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Distribution of Herbicide-Resistant Johnsongrass (*Sorghum halepense*) in Arkansas

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In 2008, a population of johnsongrass collected from a soybean field near West Memphis, AR, in Crittenden County was confirmed resistant to glyphosate. This was the first documented case of glyphosate-resistant johnsongrass in Arkansas. The purpose of this study was to determine the geographical distribution of glyphosate-resistant johnsongrass in Arkansas crops and screen for resistance to additional herbicides. A total of 141 johnsongrass accessions were collected from 14 counties in Arkansas in the fall of 2008, 2009, and 2010 and screened for resistance to four of the most commonly used POST herbicides for johnsongrass control—imazethapyr, glyphosate, clethodim, and fluazifop. One accession potentially resistant to glyphosate (J12) and another with apparent resistance to imazethapyr (J14) were further evaluated in a dose–response experiment. The lethal dose required to kill 50% of the plants from the putative glyphosate-resistant and imazethapyr-resistant accessions was higher than that of a biotype known to be susceptible to these herbicides. The J12 accession had an LD_{50} of 1,741 g ae ha^{-1} glyphosate, which was 8.5-fold greater than the susceptible biotype. The J14 accession had an LD_{50} of 73 g ai ha^{-1} imazethapyr, which was 3.7-fold greater than the LD_{50} of the susceptible biotype. All other accessions were effectively controlled by the four evaluated herbicides. Widespread herbicide-resistant johnsongrass was not found in Arkansas, although accession J12 was resistant to glyphosate and J14 resistant to imazethapyr.
Nomenclature: Clethodim; fluazifop; glyphosate; imazethapyr; johnsongrass, *Sorghum halepense* (L.) Pers.; soybean, *Glycine max* (L.) Merr.
Key words: Glyphosate resistance, mortality, weed control.

En 2008, se confirmó que una población de *Sorghum halepense* proveniente de un campo de soya cerca de Memphis Oeste, AR, en el condado Crittenden, era resistente a glyphosate. Este fue el primer caso documentado de *S. halepense* resistente a glyphosate en Arkansas. El objetivo de este estudio fue determinar la distribución geográfica de *S. halepense* resistente a glyphosate en cultivos en Arkansas y evaluar la resistencia a otros herbicidas. Un total de 141 accesiones de *S. halepense* fueron colectadas en 14 condados en Arkansas en el otoño de 2008, 2009, y 2010 y fueron evaluadas por resistencia a cuatro de los herbicidas POST más comunes usados para el control de *S. halepense*: imazethapyr, glyphosate, clethodim, y fluazifop. Una accesión potencialmente resistente a glyphosate (J12) y otra con resistencia aparente a imazethapyr (J14) fueron evaluadas en más detalle en un experimento de respuesta a dosis. La dosis letal para matar 50% de las plantas (LD_{50}) de las accesiones con resistencia putativa a glyphosate e imazethapyr fue mayor que la de un biotipo con susceptibilidad conocida a estos herbicidas. La accesión J12 tuvo una LD_{50} de 1,741 g ae ha^{-1} de glyphosate, la cual fue 8.5 veces mayor que la del biotipo susceptible. La accesión J14 tuvo una LD_{50} de 73 g ai ha^{-1} de imazethapyr, la cual fue 3.7 veces mayor que la LD_{50} del biotipo susceptible. Todas las otras accesiones fueron controladas efectivamente por los cuatro herbicidas evaluados. No se encontró que *S. halepense* resistente a herbicidas esté ampliamente distribuido en Arkansas, aunque la accesión J12 fue resistente a glyphosate y la J14 fue resistente a imazethapyr.

Repeated use of acetyl coenzyme A carboxlyase (ACCase) inhibitors (group 1), acetolactate synthase (ALS) inhibitors (group 2), and dinotroanaline (group 3) herbicides has resulted in evolved resistances to each of these mechanisms of action (MOAs) by johnsongrass (Burke et al. 2006; Heap 2013; Smeda et al. 1997). However, as reports of johnsongrass biotypes resistant to ACCase- and ALS-inhibiting herbicides became more common, a new technology was introduced that would revolutionize weed management in row crops. Glyphosate-resistant (GR) soybean was commercialized in 1996 and was soon followed by the release of GR corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and canola (*Brassica napus* L.) (Dill 2005). This new technology was rapidly adopted by soybean growers,

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Table 1. Johnsongrass accessions listed by county, crop, and global positioning system coordinates from which they were collected.

