbicide dose of 0.28 and 0.22 kg ha^{-1}s of pendimethalin and clomazone, respectively; regression analysis was not conducted.

flooded with 10-cm-deep water. Nineteen to 21 d after herbicide treatment (DAT) the aboveground shoots were harvested and fresh weight determined. Percent growth (fresh weight as percent of the untreated control) was fitted to a log-logistic regression model (Seefeldt et al. 1994; Streibig et al. 1993):

$$Y = c + \{(d - c) / [1 + (x / g)^b]\}$$

where Y is percent growth, c is the mean response at very high herbicide rates, d is the mean response when herbicide rates approach zero, b is the slope of the line, g is the herbicide rate at the point of inflection halfway between c and d, and x is the herbicide dose. Regression analysis of all data points was conducted using SigmaPlot version 4.0 (1997) statistical software.[3] Data from repeated experiments were pooled when experiment by treatment interactions were not detected by analysis of variance (ANOVA).

Results and Discussion

The herbicide doses required to inhibit growth by 50% (GR_{50}) for each dose response experiment and the param-

Table 2. Parameters of the log-logistic equations[a] used to calculate the herbicide rates required for 50% reduction of aboveground biomass (GR_{50}) of susceptible and resistant accessions of *E. oryzoides* and *E. phyllopogon* and R^2 values of the corresponding regressions.

		Experiment one					Experiment two				
Herbicide	Accession[b]	c	d	b	g	R^2	c	d	b	g	R^2
Thiobencarb	ECHPH-S	0.00	100.00	3.63	0.870	0.97	0.00	98.63	2.25	1.480	0.86
	ECHPH-R1	0.00	100.00	2.37	8.400	0.85	49.90	100.00	2.12	4.480	0.67
	ECHPH-S	0.00	100.00	8.47	1.220	0.99	1.47	100.00	2.99	1.260	0.97
	ECHPH-R2	34.17	100.00	13.54	8.710	0.78	69.36	100.00	4.94	4.000	0.71
	ECHOR-S	0.00	100.00	4.87	0.390	0.97	—[c]	—	—	—	—
	ECHOR-R	0.00	100.00	5.36	8.550	0.65	—	—	—	—	—
Molinate	ECHPH-S	0.08	100.00	5.77	1.250	0.88	0.00	100.00	12.34	1.380	0.99
	ECHPH-R1	0.00	100.00	1.60	2.740	0.89	0.00	100.00	10.62	5.770	0.89
	ECHPH-S	0.29	100.00	8.05	2.940	0.99	0.00	100.00	10.80	1.120	0.99
	ECHPH-R2	0.00	100.00	6.10	11.540	0.00	7.30	100.00	6.83	4.750	0.94
	ECHOR-S	0.00	100.00	3.84	1.370	0.97	—	—	—	—	—
	ECHOR-R	0.30	100.00	4.78	6.260	0.56	—	—	—	—	—
Fenoxaprop-ethyl	ECHPH-S	5.10	100.00	0.47	0.001	0.96	0.10	100.00	3.82	0.040	0.92
	ECHPH-R1	37.80	100.00	4.36	0.390	0.61	0.86	100.00	21.20	0.660	0.04
	ECHPH-S	0.00	100.00	6.90	0.030	0.96	0.00	100.00	3.46	0.020	0.92
	ECHPH-R2	68.34	100.00	3.19	0.020	0.51	0.00	97.81	0.97	0.410	0.54
	ECHOR-S	0.00	100.00	0.49	0.001	0.99	—	—	—	—	—
	ECHOR-R	0.00	100.00	2.96	0.001	0.91	—	—	—	—	—
Bispyribac-sodium	ECHPH-S	2.58	100.00	5.93	0.005	0.85	0.24	100.00	6.51	0.008	0.94
	ECHPH-R1	2.62	100.00	2.61	0.010	0.95	0.00	100.00	2.24	0.040	0.64
	ECHPH-S	0.00	100.00	3.63	0.005	0.94	0.00	99.67	2.36	0.008	0.84
	ECHPH-R2	0.00	100.00	1.91	0.060	0.88	0.00	100.00	2.04	0.030	0.67
	ECHOR-S	0.00	100.00	1.14	0.001	0.96	—	—	—	—	—
	ECHOR-R	0.00	100.00	4.13	0.002	0.94	—	—	—	—	—
Propanil	ECHPH-S	0.00	100.00	2.28	0.610	0.96	0.00	99.98	1.53	1.420	0.77
	ECHPH-R1	0.00	100.00	4.13	0.960	0.93	2.90	100.00	3.19	2.060	0.76
	ECHPH-S	0.00	99.50	0.60	0.510	0.81	0.00	99.98	4.90	1.590	0.97
	ECHPH-R2	0.00	100.00	55.00	0.810	0.79	0.00	100.00	16.59	2.260	0.93
	ECHOR-S	0.09	100.00	3.54	0.810	0.92	—	—	—	—	—
	ECHOR-R	0.00	100.00	1.99	0.640	0.94	—	—	—	—	—
Glyphosate	ECHPH-S	0.00	100.00	6.24	0.160	0.96	—	—	—	—	—
	ECHPH-R2	0.00	100.00	24.08	0.260	0.85	—	—	—	—	—
Gluphosinate	ECHPH-S	0.00	100.00	2.13	0.190	0.81	—	—	—	—	—
	ECHPH-R2	0.00	100.00	2.35	0.140	0.88	—	—	—	—	—
Pendimethalin	ECHPH-S	—[d]	—	—	—	—	—	—	—	—	—
	ECHPH-R2	—	—	—	—	—	—	—	—	—	—
Clomazone	ECHPH-S	—	—	—	—	—	—	—	—	—	—
	ECHPH-R2	—	—	—	—	—	—	—	—	—	—

