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Short title: Southcentral US Johnsongrass

Sensitivity of Southcentral U.S. Johnsongrass Accessions to Selected Herbicides

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Abstract

New technologies in grain sorghum allow for the use of multiple acetyl CoA carboxylase- (ACCase) or acetolactate synthase- (ALS) inhibiting herbicides for johnsongrass control. With the growing issue of herbicide resistance, producers need to understand which herbicides will successfully control johnsongrass accessions. To determine the efficacy of herbicides recently registered or ones with potential to become available for use in grain sorghum, johnsongrass seeds were collected from 2017 to 2021 in Arkansas, Kansas, Texas, and Oklahoma and were screened for sensitivity to fluazifop, quizalofop, nicosulfuron, and imazamox. Additionally, glyphosate sensitivity was evaluated because of its use before planting or postharvest. Quizalofop resulted in 100% mortality of all johnsongrass accessions. Of the johnsongrass accessions evaluated, 89% were completely controlled with glyphosate. The ALS inhibitors nicosulfuron and imazamox resulted in 100% mortality of all Oklahoma accessions, but failures occurred on samples from other states. One accession from Kansas, 12 from Texas, and eight from Arkansas were found to have reduced sensitivity to nicosulfuron and imazamox. If producers plan to plant grain sorghum in areas with johnsongrass populations, an ACCase-inhibitor herbicide will most likely provide effective control. Imazamox and nicosulfuron, in conjunction with the appropriate trait, can be utilized in areas with sensitive johnsongrass populations or where other sensitive grass species are present.

Nomenclature: Fluazifop; glyphosate; imazamox; nicosulfuron; quizalofop; johnsongrass, *Sorghum halepense* (L.) Pers*;* grain sorghum, *Sorghum bicolor* (L.) Moench

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Introduction

Johnsongrass is one of the most problematic weeds in the world, causing up to 90 % yield loss in crops such as cotton (*Gossypium hirsutum* L.), soybean [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), and grain sorghum (*Sorghum bicolor* (L.) Moench) (Klein and Smith 2020). While the introduction of glyphosate in the 1970s and glyphosate-resistant crops in the 1990s significantly decreased johnsongrass infestations in cotton, corn, and soybean. The genetic similarity between grain sorghum and johnsongrass, which are members of the genus *Sorghum*, makes chemical removal in the absence of a herbicide-resistant trait challenging (Smith and Scott 2010).

Johnsongrass is a spreading perennial grass native to Asia and was brought to the southern United States (US) in the 1800s as a forage crop (Mitch 1987). Johnsongrass has the ability to grow greater than two meters tall and create large quantities of biomass, which was optimal for forage producers but made it detrimental as a weed. Johnsongrass quickly escaped managed cultivation, spreading via seeds and rhizomes. Rhizomes are horizontally growing underground stems from which new plants can develop, and one single johnsongrass plant can produce up to 5,000 rhizomes in one growing season (McWhorter 1971). Rhizomes are often responsible for escapes or herbicide control failures. Herbicides that control aboveground growth must also be able to translocate and control rhizomes below ground, the lack of which can lead to regrowth through the production of new rhizomatous shoots. Therefore, producers must successfully control johnsongrass before rhizome development at the 5-leaf stage (Horowitz 1972).

New herbicide resistance technologies are being researched to help grain sorghum producers better control johnsongrass, allowing producers to utilize either ACCase or ALS inhibitors for grass control in grain sorghum (Pinkerton 2020). Currently, an ACCase inhibitor-resistant technology [developed by S&W seed company (Longmont, CO)] is commercially available in grain sorghum, known as Double Team™, with resistance to quizalofop herbicide (FirstAct™, ADAMA Ltd., Raleigh, NC). The University of Arkansas System Division of Agriculture and Texas A&M AgriLife Research jointly developed TamArk™ grain sorghum from a known johnsongrass population with resistance to quizalofop and fluazifop, with a mutation different from that in Double Team™. The two ALS inhibitor technologies in grain

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sorghum include a genetic line developed by Corteva (Indianapolis, IN) known as Inzen™ with resistance to nicosulfuron and a line developed by Alta seeds (Amarillo, TX) and UPL (King of Prussia, PA) known as igrowth™ with resistance to imazamox (Pinkerton 2020). While lines resistant to glyphosate are unavailable, the herbicide is important for johnsongrass control across the US in fallow areas, before crop planting, and in glyphosate-resistant crops (Brown et al. 1988; Smith and Scott 2010).