Accession	County	Crop	Latitude °N	Longitude °W
J1	Arkansas	Soybean	33.408	91.316
J2	Chicot	Soybean	33.347	91.294
J3	Chicot	Soybean	33.304	91.287
J4	Chicot	Soybean	33.313	91.291
J5	Chicot	Soybean	33.340	91.291
J6	Chicot	Corn	33.394	91.311
J7	Chicot	Soybean	33.444	91.331
J8	Chicot	Soybean	33.35	91.376
J9	Crittenden	Soybean	35.229	90.398
J10	Crittenden	Soybean	35.195	90.397
J11	Crittenden	Soybean	35.206	90.353
J12	Crittenden	Soybean	35.198	90.121
J13	Crittenden	Soybean	35.204	90.116
J14	Crittenden	Soybean	35.218	90.113
J15	Crittenden	Soybean	35.240	90.116
J16	Crittenden	Soybean	35.243	90.127
J17	Crittenden	Soybean	35.245	90.136
J18	Crittenden	Soybean	35.247	90.176
J19	Crittenden	Soybean	35.286	90.226
J20	Crittenden	Soybean	35.295	90.218
J21	Crittenden	Soybean	35.295	90.212
J22	Crittenden	Soybean	35.293	90.229
J23	Crittenden	Soybean	35.310	90.169
J24	Crittenden	Soybean	35.314	90.182
J25	Crittenden	Soybean	35.306	90.254
J26	Crittenden	Soybean	35.307	90.267
J27	Crittenden	Soybean	35.316	90.377
J28	Crittenden	Soybean	35.379	90.249
J29	Crittenden	Soybean	35.380	90.243
J30	Crittenden	Soybean	35.349	90.181
J31	Crittenden	Soybean	35.328	90.182
J32	Crittenden	Soybean	35.265	90.201
J33	Crittenden	Soybean	35.263	90.264
J34	Crittenden	Soybean	35.263	90.271
J35	Crittenden	Soybean	35.264	90.319
J36	Crittenden	Soybean	35.102	90.195
J37	Crittenden	Soybean	35.091	90.203
J38	Crittenden	Soybean	35.090	90.203
J39	Crittenden	Soybean	35.092	90.212
J40	Crittenden	Soybean	35.147	90.395
J41	Crittenden	Soybean	35.147	90.397
J42	Crittenden	Soybean	35.149	90.336
J43	Crittenden	Soybean	35.109	90.229
J44	Crittenden	Soybean	35.081	90.231
J45	Cross	Soybean	35.251	90.955
J46	Cross	Soybean	35.251	90.936
J47	Cross	Soybean	35.275	90.791
J48	Desha	Soybean	33.569	91.383
J49	Desha	Soybean	33.672	91.422
J50	Desha	Soybean	33.842	91.475
J51	Desha	Soybean	33.868	91.480
J52	Desha	Soybean	33.882	91.457
J53	Desha	Soybean	33.896	91.420
J54	Desha	Soybean	34.103	91.014
J55	Jackson	Soybean	35.571	91.250
J56	Jackson	Soybean	35.575	91.248
J57	Lee	Soybean	34.895	90.791
J58	Lee	Cotton	34.835	90.797
J59	Lee	Soybean	34.730	90.769
J60	Lee	Cotton	34.657	90.770
J61	Lee	Soybean	34.657	90.743
J62	Lee	Soybean	34.657	90.833
J63	Lee	Soybean	34.658	90.882
J64	Lee	Soybean	34.774	90.872
J65	Lee	Soybean	34.685	90.736
J66	Lee	Soybean	34.811	90.673
J67	Lee	Cotton	34.833	90.645
J68	Lonoke	Soybean	34.600	90.706
J69	Lonoke	Soybean	34.762	91.853
J70	Mississippi	Soybean	35.466	90.170
J71	Mississippi	Soybean	35.740	90.144
J72	Mississippi	Soybean	35.512	90.089
J73	Mississippi	Soybean	35.516	90.089
J74	Mississippi	Soybean	35.523	90.089
J75	Mississippi	Soybean	35.590	90.071
J76	Mississippi	Soybean	35.573	90.053
J77	Mississippi	Soybean	35.631	89.949
J78	Mississippi	Soybean	35.791	90.073
J79	Mississippi	Soybean	35.788	90.073
J80	Mississippi	Soybean	35.776	90.074
J81	Mississippi	Grain sorghum	35.771	90.073
J82	Mississippi	Soybean	35.771	90.079
J83	Mississippi	Soybean	35.573	90.213
J84	Mississippi	Soybean	35.568	90.216
J85	Mississippi	Soybean	35.554	90.249
J86	Mississippi	Soybean	35.484	90.251
J87	Mississippi	Soybean	35.483	90.251
J88	Mississippi	Soybean	35.481	90.223
J89	Mississippi	Soybean	35.466	90.202
J90	Mississippi	Soybean	35.464	90.199
J91	Mississippi	Soybean	35.465	90.199
J92	Mississippi	Soybean	35.465	90.128
J93	Mississippi	Soybean	35.465	90.137
J94	Mississippi	Soybean	35.462	90.129
J95	Mississippi	Soybean	35.461	90.129
J96	Mississippi	Soybean	35.487	90.077
J97	Mississippi	Soybean	35.488	90.079
J98	Mississippi	Soybean	35.560	91.039
J99	Mississippi	Soybean	35.563	91.180
J100	Monroe	Soybean	34.765	91.197
J101	Monroe	Soybean	34.766	91.226
J102	Monroe	Soybean	34.447	91.049
J103	Phillips	Soybean	34.553	90.641
J104	Phillips	Soybean	34.627	90.675
J105	Phillips	Soybean	34.583	90.692
J106	Phillips	Soybean	34.564	90.658
J107	Phillips	Soybean	34.570	90.820

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Table 1. Continued.

Accession	County	Crop	Latitude °N	Longitude °W
J108	Phillips	Soybean	34.452	90.776
J109	Phillips	Soybean	34.549	91.017
J110	Phillips	Soybean	34.601	91.032
J111	Phillips	Soybean	34.584	90.712
J112	Phillips	Soybean	34.492	90.695
J113	Phillips	Soybean	34.434	90.632
J114	Phillips	Soybean	34.416	90.666
J115	Phillips	Corn	34.493	90.648
J116	Phillips	Soybean	34.592	90.812
J117	Phillips	Soybean	34.550	90.803
J118	Phillips	Soybean	34.515	90.649
J119	Phillips	Soybean	34.435	90.726
J120	Phillips	Soybean	34.415	90.765
J121	Phillips	Soybean	34.438	90.785
J122	Phillips	Cotton	34.555	90.778
J123	Phillips	Soybean	34.273	90.973
J124	Phillips	Soybean	34.341	90.882
J125	Phillips	Soybean	34.386	90.842
J126	Phillips	Soybean	34.128	91.009
J127	Poinsett	Soybean	35.449	90.742
J128	Poinsett	Soybean	35.543	90.721
J129	Prairie	Soybean	34.845	91.423
J130	Prairie	Soybean	34.813	91.417
J131	St. Francis	Soybean	35.128	90.507
J132	St. Francis	Soybean	35.135	90.467
J133	St. Francis	Soybean	35.130	90.468
J134	St. Francis	Soybean	35.114	90.557
J135	St. Francis	Soybean	35.108	90.575
J136	St. Francis	Soybean	34.935	90.501
J137	St. Francis	Soybean	34.945	90.488
J138	St. Francis	Soybean	34.984	90.429
J139	St. Francis	Soybean	35.046	90.401
J140	St. Francis	Soybean	35.000	90.818
J141	St. Francis	Soybean	34.944	90.790

specifically in the United States and Argentina, where GR cultivars currently represent greater than 90% of the planted soybean acreage (Duke and Powles 2009). The weed management difficulties that growers had grown accustomed to before commercialization of GR crops were resolved by the in-crop use of glyphosate in soybean (Johnson et al. 2013). Extensive use of glyphosate-based weed control programs and a lack of diversity in weed management programs eventually led to the evolution of glyphosate resistance. Since the commercialization of GR crops, weed species have evolved resistance to glyphosate at an alarming rate. Currently, 24 weed species with evolved GR exist in 19 countries, including 14 species in the United States (Heap 2013).