[a] $Y = c + \{(d - c)/[1 + (x/g)^b]\}$, where Y is fresh aboveground weight as percent of the untreated control, c and d are coefficients corresponding to the lower and upper asymptotes, b is the slope of the line, g is the herbicide rate at the point of inflection halfway between the upper and lower asymptotes, and x is the herbicide dose.

[b] Name of resistant accessions of *E. oryzoides* (ECHOR-R) and *E. phyllopogon* (ECHPH-R1 and ECHPH-R2) that were tested against the corresponding susceptible *E. oryzoides* (ECHOR-S) and *E. phyllopogon* (ECHPH-S) controls.

[c] Experiments one and two pooled for *E. oryzoides.*

[d] The susceptible and resistant accessions were killed at the lowest herbicide dose of 0.28 and 0.22 kg ha^{-1}s of pendimethalin and clomazone, respectively; regression analysis was not conducted.

eters of the log-logistic equations used to estimate GR_{50} values are presented in Tables 1 and 2, respectively. For a given accession and herbicide, the dose-responses varied somewhat between experiments possibly because of seasonal variations in growing conditions, experimental handling, and the natural heterogeneity of field-collected populations. However, accessions responded differentially to the herbicides confirming simultaneous resistance to different herbicides: minimum and maximum resistance ratios (ratio of the GR_{50} values of resistant to susceptible plants, R/S) for *E. phyllopogon* observed in two experiments involving two resistant accessions were 7.8 (ECHPH-R2, experiment one) and > 13.3 (ECHPH-R2, experiment two) for thiobencarb, 2.2 (ECHPH-R1, experiment one) and 4.3 (ECHPH-R2, experiment two) for molinate, and 16.5 (ECHPH-R1, experiment two) and 428.7 (ECHPH-R1, experiment one) for fenoxaprop-ethyl (Table 1). Resistance ratios for propanil were close to 1.0. Resistant accessions of *E. phyllopogon* and *E. oryzoides* responded similarly to thiobencarb and molinate, and on average, resistance to thiobencarb tended to be higher than to molinate (Table 1). Resistant and susceptible *E. oryzoides* accessions were killed by bispyribac-sodium and fenoxaprop-ethyl at rates below the recommended field rates (data not shown), although the resistant type showed a modicum of tolerance to bispyribac-sodium (Table 1).

Resistance to thiobencarb and molinate in *E. phyllopogon* and *E. oryzoides* can be associated with the continuous use of these herbicides for many years in California *O. sativa*. Widespread resistance to thiobencarb has also been found in *E. crus-galli* in China (Huang and Gressel 1997). Although their mode of action is not fully understood (Devine et al. 1993), both molinate and thiobencarb are thiocarbamates that interfere with lipid biosynthesis and perhaps other processes. Thus, cross-resistance, as defined by Heap (1997), to these herbicides could involve a common resistance mechanism. Fenoxaprop, an acetyl-CoA carboxylase (ACCase) inhibitor, was introduced in California *O. sativa* in the early 1990s and is used less frequently than molinate and thiobencarb. However, its use has become more frequent to control grass weeds that emerge late or escape treatment by molinate or thiobencarb. Selection pressure for resistance to fenoxaprop in *E. phyllopogon* accessions (Table 1) could have occurred. Rapid development of resistance to fenoxaprop in *E. colona* has already been found in Central America (Riches et al. 1996).