Both fluazifop and quizalofop control grasses but not broadleaf plants because the ACCase enzyme is sensitive to these herbicides only in grasses (Focke and Lichtenthaler 1987; Burton et al. 1989; Stoltenberg et al. 1989). Fluazifop and quizalofop have been used for grass control in broadleaf crops such as cotton and soybean. Fluazifop has been shown to control broadleaf signalgrass [*Urochloa platyphylla* (Nash) R.D. Webster], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], goosegrass [*Eleusine indica* (L.) Gaertn], and johnsongrass greater than 90 % (Byrd and York 1987; Clegg 1987). Quizalofop also effectively controlled similar grasses in broadleaf crops (Brewster and Spinney 1989; Sanders et al. 2021). Recently, quizalofop has been utilized for grass control in wheat (*Triticum aestivum* L.) through CoAXium™ wheat production system developed by Colorado Wheat Research Foundation and Albaugh (St. Joseph, MO), in rice (*Oryza sativa* L.) through the Provisia™ technology developed by BASF (Beaumont, TX), and Max-Ace™ technology from Rice Tec (Alvin, TX) (Kumar et al. 2020; Lancaster et al. 2018; Sanders et al. 2021; Tarundeep et al. 2019).

Nicosulfuron and imazamox can control grasses in both broadleaf and grass crops (Dobbels and Kapusta 1993; Geier et al. 2004; Gubbiga et al. 1995; Nelson et al. 1998). Nicosulfuron was used primarily for grass and broadleaf control in corn before the introduction of glyphosate-resistant crops in the mid to late 1990s. Nicosulfuron can control johnsongrass by greater than 90 % in production situations and is also desirable to producers because of the low herbicide use rate (Camacho et al. 1991; Dobbels and Kaptusa 1993). Imazamox became popular through the Clearfield® (BASF, Triangle Park, NC) production system, which has allowed for the use of imazamox and imazethapyr for preemergence and postemergence (POST) applications primarily in wheat, corn, and rice but also other broadleaf and grass crops (Bond and Walker 2011; Jimenez et al. 2015; Larson et al. 2000). Although imazamox was not previously used specifically for johnsongrass control, it has successfully controlled annual grasses such as

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barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], foxtails (*Setaria* spp.), and red rice (*Oryza sativa* L.) (Fish et al. 2016).

While ACCase and ALS inhibitors, as well as glyphosate, have been successful at controlling johnsongrass and other grasses, cases of resistance have been confirmed, threatening the sustainability of these herbicides (Kumar et al. 2023; Riar et al. 2011; Scarabel et al. 2014; Werle et al. 2016). Johnsongrass with resistance to ACCase-inhibiting herbicides was first documented in Mississippi in the 1980s, with biotypes showing less than 35% control when treated with either fluazifop, quizalofop, or sethoxydim (Smeda et al. 1997). In 2007, erratic johnsongrass control was seen in a field of glyphosate-resistant soybean in Arkansas. After further evaluation, the accession was determined to be glyphosate-resistant, with greater than twice the labeled rate of glyphosate required to reach 50% control (Riar et al. 2011). In 2016, a study was conducted across Nebraska and Kansas to document ALS-resistant johnsongrass accessions. A total of eight resistant accessions were found out of 59 johnsongrass accessions evaluated, three being resistant to nicosulfuron and five being resistant to imazethapyr, an imidazolinone herbicide (Werle et al. 2016). A survey of roadside johnsongrass accessions was conducted in Arkansas in 2014, and accessions resistant to glyphosate, fluazifop, and nicosulfuron were reported (Bagavathiannan and Norsworthy 2014). Considering that glyphosate is widely used to control johnsongrass in glyphosate-resistant crops and before crop planting and the use of ACCase- and ALS-inhibiting herbicides will likely increase in grain sorghum as new trait technologies are commercialized, a survey to determine the response of johnsongrass accessions collected from Arkansas, Texas, Oklahoma, and Kansas to glyphosate, quizalofop, fluazifop, nicosulfuron, and imazamox was conducted.

Materials and Methods

The herbicide resistance evaluations presented in this study were conducted in two locations: the University of Arkansas, Fayetteville, AR (*hereafter* AR), and Texas A&M University, College Station, TX (*hereafter* TX). The resistance screenings were conducted under greenhouse conditions using standard protocols in both locations.

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Resistance screenings at AR

The greenhouse study was conducted twice at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR. This completely randomized design evaluated five herbicides (fluazifop, quizalofop, nicosulfuron, imazamox, and glyphosate) on johnsongrass samples collected from Arkansas, Kansas, Oklahoma, and Texas. In the fall of 2020 and 2021, johnsongrass panicles from 117 different crop production fields were collected (Table 1; Figure 1). A minimum of 10 johnsongrass panicles with mature seeds were collected for each accession, and GPS coordinates were recorded using a handheld GPS; the coordinates were not recorded for samples collected in Kansas. Samples were then hand-threshed, cleaned, and bagged. Samples were placed in cold storage (10 C) for two weeks before transferring to a cold room at 0 C for two days to attempt to break dormancy. Johnsongrass seeds from each accession were planted into individual 45 cm by 30 cm by 3 cm plastic trays (Greenhouse Megastore, Danville, IL) filled with Premier Tech (Quakertown, PA) Pro-Mix with a composition of 90% sphagnum peat moss and 10% perlite. These trays were then placed in a greenhouse temperature controlled at 25 +/- 8 C, with 16 hours of light, and watered twice daily. Once the johnsongrass plants emerged, they were transplanted into 50 cell trays (Greenhouse Megastore, Danville, IL) filled with Premier Tech (Quakertown, PA) Pro-Mix at one plant per cell and returned to the greenhouse. Once johnsongrass plants reached the 2- to 3-leaf stage, applications were made using a spray chamber with TeeJet (TeeJet, Springfield, IL) 1100067 flat fan nozzles at 1.6 kph calibrated to deliver 187 L ha^{-1} (Table 2). Due to some johnsongrass accessions' low seed germination percentage, not all herbicides were evaluated on all accessions collected. The initial number of plants per tray was recorded before herbicide application. Then, at 28 days after application (DAA), the final number of living plants was recorded per tray, and the survival percentage was calculated.