Johnsongrass has long been considered one of the most competitive and troublesome weeds in crop production (Buchanan 1974; Elmore 1983; Webster and Coble 1997); albeit, in a recent survey, johnsongrass was listed as only the 18th most troublesome weed of soybean in the southern United States (Webster and Nichols 2012). This drastic reduction in importance can be attributed to the widespread adoption of GR crops and the efficacy of glyphosate on this weed (Webster and Nichols 2012). Most recently, the concern over this once troublesome and difficult-to-control weed has been brought to the forefront because of evolved GR (Norsworthy et al. 2008; Vila-Aiub et al. 2007). In 2005, the first incidence of GR johnsongrass occurred in the Salta Province of Argentina, when erratic control of johnsongrass with glyphosate was observed in soybean fields and fallowed ground. Further evaluation revealed that the glyphosate dose required to kill 50% of the suspected GR population was 3.5- to 10.5-fold that of a known susceptible biotype (Vila-Aiub et al. 2007). In the fall of 2007, glyphosate failed to control a population of johnsongrass effectively in a soybean field near West Memphis, AR, where glyphosate had been solely relied upon for weed control for several years (Norsworthy et al. 2008; Riar et al. 2011). This was the first confirmed case of GR johnsongrass in the United States, but confirmations in neighboring states (Mississippi 2008 and Louisiana 2010) soon followed (Heap 2013).

With resistance confirmed in johnsongrass to glyphosate and ACCase- and ALS-inhibiting herbicides in Arkansas and surrounding states (Burke et al. 2006; Heap 2013; Smeda et al. 1997), it was suspected that additional accessions of herbicide-resistant johnsongrass might exist in Arkansas. However, the extent to which johnsongrass resistant to glyphosate and ACCase- and ALS-inhibiting herbicides occur in Arkansas is unknown. The objective of this research was to determine the geographical distribution of herbicide-resistant johnsongrass in Arkansas crops.

Materials and Methods

Collection and Plant Materials. Johnsongrass panicles were collected from 141 agricultural fields in 14 Arkansas counties in the fall of 2008, 2009, and 2010 (Table 1; Figure 1). The number of panicles collected was dependent on the number of plants present in a field. For instance, some fields had as few as a single clump of johnsongrass from which approximately five panicles were collected. For fields having a dense population of johnsongrass, as many as 30 to 40 panicles were collected.

A handheld global positioning system was used to record the coordinates for each sampling site. Accessions (samples) were designated as J (johnsongrass) and given a number value (1–141) (Bond et al. 2006; Norsworthy et al. 2008; Wise et al. 2009). Sites were chosen based solely on johnsongrass presence at the time of sampling in the early fall. It was not known at the time of collection what herbicides the plants had been exposed to, whether plants were present when herbicide applications occurred, or whether emergence occurred after the last herbicide application. After a 7-d drying period in a greenhouse (32/22 C day/night temperatures), seed were threshed from the panicles and combined into a single composite sample for each accession. Seed samples for accessions were stored at room temperature for approximately 4 mo to overcome seed dormancy (Harrington 1916; Taylorson and Brown 1977). Seed from each accession along with a known susceptible biotype (Azlin Seed Company, 112 Lilac Drive, Leland, MS 38756) were sown in 10-cm-diam pots containing a commercial potting media (professional growing mix, LC1 Mix, Sun Gro Horticultural Distribution Inc., Bellevue, WA 98008). After seeding, pots were placed in a greenhouse under conditions of 32/22 ± 3 C day/night temperatures with a 16-h photoperiod consisting of natural light supplemented by a metal halide lighting system. All pots were irrigated as needed on a daily basis and fertilized weekly to ensure good plant growth.

The experiment was conducted in a randomized complete block design with four replications per treatment and five plants per replication for a total of 20 plants per treatment. Herbicide treatments were applied to two- to three-leaf seedling johnsongrass plants that were approximately 8- to 12-cm tall. Herbicide treatments consisted of four of the most commonly used herbicides for johnsongrass control, which represents three herbicide MOAs. A nontreated control from each accession was also included. Johnsongrass accessions were screened for resistance to glyphosate at 420 g ae ha^{-1} (Weed Science Society of America [WSSA] group 9), imazethapyr at 70 g ai ha^{-1} (WSSA group 2), and clethodim and fluazifop at 68 and 210 g ai ha^{-1} (WSSA group 1). Imazethapyr was chosen over other ALS-inhibiting herbicides because of the overwhelming number of samples recovered from soybean fields and the widespread use of imazethapyr in soybean weed control programs before commercialization of GR soybean. Applications of clethodim and fluazifop included a crop oil concentrate (Agri-Dex, Helena Chemical Co., West Helena, AR 72390) at 1% (v/v), and imazethapyr included a nonionic surfactant (NIS) (Induce, Helena Chemical Co., West Helena, AR 72390) at 0.25% (v/v), as suggested by their respective product labels. Treatments were applied inside of a stationary spray chamber with a boom containing two flat-fan 800067 nozzles (Teejet Technologies, Springfield, IL 62703) calibrated to deliver 187 L ha^{-1} at 276 kPA. After treatments were applied, pots were returned to the greenhouse.