Resistant *E. phyllopogon* was up to five times more resistant to bispyribac-sodium than the susceptible accession (Table 1), and it tolerated from two to more than four times the 10 g ha^{-1} field rate (data not shown). Bispyribac-sodium is an ALS inhibitor not yet used in California. Thus, resistance in *E. phyllopogon* cannot be attributed to repeated exposure to this herbicide. We suggest that indirect selection pressure for resistance could have resulted from the previous use of bensulfuron, another ALS inhibitor, to control broadleaf weeds and sedges. Bensulfuron has some activity on *E. phyllopogon* and *E. oryzoides*, and has been widely used in California for many years. Resistance to bensulfuron has already developed in several species (Hill et al. 1994).

There was no evidence of propanil resistance in *E. phyllopogon* and *E. oryzoides* (Table 1), which can be attributed to the discontinuous use of this herbicide in California caused by restrictions following drift damage to sensitive crops (Miller 1979). Repeated use of propanil in southern U.S. *O. sativa* and in Central and South America has led to the development of propanil resistance in *Echinochloa* spp. (Fischer et al. 1993; Garita et al. 1995; Smith et al. 1992). Resistance to propanil could also develop in California if propanil continues to be the sole tool for managing herbicide-resistant *E. phyllopogon* and *E. oryzoides* in *O. sativa.*

Both resistant *E. phyllopogon* accessions had similar average GR_{50} values for each herbicide, but ECHPH-R2 tended to have higher GR_{50} values for molinate and bispyribac than ECHPH-R1 (Table 1). Thus, ECHPH-R2 was tested against glyphosate, glufosinate, clomazone, and pendimethalin. ECHPH-R2 and a susceptible *E. phyllopogon* control (ECHPH-S) were killed by these herbicides (Table 1). Some of these herbicides may soon be available for use in *O. sativa* in California where glyphosate and glufosinate can be used in conjunction with transgenic herbicide-resistant *O. sativa* cultivars (Fischer and Hill 1998). The introduction of these herbicides with different modes of action will provide farmers with new options for controlling herbicide-resistant *E. phyllopogon* and also allow for herbicide rotation to delay the buildup of resistance (Gressel and Segel 1982). Pendimethalin is a useful treatment on propanil-resistant *E. crus-galli* in dry-seeded *O. sativa* in Arkansas (Baltazar and Smith 1994). In a long-term experiment started in 1999, a natural population of *E. oryzoides* known to be resistant to molinate, thiobencarb, and fenoxaprop was tested for resistance to glyphosate and glufosinate. Both herbicides, at the commercial rates described in the Materials and Methods section, provided 100% control 42 d after herbicide application (data not shown). Clomazone and pendimethalin were not included in this field experiment because their safe use in water-seeded *O. sativa* has not yet been fully achieved.

Herbicide resistance is not new to *O. sativa* in California where populations of *Sagittaria montevidensis* Cham. & Schlecht. ssp. *calycina* (Engelm.) Bogin, *Ammania coccinea* Rottb., *Scirpus nucronatus* L., and *Cyperus difformis* L. have developed resistance to the ALS-inhibitor bensulfuron (Heap 1997; Hill et al. 1994). We have now established that herbicide resistance is also present in populations of *E. phyllopogon* and *E. oryzoides* involving four different herbicides in three chemical families with different modes of action. The mechanisms of resistance to these herbicides have not yet been studied in the accessions tested, but *E. phyllopogon* populations may have developed multiple resistance through more than one resistance mechanism, as suggested by Heap (1997) for similar cases, following repeated herbicide exposure. A common resistance mechanism such as enhanced degradation may be one possibility. Research on the mechanisms of resistance is needed to establish criteria for herbicide management. Cross- and multiple resistance jeopardize the effectiveness of herbicide rotation for resistance management (Powles et al. 1998). This is particularly serious for California *O. sativa* growers where water-seeding and continuous flooding on poorly drained soils make cultural weed management and crop rotation difficult (Miller 1979). In addition, *E. oryzoides* and *E. phyllopogon* are difficult to suppress by flooding because of their aquatic character, thus requiring a heavy reliance on herbicides. An integrated, long-term approach that directs selection pressure away from herbicides is needed (Powles and Mathews 1992) to eliminate weeds that escape herbicide control. The limited flexibility to implement cultural weed management in *O. sativa* must be overcome with strong measures to prevent seed dispersal and with novel solutions such as the development of competitive cultivars (Fischer et al. 1997) and submergence-tolerant varieties allowing increased water depth for weed suppression.

Sources of Materials

[1] Flat fan nozzle, Spraying Systems Co., North Ave., Wheaton, IL 60180.

[2] Silicon-based surfactant, Osi Specialties, Inc., 777 Old Saw Mill River Road, Tarrytown, NY 10591-6728.

[3] SigmaPlot 4.0 software, Jandel Scientific, P.O. Box 3457, San Rafael, CA 94912-3457.

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