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Resistance screenings at TX

The greenhouse experiment was conducted twice at the Texas A&M University Norman Borlaug greenhouse complex at College Station, TX, during February-May 2022 and January-March 2024. The experiment was arranged in a completely randomized design. A total of 34 johnsongrass accessions collected from across Texas from 2017 to 2022 were evaluated for four herbicides (quizalofop, nicosulfuron, imazamox, and glyphosate) (Table 1; Figure 1). For each accession, a minimum of 15 mature johnsongrass panicles were randomly collected, and the geo-coordinates of the sampling sites were recorded using a handheld GPS. The samples were dried, threshed, and placed in cold storage (4 C). Before being used in this study, johnsongrass samples were transferred to room temperature for a week and were sandpaper scarified to break dormancy. Johnsongrass seeds from each accession were planted in individual plastic trays (50 cm x 25 cm) filled with a potting soil mix (Pro-line C/20, Jolly Gardener). These trays were placed in a greenhouse maintained at 28 C/22 C (day/night) temperature regime with a 14-hour photoperiod and watered as needed. The seedlings were transplanted into 6-six cell trays (one plant/cell) filled with the potting soil mix at the single-leaf stage. Herbicide applications were made to 2- to 3-leaf stage johnsongrass, using a track-sprayer (DeVries, Hollandale, MN) fitted with a flat fan nozzle (TeeJet XR110015) that was calibrated to deliver a spray volume of 140 L ha^{-1} at 276 kPa pressure, and an operating speed of 4.8 kph (Table 2). Like the AR screening, not all herbicides were evaluated on all accessions due to limited seed availability and germination issues. The number of seedlings treated per accession for each herbicide ranged from 6 to 63. The experiment was repeated twice. At 28 DAA, plant survival (0 or 1) and % injury (0 to 100%) were recorded. Priority was given to resistance screening for imazamox and quizalofop, given the current market availability of the igrowth® and Double Team® sorghum cultivars, with resistance to imazamox and quizalofop, respectively.

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Results and Discussion

Fluazifop. Out of the 117 johnsongrass accessions collected and screened, 113 were evaluated for sensitivity to fluazifop. The mean mortality of the 113 johnsongrass accessions screened to fluazifop was 2% (Table 3). Only four accessions evaluated had less than complete mortality (all from AR), with two, AR5 and AR7, showing 4% survival and the other two accessions, AR8 and AR9, at 80 and 94% survival, respectively (Table 4). This indicates fluazifop resistance in AR8 and AR9, especially considering the surviving plants showed no more than 5% injury from fluazifop. AR8 and AR9 are putative-resistant accessions but require dose-response evaluations to determine the resistance level. While johnsongrass resistant to fluazifop has been found previously in Arkansas, likely due to its use in broadleaf crops such as cotton and soybean, it has not been widespread (Johnson et al. 2014; Norsworthy et al. 2007; Schwartz-Lazaro et al. 2017). Because so few accessions were found to have reduced sensitivity, fluazifop remains an effective herbicide for johnsongrass control in most fields; however, overuse and heavy reliance on fluazifop could lead to an expansion of resistance in the future.

Quizalofop. A total of 104 johnsongrass accessions were evaluated for sensitivity to quizalofop (Table 3); other accessions were not tested due to limited seed supply or lack of germination. The quizalofop application resulted in 100% mortality of all accessions evaluated in AR and TX (Table 3). Quizalofop-resistant johnsongrass has never been reported (Heap 2023). Interestingly, AR8 and AR9, both less sensitive to fluazifop, were controlled successfully by quizalofop even though both herbicides are from the aryloxyphenoxypropionate family of ACCase inhibitors. Similarly, in other research, Tardiff and Powles (1994) and Leach et al. (1995) reported grasses resistant to fluazifop but not to other ACCase-inhibiting herbicides. Hence, quizalofop would be a highly effective option for johnsongrass control in grain sorghum technologies such as TamArk™ or Double Team™, which will allow POST application of the herbicide. Since these technologies are new for grain sorghum producers and offer increased johnsongrass control compared to previously available options, it will be important to utilize quizalofop in a systems approach with other effective herbicide sites of action, such as burndown applications of glyphosate or rotation to other crops, to mitigate the risk for resistance in the future.