Visual estimates of johnsongrass control were taken 14 and 21 d after treatment (DAT). Johnsongrass control was evaluated by comparing treated plants to the nontreated control for each accession. Control was assessed on a scale of 0 (no control) to 100% (complete plant mortality). Biomass of living plants was harvested immediately after the 21 DAT control evaluation. Plant shoots were clipped at the soil surface and oven-dried at 66 C for 7 d, and dry weights were determined for surviving plants. For each johnsongrass accession, dry weights of treated plants were converted to a percent dry weight reduction relative to the nontreated control for each accession.

Visual estimates of johnsongrass control and percent dry weight reduction data were subjected to ANOVA using PROC GLM in SAS (SAS, version 9.3, SAS Institute Inc., P.O. Box 8000, Cary, NC 25712). Means were separated using Tukey's honest significant difference (HSD) at a 5% level of significance. The principal objective of the experiment was to compare the response of accessions to each herbicide treatment. Therefore, accession was considered as a fixed effect, and replication was analyzed as a random effect. Accessions having 100% control or biomass reduction across all replications were excluded from the analysis.

Dose Response. Results of the initial screening experiment revealed that the J12 accession exhibited

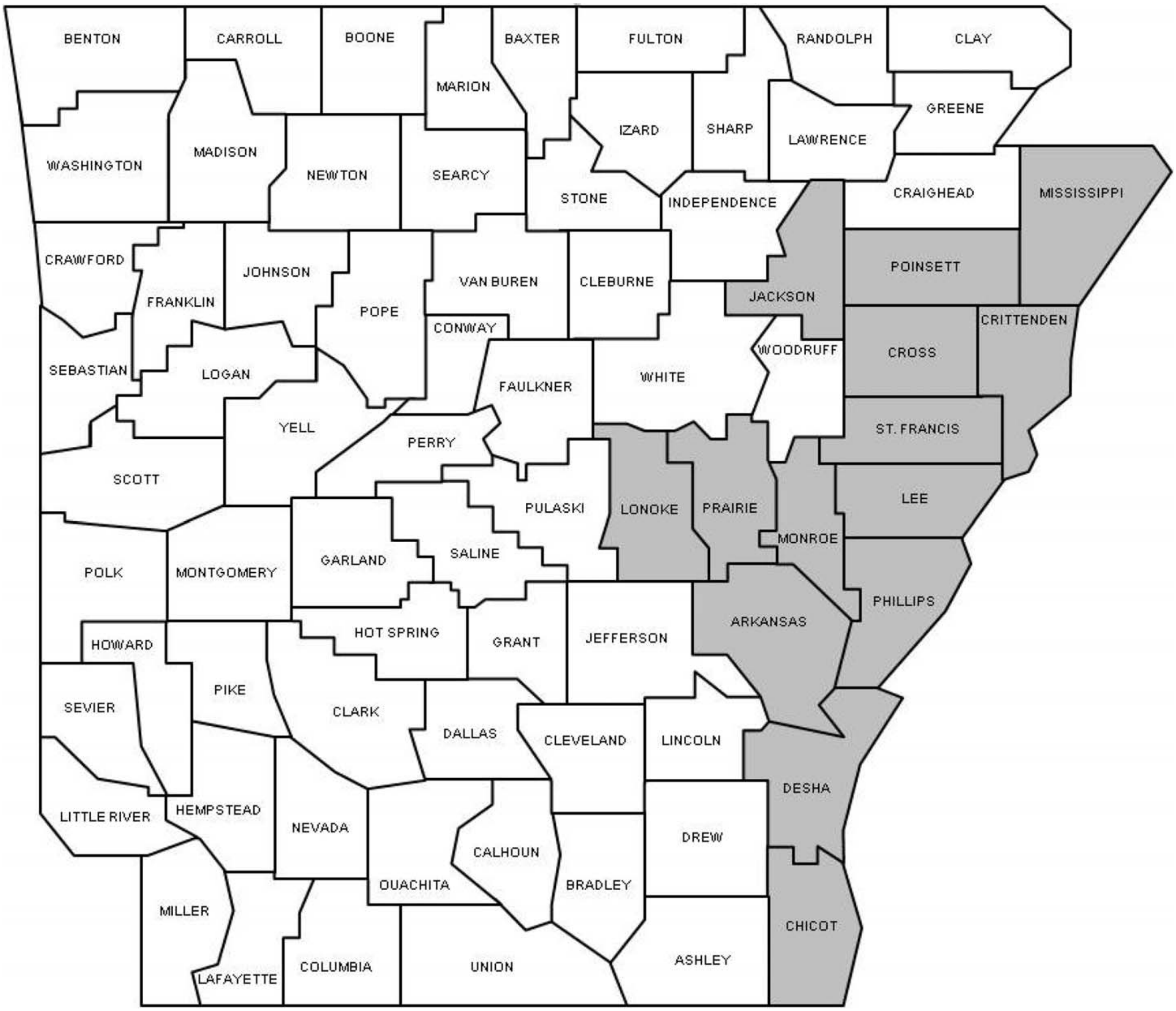

Figure 1. A total of 141 Johnsongrass accessions were collected from 14 Arkansas counties (counties shaded in gray) in the Mississippi River Delta.

potential resistance to glyphosate, and the J14 accession also appeared to have reduced sensitivity to imazethapyr compared with the susceptible standard. A rate titration experiment was established to further evaluate the response of the J12 accession to glyphosate and the J14 accession to imazethapyr. Seeds from each accession and a susceptible biotype were sown in separate 45- by 60-cm trays. At the cotyledon to one-leaf stage, johnsongrass seedlings from each biotype were transplanted into 10-cm-diam pots containing potting mix. After transplanting, plants were returned to a greenhouse under the same environmental conditions as described in the previous experiment.

Seedlings of the susceptible biotype were treated with nine rates of MON 78623 (potassium salt of glyphosate), ranging from 7 to 1,680 g ae ha^{-1}. The rate range corresponds to 1/128 to 2 times the recommended glyphosate rate of 840 g ha^{-1}. For the J12 accession, three additional rates of 3,360, 6,720, and 13,440 g ha^{-1} were also added. In the imazethapyr dose–response study, the susceptible biotype was exposed to rates ranging from 0.5 to 140 g ha^{-1}, which corresponds to 1/128 to 2 times

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the recommended rate of 70 g ha^{-1}. Three additional rates of 280, 560, and 1,120 g ha^{-1} were included for the J14 accession. Applications of MON 78623 and imazethapyr contained NIS at 0.25% (v/v). Treatments were applied once seedlings had reached the two- to three-leaf stage (8 to 12 cm tall). Spray applications were made at 187 L ha^{-1} in a stationary spray chamber with a boom containing two flat fan 800067 spray nozzles. Upon completion of all treatments, plants were returned to the greenhouse. The experiment was arranged in a completely random design with 20 replications $biotype^{-1}$ $herbicide^{-1}$ dose, and the experiment was repeated. Plant survival (live or dead) counts were taken 21 DAT. A plant was considered to be alive if at least one green leaf was present. Plant mortality data were subjected to probit analysis using JMP (Version 10, SAS Institute Inc.) to determine the LD_{50} from each biotype along with 95% confidence intervals. Means for the LD_{50} were separated using a chi-square probability test ($P = 0.05$).

Results and Discussion

Johnsongrass Screening. Overall, the herbicides evaluated in this experiment were generally effective for controlling the accessions tested. At 21 DAT, average johnsongrass control across accessions was 97% for glyphosate, 95% for imazethapyr, and 99% for both fluazifop and clethodim. These herbicides yielded 100% control of most accessions evaluated. However, control across accessions varied for each herbicide; therefore, only data for accessions that were not completely controlled 21 DAT are presented. Additionally, these were the only treatments included in the analysis.

Glyphosate. Glyphosate at 420 g ha^{-1}, one-half of the registered field use rate of 840 g ha^{-1}, completely controlled 95 of the 141 accessions tested (Table 2). The 46 accessions that were not completely controlled varied in response to glyphosate. Visual estimates of control of all accessions ranged from 85 to 99%, and all but six accessions were controlled 90% through 21 DAT (Table 2). Shaw and Arnold (2002) reported greater than 93% control of seedling johnsongrass with glyphosate at 280 to 1,120 g ha^{-1}. However, glyphosate did not effectively control the J12 accession. At 21 DAT, glyphosate resulted in only 20% control of the J12

Table 2. Response and percent dry weight reductions of 46 johnsongrass accessions 21 d after a POST application of glyphosate at 420 g ae ha^{-1}.[a]

Accession[b]	Control	Dry weight reduction
	% of nontreated	
J1	95	96
J4	96	97
J9	97	97
J10	98	98
J11	94	95
J12	20	47
J13	94	96
J14	93	92
J17	99	98
J20	97	96
J21	96	95
J23	99	99
J24	97	98
J28	97	96
J36	96	95
J40	99	98
J41	96	95
J43	98	96
J49	98	98
J50	96	95
J53	91	90
J62	98	98
J68	86	90
J70	95	94
J72	95	96
J74	98	98
J76	92	97
J78	88	88
J79	89	89
J80	91	91
J82	99	99
J83	96	94
J84	99	99
J85	92	93
J86	98	97
J90	90	93
J93	86	88
J95	95	95
J98	99	98
J106	85	86
J109	92	90
J114	98	98
J117	96	94
J120	93	92
J127	97	98
J141	91	93
HSD[c]	12	11

[a] Herbicide applied to two- to three-leaf seedling johnsongrass.

[b] A total of 141 accessions were evaluated (J1–J141). Accessions that were completely controlled (100% mortality) are not presented and were excluded from the analysis.

[c] Tukey–Kramer honest significant difference (HSD) means separation within column ($P < 0.05$).

Table 3. Response and percent dry weight reductions of 67 johnsongrass accessions 21 d after a POST application of imazethapyr at 70 g ai ha^{-1}.[a]

Accession[b]	Control	Dry weight reduction
	% of nontreated	
J1	90	92
J3	97	96
J5	90	92
J9	94	95
J10	92	92
J11	87	92
J12	87	89
J13	94	93
J14	64	14
J17	83	89
J19	97	97
J20	89	89
J21	94	94
J22	94	93
J23	93	94
J24	91	93
J28	90	91
J29	92	95
J31	93	91
J32	92	94
J33	90	90
J36	88	88
J38	97	97
J40	96	92
J41	89	92
J43	90	88
J46	98	97
J47	91	91
J50	86	90
J54	98	96
J56	97	97
J61	91	92
J62	94	94
J65	95	94
J66	90	92
J68	81	87
J70	89	91
J72	84	90
J76	87	89
J78	87	89
J79	87	89
J83	94	92
J85	88	89
J87	85	89
J88	86	88
J89	81	82
J90	83	88
J95	89	91
J98	94	93
J103	83	86
J106	84	88
J107	89	90
J109	84	89
J111	88	89
J115	94	94
J117	90	91
J120	84	87
J121	93	93
J123	83	85
J124	88	87
J125	95	93
J126	96	96
J127	96	94
J131	91	91
J136	92	93
J137	98	98
J138	97	96
HSD[c]	12	11

[a] Herbicide applied to two- to three-leaf seedling johnsongrass.

[b] A total of 141 accessions were evaluated (J1–J141). Accessions that were completely controlled (100% mortality) are not presented and were excluded from the analysis.

[c] Tukey–Kramer honest significant difference (HSD) means separation within column ($P < 0.05$).

accession, the lowest level of control of all accessions evaluated.

Dry weight reduction across accessions was similar to visual estimates of weed control observed for each accession. Much like control estimates, the lowest level of biomass reduction was observed with the J12 accession (Table 2). Applications of glyphosate at 420 g ha^{-1} reduced dry matter production of the J12 accession 47% when compared with the nontreated 21 DAT. Minimal differences in dry weight reduction existed among other accessions, with biomass reduced at least 86%.