Nicosulfuron. Johnsongrass resistant to nicosulfuron has been found in Arkansas, Texas, and Kansas, but resistance has not been widespread (Bagavathiannan and Norsworthy 2014; Werle et

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al. 2016; Heap 2023). Nicosulfuron at 47 g ha^{-1} resulted in the complete mortality of 80% of the johnsongrass accessions evaluated in AR, whereas complete mortality was only achieved for 15% of the samples screened in TX at a nicosulfuron rate of 36 g ha^{-1}. Of the samples evaluated in AR with survivors, none of the surviving plants exhibited more than 40% injury from the herbicide (Table 4). Johnsongrass accessions having survivors were found in Arkansas, Texas, and Kansas, all states with previously documented nicosulfuron-resistant johnsongrass (Table 4). There were 16 accessions screened in TX, with plant survival to nicosulfuron ranging from 0 to 100%, and injury to the surviving plants ranging from 20 to 80%. These accessions also exhibited reduced sensitivity to imazamox like those in the AR screening (Table 4). Johnsongrass accessions surviving nicosulfuron, especially with minimal injury, are worrisome with the new Inzen™ sorghum technology being released that allows producers to use nicosulfuron for POST control of the weed in grain sorghum. Similarly, nicosulfuron is also one of the few effective ALS-inhibiting herbicide options available for johnsongrass control in corn, specifically in the absence of glyphosate and glufosinate. Therefore, it will be important for producers to monitor johnsongrass control levels in fields when using nicosulfuron and to develop a crop rotation program incorporating different effective herbicide sites of action in the following crop to control any potential johnsongrass escapes.

Imazamox. Of the 69 johnsongrass accessions evaluated in AR for sensitivity to imazamox, 58 had no survival following treatment. The other 11 accessions had survival ranging from 2 to 40% (Table 4). Accessions with <80% mortality were found in Arkansas, Texas, and Kansas (Table 4). Of the 34 johnsongrass accessions screened at TX, 14 were completely controlled with imazamox, and survival of the remaining accessions ranged from 9 to 96%, with injury on the survivors ranging from 5 to 78% (Table 4). One notable observation was that the accession TX56 had only 1% survival following imazamox, yet the injury was negligible in the survivors (Table 4), indicating a high level of resistance at a low frequency within the population. Another notable observation was that six accessions from AR with reduced sensitivity to imazamox also exhibited reduced sensitivity to nicosulfuron. Trends of ALS resistance similar to this have been observed where weed species resistant to a herbicide within the sulfonylurea family of ALS inhibitors, such as rice flatsedge (*Cyperus iria* L.), smallflower umbrella sedge (*Cyperus difformis* L.), barnyardgrass, and even johnsongrass, are also resistant to herbicides within the imidazolinone family like imazamox (Heap 2023; Merotto et al. 2009; Riar et al. 2015). Because

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of this cross-resistance trend, it is difficult to determine whether the reduced sensitivity is due to exposure to imazamox or only due to the cross-resistance trend with nicosulfuron

Glyphosate. Glyphosate resulted in the mortality of all johnsongrass plants in 57 of the 64 accessions evaluated at AR. Of the seven accessions with plants surviving glyphosate, survival percentages ranged from 6 to 86% (Table 4). Injury to plants surviving glyphosate was 40 - 60% in accessions AR3, AR5, and AR40, which would indicate that there is a high likelihood that these plants are resistant to the herbicide. All 15 johnsongrass accessions screened in TX were susceptible to glyphosate (Table 3). The number of glyphosate-resistant johnsongrass accessions has been increasing since the mid-2000s due to the frequent use of the herbicide in crops like corn, cotton, and soybean, where weeds such as johnsongrass were prevalent (Heap 2023). Although glyphosate is not available for POST in-crop use in grain sorghum, many producers use it for fall and spring burndown of johnsongrass and as an effective POST option in the following crop (Smith and Scott 2010). While glyphosate is still an effective option in most situations, based on these data, it will be important for producers to understand the effectiveness of the herbicide in particular fields and use alternative options when available to help preserve the herbicide for the future.

Practical Implications. Resistant johnsongrass accessions are becoming more prominent each growing season as the reliance on the same herbicides continues due to the lack of options for successful Johnsongrass control. Based on this screening, quizalofop is the best option for producers to use for POST johnsongrass control in Double Team™ grain sorghum or the soon-to-be-registered TamArk™ grain sorghum. However, other effective control options should be utilized with quizalofop to ensure maximum control and reduce the risk of herbicide resistance.

Although johnsongrass resistant to both ALS inhibitors was found, these two technologies can still be utilized in areas with known susceptible johnsongrass accessions in a rotation with other crops that can utilize different herbicide sites of action; albeit johnsongrass is not listed as a controlled weed on the FirstAct label. Lower levels of control would be expected under dryland conditions compared to the greenhouse since growing conditions are optimal in the greenhouse. Overall, producers must know which herbicides are effective in specific fields and develop programs incorporating integrated weed management strategies to mitigate further resistance.