Imazethapyr. Of the four herbicides evaluated, imazethapyr was the least effective and most inconsistent. Imazethapyr at the highest application rate (70 g ha^{-1}) provided complete control of 52% of the accessions evaluated. Response was variable among accessions for which imazethapyr failed to provide complete control 21 DAT (Table 3). Accession J14 exhibited the least sensitivity to imazethapyr compared with all other accessions, resulting in 64% control 21 DAT. Excluding J14, greater than 90% control was achieved for 39 accessions, whereas the remaining 28 accessions were controlled 81 to 89%.

In Mississippi, Riley and Shaw (1989) reported no greater than 50% control of 8- to 12-leaf

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Table 4. Response and percent dry weight reduction of 10 johnsongrass accessions 21 d after a POST application of clethodim at 68 g ai ha^{-1}.[a]

Accession[b]	Control	Dry weight reduction
	%	
J17	90	91
J24	94	92
J49	91	96
J54	95	91
J61	91	92
J65	93	93
J102	90	91
J103	95	95
J126	91	92
J140	89	88
HSD[c]	NS	6

[a] Herbicide applied to two- to three-leaf seedling johnsongrass.

[b] A total of 141 accessions were evaluated (J1–J141). Accessions that were completely controlled (100% mortality) are not presented and were excluded from the analysis.

[c] Tukey–Kramer honest significant difference (HSD) means separation within column ($P < 0.05$).

rhizome johnsongrass with imazethpyr applied at 70 and 105 g ha^{-1}. In a separate field study, Shaw et al. (1990) reported less than 75% control of 15- to 60-cm rhizome johnsongrass with imazethapyr applied at 70 g ha^{-1}. In this experiment, imazethapyr was evaluated for control of seedling johnsongrass, hence the increased control. Furthermore, the johnsongrass in the above-mentioned research was larger at application than the plants treated in this research, hence the lower control observed. Efficacy of foliar herbicides has previously been reported to vary between seedling and rhizomatous johnsongrass plants, with control of seedlings often greater (Rosales-Robles et al. 1999). Inadequate translocation of herbicides allows the rhizomes to survive and regrow after applications of most POST-applied herbicides (Kells and Rieck 1979; Sprankle et al. 1975).

Dry weight reduction among accessions deviated only slightly from the levels of control observed for each accession. Twenty-one d after application, imazethapyr rendered only 14% dry matter reduction of accession J14 (Table 3). Dry weight reduction among other accessions ranged from 82 to 97%.

Clethodim. The johnsongrass accessions evaluated in this experiment were highly responsive to clethodim at 68 g ha^{-1}. Across accessions, clethodim was the most consistent and efficacious herbicide, completely controlling 131 of the 141 accessions. No differences in control were observed among accessions, with at least 89% control of all accessions achieved (Table 4). The results of this experiment are similar to those of previous research, in which it was concluded that clethodim, applied across a range of rates and johnsongrass sizes, is an effective johnsongrass control option (Bridges 1989; Jordan et al. 1996; Rosales-Robles et al. 1999).

The efficacy of clethodim on all accessions in this experiment also resulted in effective dry weight reduction compared with that of the nontreated control. Percentage dry weight reduction among accessions ranged from 88 to 96%. With the exception of accession J140, no differences could be detected for dry weight reduction among the other accessions evaluated.

Fluazifop. Fluazifop was second to clethodim in providing the most consistent and effective control of johnsongrass across accessions. Fluazifop at 210 g ha^{-1}, the registered field use rate, provided complete (100%) control of 121 of the 141 accessions. Control of the accessions in which complete control was not obtained ranged from 83 to 97% (Table 5). Of the accessions not completely controlled, fluazifop achieved at least 90% control of all but five accessions. Control of J92 was significantly lower 21 DAT than accessions that were controlled greater than 93%, which was exactly half of the accessions (Table 5). Accession J92 was less responsive to fluazifop than most accessions evaluated, including the susceptible standard. Therefore, it is hypothesized that this accession may have a low level of resistance to fluazifop. However, because of a shortage of seed, this accession was unable to be subjected to any further evaluation to test our hypothesis.

Bridges and Chandler (1987) observed johnsongrass control of 95 and 83% over a 2-year period with fluazifop, and in two separate studies conducted by Banks and Bundschuh (1989) and Brewster and Spinney (1989), greater than 90% johnsongrass control was reported with fluazifop. The results of this experiment were also similar to that observed by Shaw et al. (1990), who reported johnsongrass control ranged from 83 to 90% when fluazifop was applied to 15- to 60-cm-tall plants.

Dry weight reduction for all accessions after an application of fluazifop was at least 87% 21 DAT

Table 5. Response and percent dry weight reduction for 20 johnsongrass accessions 21 d after a POST application of fluazifop at 210 g ai ha^{-1}.[a]

Accession[b]	Control	Dry weight reduction
	%	
J13	94	94
J14	96	95
J16	86	91
J19	97	95
J24	95	94
J36	91	91
J41	90	91
J46	97	93
J49	93	93
J54	92	88
J61	93	93
J68	95	96
J89	85	87
J92	83	87
J93	87	91
J109	90	93
J117	91	91
J123	96	94
J126	88	89
J130	94	91
HSD[c]	9	6

[a] Herbicide applied to two- to three-leaf seedling johnsongrass.

[b] A total of 141 accessions were evaluated (J1–J141). Accessions that were completely controlled (100% mortality) are not presented and were excluded from the analysis.

[c] Tukey–Kramer honest significant difference (HSD) means separation within column ($P < 0.05$).

(Table 5). However, with the exception of accessions J54, J89, J92, and J126, dry weight reduction of all accessions was at least 91%.

J12 Dose Response. The probability of death for increasing doses of glyphosate for the J12 accession and susceptible biotype are shown in Figure 2. A glyphosate dose of 205 g ha^{-1} was needed to kill 50% of the susceptible plants. The LD_{50} value for the susceptible plants is less than one-quarter times the registered field use rate for glyphosate. The LD_{95} values indicate that 95% mortality of the susceptible biotype is achieved at 363 g ha^{-1}, which is less than one-half times the recommended field rate for weed control in cotton, corn, and soybean (Anonymous 2013a). Mortality of all susceptible plants was achieved with less than the registered field use rate of 840 g ha^{-1}.

The LD_{50} value of glyphosate for the putative resistant J12 accession was 1,741 g ha^{-1}, an 8.5-fold increase in glyphosate dose compared with the susceptible biotype (Figure 2; Table 6). To achieve 95% mortality of the J12 accession, glyphosate would have to be applied at 4,069 g ha^{-1}, which is an 11-fold increase over the susceptible biotype (Table 6), and five times the labeled field use rate of 840 g ha^{-1}. Complete control of all treated plants of the J12 accession was accomplished at a glyphosate rate six times the labeled use rate; hence, it is concluded that the J12 accession exhibits resistance to glyphosate. Interestingly, the J12 accession was collected in Crittenden County approximately 12 km north of where the first glyphosate-resistant

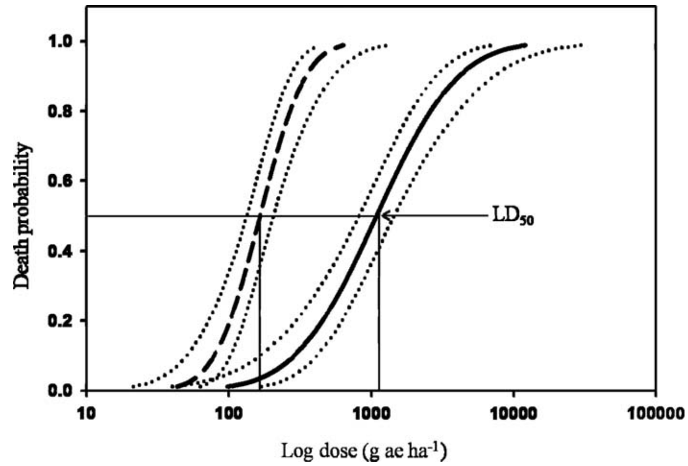

Figure 2. Probit analysis ($y = a + bX + e$) with 95% confidence intervals (dotted lines) to predict the lethal dose (dashed line = susceptible, solid line = J12 accession) of glyphosate needed to kill the susceptible biotype and the J12 accession.

Table 6. Dose needed to kill 50% of accessions J12 (glyphosate) and J14 (imazethapyr) compared with a susceptible standard.

Accession	LD_{50}	LD_{95}
Glyphosate[a,b]	g ae ha^{-1}	
J12	1,741 a	4,069 a
Susceptible	205 b	363 b
R/S ratio[c]	8.5	11.2
Imazethapyr[a,b]	g ai ha^{-1}	
J14	73 a	282 a
Susceptible	20 b	36 b
R/S ratio[c]	3.7	7.8

[a] LD_{50} and LD_{95} doses within a column followed by different lowercase letters are statistically different at $P \leq 0.05$.

[b] LD_{50} and LD_{95} values were determined by probit analysis in JMP.

[c] R/S ratio was calculated by dividing the LD_{50} or LD_{95} of the resistant biotype by the LD_{50} or LD_{95} of the susceptible biotype.

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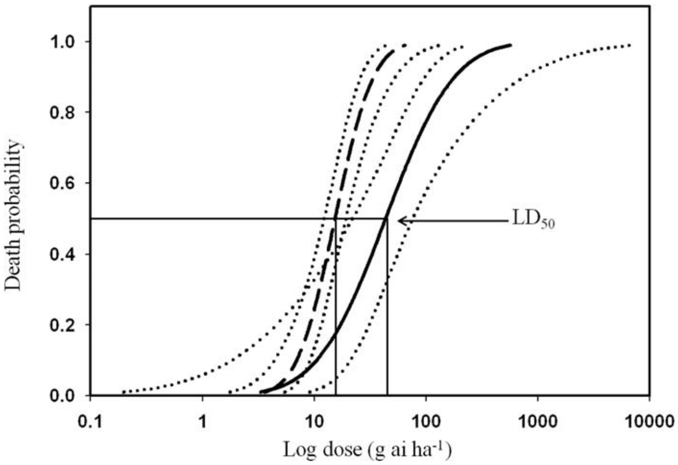

Figure 3. Probit analysis ($y = a + bX + e$) with 95% confidence intervals (dotted lines) to predict the lethal dose (dashed line = susceptible, solid line = J14 accession) of imazethapyr needed to kill the susceptible biotype and the J14 accession.

johnsongrass population was confirmed in Arkansas (Norsworthy et al. 2008).

J14 Dose Response. The probability of death for progressing doses of imazethapyr is displayed in Figure 3. The LD_{50} value for imazethapyr for the susceptible biotype was 20 g ha^{-1}, which is approximately one-quarter times the recommended field use rate of 70 g ha^{-1}(Anonymous 2013b). For the susceptible biotype, greater than 95% mortality was achieved at 36 g ha^{-1}, which is approximately one-half of the recommended field-use rate. Based on the dose–response curve for the susceptible biotype, 99% mortality was predicted at 43 g ha^{-1}.

For the J14 accession, the LD_{50} value was 73 g ha^{-1}, equivalent to a 3.7-fold reduction in sensitivity to imazethapyr compared with the susceptible biotype (Table 6). The LD_{95} value of 282 g ha^{-1} of imazethapyr was a 7.8-fold increase over the susceptible biotype. Based on these differences between biotypes and the inability to achieve effective control of J14 at the recommended field use rate (Figure 2), it is concluded that this accession exhibits resistance to imazethapyr.

With the previous documentation of ALS-resistant johnsongrass in recent decades and the overwhelming dependence on glyphosate for weed control in virtually all U.S. cropping systems, it comes as no surprise that johnsongrass continues to exhibit resistance to the most frequently used herbicides (Riar et al. 2011). With the extensive use of ALS-inhibiting herbicides, not only in soybean but other economically important row crops, the existence of only 1 of 141 accessions exhibiting resistance to this mechanism of action was somewhat surprising. Furthermore, the massive acreage of glyphosate-resistant crops that occurred in response to the commercialization of glyphosate-resistant crop technology in 1996 and exclusive reliance on glyphosate has led to resistance to glyphosate in johnsongrass and numerous other species worldwide (Heap 2013). Herbicide-resistant johnsongrass is not currently widespread in Arkansas, and in general, control can be achieved with glyphosate and ALS- and ACCase-inhibiting herbicides. However, with resistance to glyphosate and the ALS-inhibiting herbicides existing within the state and resistance to the ACCase-inhibiting herbicides existing in neighboring states, appropriate management tactics should be employed to ensure long-term sustainability of these herbicides.