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References

Bagavathiannan MV, Norsworthy JK (2014) Do roadside herbicide applications select for resistance in johnsongrass populations? Proc South Weed Sci Soc 67:105

Bond, JA, Walker TW (2011) Differential tolerance of Clearfield rice cultivars to imazamox. Weed Technol 25:192–197

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

Brown SM, Chandler JM, Morrison JE (1988) Glyphosate for johnsongrass control in no-till sorghum. Weed Sci 36:510-513

Burton JD, Gronwald JW, Somers DA, Gengenbach BG, Wyse DL (1989) Inhibition of corn acetyl-CoA carboxylase by cyclohexanedione and aryloxyphenoxypropionate herbicides. Pestic Biochem Physiol 34:76-85

https://doi.org/10.1017/wet.2024.75 Published online by Cambridge University Press

Byrd JD, York AC (1987) Annual grass control in cotton (*Gossypium hirsutum*) with fluazifop, sethoxydim, and selected dinitroaniline herbicides. Weed Sci 35:388–394

Camacho RF, Moshier LJ, Morishita DW, Devlin DL (1991) Rhizome johnsongrass *(Sorghum halepense*) control in corn (*Zea mays*) with primisulfuron and nicosulfuron. Weed Technol 5:789–794

Clegg BS (1987) Gas chromatographic analysis of fluazifop-butyl (Fusilade) in potatoes, soybeans, and soil. J Ag Food Chem 35:269-273

Dobbels AF, Kapusta G (1993) Postemergence weed control in corn (*Zea mays*) with nicosulfuron combinations. Weed Technol 7:844–850

Fish JC, Webster EP, Blouin DC, Bond JA (2016) Imazamox plus propanil mixtures for grass weed management in imidazolinone-resistant rice. Weed Technol 30:29–35

Focke M, Lichtenthaler HK (1987) Inhibition of the acetyl-CoA carboxylase of barley chloroplasts by cycloxydim and sethoxydim. Z Naturforsch 42c:1361

Geier PW, Stahlman PW, White AD, Miller SD, Alford CM, Lyon DJ (2004) Imazamox for winter annual grass control in imidazolinone-tolerant winter wheat. Weed Technol 18:924–930

Gubbiga NG, Worsham AD, Coble HD, Lemons RW (1995) Effect of nicosulfuron on johnsongrass (*Sorghum halepense*) control and corn (*Zea mays*) performance. Weed Technol 9:574–58

Heap I (2023) The International Herbicide-Resistant Weed Database www.weedscience.org/pages/MOA.aspx?MOAID=2

Horowitz M (1972) Early development of johnsongrass. Weed Sci 20:271-273

https://doi.org/10.1017/wet.2024.75 Published online by Cambridge University Press

Jimenez F, Fernandez P, Rojano-Delgado AM, Alcantara R, De Prado R (2015) Resistance to imazamox in Clearfield soft wheat. Crop Prot 78:15-19

Johnson DB, Norsworthy JK, Scott RC (2014) Distribution of herbicide resistant johnsongrass (*Sorghum halepense*) in Arkansas. Weed Technol 28:111-121

Klein P, Smith CM (2020) Invasive johnsongrass, a threat to native grasslands and agriculture. Biologia 76:413-420

Kumar V, Liu R, Manuchehri MR, Westra EP, Gaines TA, Shelton CW (2020) Feral rye control in quizalofop-resistant wheat in Central Great Plains. Agron J 113 (1): 407-418

Kumar V, Liu R, Chauhan D, Perumal R, Morran S, Gaines TA, Jha P (2023) Characterization of imazamox-resistant shattercane (*Sorghum bicolor* L.) populations from Kansas. Weed Technol DOI: https://doi.org/10.1017/wet.2023.55

Lancaster ZD, Norsworthy JK, Scott RC (2018) Evaluation of quizalofop-resistant rice for Arkansas rice production systems. Int J Ag 2018. DOI: 10.1155/2018/6315865

Larson EJ, Buehring NW, Ivy RL, Kenty MM (2000) Yield performance of Clearfield corn hybrids. Mississippi State Research Reports 22:13

Leach GE, Devine, MD, Kirkwood RC, Marshall G (1995) Target enzyme-based resistance to acetyl-coenzyme A carboxylase inhibitors in *Eleusine indica*. Pestic Biochem Physiol 51:129-136

McWhorter CG (1971) Anatomy of johnsongrass. Weed Sci 19:385-393

Merotto A, Jasieniuk M, Osuna MD, Vidotto F, Ferrero A, Fischer AJ (2009) Cross-resistance to herbicides of five ALS-inhibiting groups and sequencing of the ALS gene in *Cyperus difformis* L. J Agric Food Chem 57:1389-1398

https://doi.org/10.1017/wet.2024.75 Published online by Cambridge University Press

Mitch LW (1987) Colonel Johnson’s Grass: johnsongrass. Weed Technol 1:112-113

Nelson KA, Renner KA, Penner D (1998) Weed control in soybean (*Glycine max*) with imazamox and imazethapyr. Weed Sci 46:587–594

Norsworthy JK, Smith KL, Scott RC, Gbur EE (2007) Consultant perspectives on weed management needs in Arkansas cotton. Weed Technol 21:825-831

Pinkerton S (2020) Advanced cropping solutions for sorghum coming soon. https://sorghumgrowers.com/magazine/checkoff-newsletter-spring-2020/ Accessed: September 14, 2022