Acknowledgments

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Literature Cited

Anonymous (2013a) Roundup Powermax specimen label. Marysville, CA: Crop Data Management Systems Inc. http://www.cdms.net/LabelsMsds/LMDefault.aspx?pd=8837&t=. Accessed March 21, 2013

Anonymous (2013b) Pursuit specimen label. Marysville, CA: Crop Data Management Systems Inc. http://www.cdms.net/LabelsMsds/LMDefault.aspx?pd=797&t=. Accessed March 21, 2013

Banks PA, Bundschuh SA (1989) Johnsongrass control in conventionally tilled and no-tilled soybean with foliar-applied herbicides. Agron J 81:757–760

Bond JA, Oliver LR, Stepehenson DO IV (2006) Response of Palmer amaranth (*Amaranthus palmeri*) accessions to glyphosate, fomesafen, and pyrothiobac. Weed Technol 20:885–892

Brewster BD, Spinney RL (1989) Control of seedling grasses with postemergence grass herbicides. Weed Technol 3:39–43

Bridges DC (1989) Adjuvant and pH effects on sethoxydim and clethodim activity on rhizome johnsongrass (*Sorghum halepense*). Weed Technol 3:615–620

Bridges DC, Chandler JM (1987) Effect of herbicide and weed height on johnsongrass (*Sorghum halepense*) control and cotton (*Gossypiumhirsutum*) yield. Weed Technol 1:207–211

Buchanan GA (1974) Weed survey: southern states. South Weed Sci Soc Res Rep 27:215–249

Burke IC, Wilcut JW, Crammer J (2006) Cross-resistance of a johnsongrass (*Sorghum halepense*) biotype to aryloxyphenoxypropionate and cyclohexanedione herbicides. Weed Technol 20:571–575

Dill GM (2005) Glyphosate-resistant crops: history, status, and future. Pest Manag Sci 61:219–224

Duke SO, Powles SB (2009) Glyphosate-resistant crops and weeds: now and in the future. Agbioforum 12:346–357

Elmore CD (1983) Weed survey—southern states. South Weed Sci Soc Res Rep 39:136–158

Harrington, GT 1916. Germination and viability test of Johnson grass seed. Proc Assoc Off Seed Anal 9:24–28

Heap I (2013)The International Survey of Herbicide-Resistant Weeds. http://www.weedscience.org. Accessed February 7, 2013

Johnson DB, Norsworthy JK, Bell HD, Schrage BW, Riar DS, Scott B (2013) Herbicide programs for controlling glyphosate-resistant johnsongrass in Liberty Link soybean. Proc South Weed Sci Soc 66: 133

Jordan DL, Vidrine PR, Griffin JL, Reynolds DB (1996) Influence of adjuvants on efficacy of clethodim. Weed Technol 10:738–743

Kells JJ, Rieck CE (1979) Effects of illuminance and time on accumulation of glyphosate in johnsongrass (*Sorghum halepense*). Weed Sci 27:235–237

Norsworthy JK, Scott RC, Estorninos J, Still J, Bangarwa S, Griffith G, Oliver L (2008) Confirmation and control of glyphosate-resistant johnsongrass in Arkansas. Arkansas Crop Prot Assoc 12:18

Riar DS, Norsworthy JK, Johnson DB, Scott RC, Bagavathiannan M (2011) Glyphosate resistance in a johnsongrass (*Sorghum halepense*) biotype from Arkansas. Weed Sci 59:299–304

Riley DG, Shaw DR (1989) Johnsongrass (*Sorghum halepense*) and pitted morningglory (*Ipomoea lacunosa*) control with imazaquin and imazethapyr. Weed Technol 3:95–98

Rosales-Robles E, Chandler JM, Senseman SA, Prostko EP (1999) Influence of growth stage and herbicide rate on postemergence johnsongrass (*Sorghum halepense*) control. Weed Technol 13:525–529

Shaw DR, Arnold JC (2002) Weed control from herbicide combinations with glyphosate. Weed Technol 16:1–6

Shaw DR, Ratnayake S, Smith CA (1990) Effects of herbicide application timing on johnsongrass (*Sorghum halepense*) and pitted morningglory (*Ipomoea lacunosa*) control. Weed Technol 4:900–903

Smeda RJ, Snipes CE, Barrentine WL (1997) Identification of graminicide-resistant johnsongrass (*Sorghum halepense*). Weed Sci 45:132–137

Sprankle P, Meggitt WF, Penner D (1975) Absorption, action, and translocation of glyphosate. Weed Sci 23:235–240

Taylorson RB, Brown MM (1977) Accelerated afterripening for overcoming seed dormancy in grass weeds. Weed Sci 25:473–476

Vila-Aiub MM, Balbi MC, Gundel PE, Ghersa CM, Powles SB (2007) Evolution of glyphosate-resistant johnsongrass (*Sorghum halepense*) in glyphosate-resistant soybean. Weed Sci 55:566–571

Webster TM, Coble HD (1997) Changes in the weed species composition of the southern United States: 1974 to 1995. Weed Technol 11:308–317

Webster TM, Nichols R (2012) Changes in the weed species in the major agronomic crops of the United States: 1994/1995 to 2008/2009. Weed Sci 60:145–157

Wise AM, Grey TL, Prostko EP, Vencill WK, Webster TM (2009) Establishing the geographical distribution and level of acetolactate synthase resistance of Palmer amaranth (*Amaranthus palmeri*) accessions in Georgia. Weed Technol 23:214–220

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