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

Riar DS, Tehranchian P, Norsworthy JK, Nandula V, McElroy S, Srivastava V, Chen S, Bond JA, Scott RC (2015) Acetolactate synthase–inhibiting, herbicide-resistant rice flatsedge (*Cyperus iria*): cross-resistance and molecular mechanism of resistance. Weed Sci 63:748–757

Sanders, TL, Bond JA, Lawrence BH, Golden BR, Allen TW, Bararpour T (2021) Evaluation of sequential applications of quizalofop-P-ethyl and florpyrauxifen-benzyl in acetyl CoA carboxylase-resistant rice. Weed Technol 35:258–26

Scarabel L, Panozzo S, Savvoia W, Sattin M (2014) Target-site ACCase-resistant johnsongrass selected in summer dicot crops. Weed Technol 28:307-315

Schwartz-Lazaro LM, Norsworthy JK, Scott RC, Barber LT (2017) Resistance of two Arkansas palmer amaranth populations to multiple herbicide sites of action. Crop Prot 96:158-163

https://doi.org/10.1017/wet.2024.75 Published online by Cambridge University Press

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

Smith K, Scott B (2010) Weed Control in Grain Sorghum. Grain Sorghum Handbook UAEX Publications. pgs. 47-49

Stoltenberg DE, Gronwald JW, Wyse DL, Burton JD, Somers DA, Gengenbach BG (1989) Effect of sethoxydim and haloxyfop on acetyl-coenzyme A carboxylase activity in *Festuca* species Weed Sci 37:512-516

Tardif FJ, Powles SB (1994) Herbicide multiple-resistance in a *Lolium rigidum* biotype is endowed by multiple mechanisms isolation of a subset with resistant acetyl-CoA carboxylase. Plant Physiol 91:488-494.

Tarundeep K, Bhullar MS, Kaur K (2019) Weed control in Bt cotton with premix of pyrithiobac sodium plus quizalofop ethyl in north-west India. Crop Prot 119:69-75

Werle R, Jhala AJ, Yerka MK, Dille JA, Lindquist JL (2016) Distribution of herbicide-resistant shattercane and johnsongrass populations in sorghum production areas of Nebraska and Northern Kansas. Agron J 108:321-328

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Table 1. Location, year, and crop present for each johnsongrass accession collected for the screening.

Accession	Year collected	Latitude	Longitude	Crop present[a]
Accessions screened at AR				
AR1	2020	35.215933	-90.196417	Soybean
AR2	2020	35.251267	-90.166	Soybean
AR3	2020	35.24755	-90.148217	Soybean
AR4	2020	35.120717	-90.18975	Soybean
AR5	2020	35.092217	-90.215767	Soybean
AR6	2020	35.0909	-90.2153	Soybean
AR7	2020	35.090883	-90.216433	Soybean
AR8	2020	35.086417	-90.3058	Soybean
AR9	2020	34.962083	-90.30235	Corn
AR10	2020	35.962083	-90.643367	Soybean
AR11	2020	35.733817	-90.640667	Soybean
AR12	2020	35.733827	-90.640698	Soybean
AR13	2020	35.718067	-90.588883	Soybean
AR14	2020	35.79645	-90.4655	Soybean
AR15	2020	35.876383	-90.535517	Soybean
AR16	2020	35.836783	-90.55535	Soybean
AR17	2020	35.521317	-90.604	Soybean
AR18	2020	35.514633	-90.644817	Rice
AR19	2020	35.514583	-90.6448	Soybean
AR20	2020	35.464117	-90.663783	Soybean
AR21	2020	35.507367	-90.646683	Soybean
AR22	2020	35.507392	-90.646724	Soybean
AR23	2020	35.507357	-90.646854	Soybean
AR24	2020	35.56995	-90.6432	Soybean
AR25	2020	35.570233	-90.638783	Soybean
AR26	2020	35.570833	-90.63855	Rice
AR27	2020	35.569217	-90.638717	Soybean
AR28	2020	35.566533	-90.625267	Soybean
AR29	2020	35.566453	-90.625289	Soybean
AR30	2020	35.566723	-90.625326	Soybean
AR31	2020	35.734167	-90.652817	Soybean
AR32	2020	35.73335	-90.616367	Soybean
AR33	2020	35.227683	-90.346333	Soybean
AR34	2020	35.22775	-90.345517	Soybean
AR35	2020	35.2277	-90.345533	Soybean
AR36	2020	35.180933	-90.453667	Soybean
AR37	2020	35.224433	-90.399133	Sorghum
AR38	2020	35.22475	-90.398767	Soybean
AR39	2020	35.257683	-90.445017	Soybean

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AR40	2020	35.3661	-90.329917	Soybean
AR41	2020	35.3651	-90.329823	Soybean
AR42	2020	35.365667	-90.292667	Soybean
AR43	2020	35.411717	-90.260967	Soybean
AR44	2020	35.327267	-90.18255	Soybean
AR45	2020	35.8976	-90.159133	Cotton
AR46	2020	35.90175	-90.149617	Soybean
AR47	2020	35.931167	-90.190317	Soybean
AR48	2020	35.968117	-90.275267	Soybean
AR49	2020	35.931967	-90.288017	Soybean
AR50	2020	35.932083	-90.28805	Soybean
AR51	2020	35.756883	-90.98205	Soybean
AR52	2020	35.756417	-90.0739	Cotton
AR53	2020	35.75685	-90.1736	Soybean
AR54	2020	35.769117	-90.17815	Soybean
AR55	2020	35.902067	-90.176817	Corn
AR56	2020	35.901917	-90.16665	Soybean
AR57	2020	36.187407	-90.369087	Soybean
AR58	2020	36.053002	-90.38693	Cotton
AR59	2020	36.18501	-90.663495	Soybean
AR60	2020	36.080292	-90.743387	Soybean
AR61	2020	35.667131	-90.074214	Soybean
AR62	2020	35.969103	-94.341383	Soybean
AR63	2020	35.931253	-90.190418	Soybean
TX1	2021	32.08097	-96.8172	Sorghum
TX2	2021	32.05273	-96.93	Sorghum
TX3	2021	31.97032	-97.1126	Corn
TX4	2021	32.11856	-97.2494	Corn
TX5	2021	31.85304	-96.9323	Sorghum
TX6	2021	30.99349	-97.1089	Corn
TX7	2021	30.9787	-96.753	Corn
TX8	2021	29.12965	-96.2478	Corn
TX9	2021	29.26327	-95.9469	Corn
TX10	2021	29.39906	-96.14	Soybean
TX11	2021	28.56942	-97.1948	Pasture
TX12	2021	28.51308	-96.7818	Corn
TX13	2021	27.99947	-97.5067	Cotton
TX14	2021	23.23466	-97.847	Corn
TX15	2021	29.791414	-94.472913	Rice
TX16	2021	29.858128	-94.531693	Rice
TX17	2021	26.26606	-98.1429	Corn
TX18	2021	26.28085	-98.0813	Pasture
TX19	2021	27.88906	-97.4385	Cotton
TX20	2021	28.6676	-96.7941	Corn
TX21	2021	28.38435	-96.8922	Cotton
TX22	2021	28.81035	-97.0512	Cotton

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TX23	2021	29.46468	-96.3741	Corn
TX24	2021	29.02976	-96.2562	Sorghum
TX25	2021	30.92465	-97.0033	Corn
TX26	2021	31.05275	-97.3378	Corn
TX27	2021	32.30514	-96.9969	Sorghum
TX28	2021	32.10851	-96.6322	Corn
TX29	2021	31.68768	-97.1772	Corn
TX30	2021	32.08495	-97.3593	Sorghum
TX31	2021	29.13119	-96.3702	Cotton
TX32	2021	28.96991	-96.3393	cotton
TX33	2021	29.48498	-96.3304	Soybean
TX34	2021	28.55589	-97.0123	Cotton
TX35	2021	28.58187	-96.7143	Cotton
TX36	2021	28.69579	-96.6976	Sorghum
TX37	2021	28.08474	-97.5495	Sorghum
TX38	2021	26.18314	-97.8631	Sorghum
TX39	2021	26.36166	98.0103	Sorghum
TX40	2021	29.788287	-94.580276	Rice
OK1	2021	36.131028	-97.104583	Corn
OK2	2021	35.9867665	-97.0452132	Unknown
OK3	2021	36.1086268	-97.3893772	Corn
OK4	2021	36.260972	-97.722667	Soybean
OK5	2021	35.852198	-97.6457511	Wheat
OK6	2021	36.1150718	-98.1092228	Wheat
OK7	2021	36.4050325	-98.2466897	Wheat
KS1	2020	N/A[b]	N/A	Corn
KS2	2020	N/A	N/A	Corn
KS3	2020	N/A	N/A	Soybean
KS4	2020	N/A	N/A	Corn
KS5	2020	N/A	N/A	Sorghum
KS6	2020	N/A	N/A	Soybean
KS7	2020	N/A	N/A	Corn
KS8	2020	N/A	N/A	Corn
KS9	2020	N/A	N/A	Corn
KS10	2020	N/A	N/A	Sorghum
Accessions screened at TX				
TX41	2017	35.352	-101.5726	Field edge/roadside
TX42	2017	36.012	-101.2509	NA
TX43	2017	31.243	-100.2225	NA
TX44	2017	36.141	-101.0832	NA
TX45	2017	30.537	-96.4221	Cotton/corn
TX46	2017	36.012	-101.2827	NA
TX47	2017	35.561	-102.2207	NA
TX48	2017	36.155	-101.2345	Field edge/roadside
TX49	2019	28.822	-95.96547	Field edge/roadside
TX50	2019	28.956	-96.6236	Field edge/roadside

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TX51	2019	28.847	-96.67026	Field edge/roadside
TX52	2019	30.401	-96.19928	Field edge/roadside
TX53	2019	28.978	-96.27778	Field edge/roadside
TX54	2019	30.334	-97.2725	NA
TX55	2019	28.781	-96.83175	Field edge/roadside
TX56	2019	28.683	-96.81712	NA
TX57	2019	28.847	-96.48578	Field edge/roadside
TX58	2019	29.259	-96.39641	Field edge/roadside
TX59	2019	30.332	-97.28222	NA
TX60	2019	30.332	-97.28232	NA
TX61	2021	26.239	-98.10801	Field edge/roadside
TX62	2021	30.008	-94.59879	Field edge/roadside
TX63	2021	31.256	-96.1231	Field edge/roadside
TX64	2021	26.214	-97.97532	Field edge/roadside
TX65	2021	29.938	-95.02909	NA
TX66	2021	32.103	-97.19901	NA
TX67	2021	31.069	-97.32236	NA
TX68	2021	31.066	-97.57854	NA
TX69	2021	30.981	-97.50922	NA
TX70	2021	26.235	-97.847	Corn
TX71	2021	31.007	-97.1106	NA
TX72	2021	30.959	-97.34873	NA
TX73	2021	30.925	-97.0033	Corn
TX74	2021	30.842	-96.6075	Cotton

[a] Crop present or last crop grown before seed collection.

NA indicates that data is not available.

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Table 2. Herbicides and rates applied to johnsongrass accessions from Arkansas, Kansas, Texas, and Oklahoma in 2021 and 2022.

Trade name	Common name	Rate	Manufacturer	Location
		g ai ha^{-1}		
Screening at AR				
Fusilade DX	Fluazifop	105	Syngenta Crop Protection, LLC	Greensboro, NC
Assure II	Quizalofop	46	Amvac Chemical Corp.	Newport Beach, CA
ImiFlex	Imazamox	53	UPL	King of Prussia, PA
Zest	Nicosulfuron	47	Corteva Agriscience	Indianapolis, NC
Roundup PowerMax	Glyphosate	962[a]	Bayer CropScience	Research Triangle Park, NC
Screening at TX				
Assure II	Quizalofop	45	Amvac Chemical Corp.	Newport Beach, CA, IN
Beyond	Imazamox	53	BASF	Florham Park, NJ
Accent Q	Nicosulfuron	36	Corteva Agriscience	Indianapolis, NC
Roundup PowerMax	Glyphosate	785	Bayer CropScience	Research Triangle Park, NC

[a] g ae ha^{-1}

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Table 3. Survival of johnsongrass accessions from Arkansas, Texas, Oklahoma, and Kansas to different herbicides[a].

Herbicide	Rate	Accessions screened	Survival			
			Minimum	Median	Mean	Maximum
	g ai ha^{-1}		----------------------%			-----------------------
AR screening						
Fluazifop	105	113	0	0	2	94
Quizalofop	46	99	0	0	0	0
Imazamox	53	69	0	0	4	40
Nicosulfuron	47	80	0	0	5	94
Glyphosate	867[b]	64	0	0	6	86
TX screening						
Quizalofop	45	5	0	0	0	0
Imazamox	53	34	0	15	26	96
Nicosulfuron	36	16	0	20	30	100
Glyphosate	785	15	0	0	0	0

[a] Descriptive statistics were generated from mortality data.

[b] g ae ha^{-1}

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Table 4. Johnsongrass accessions surviving herbicide treatment and injury to surviving plants. Accessions are sorted by survival within a herbicide and screening location.

Herbicide	Accession	Survival	Injury
		--------------- % --------------	
AR screening			
Fluazifop	AR8	94	0
	AR9	80	5
	AR5	4	10
	AR7	4	10
Nicosulfuron	KS7	94	10
	AR2	40	40
	AR22	34	30
	AR7	26	60
	AR45	24	55
	AR47	22	75
	TX12	20	70
	AR13	18	20
	TX36	18	60
	AR12	14	55
	TX5	14	15
	TX17	14	60
	AR41	8	40
	KS1	6	85
	TX24	6	85
	KS8	4	90
Imazamox	AR2	40	20
	AR1	36	15
	AR5	32	40

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	AR9	30	25
	AR47	24	10
	AR45	22	10
	AR7	20	15
	AR28	18	40
	AR44	16	25
	KS7	16	30
	TX12	2	10
Glyphosate	AR40	86	60
	AR3	84	40
	AR5	80	40
	AR39	70	60
	AR2	44	75
	AR7	20	90
	AR34	6	90
TX screening			
Nicosulfuron	TX66	100	30
	TX61	46	20
	TX55	57	70
	TX69	82	50
	TX72	54	30
	TX64	29	40
	TX68	48	65
	TX67	32	70
	TX56	10	80
	TX73	11	40
	TX74	5	70
	TX53	2	80

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Imazamox	TX54	96	15
	TX69	94	5
	TX72	87	10
	TX43	43	65
	TX61	41	65
	TX60	68	23
	TX59	71	20
	TX74	48	40
	TX64	26	68
	TX68	42	60
	TX46	29	45
	TX55	30	78
	TX73	31	48
	TX66	31	50
	TX58	24	43
	TX67	15	70
	TX44	14	20
	TX51	9	70
	TX56	13	28
	TX52	14	75

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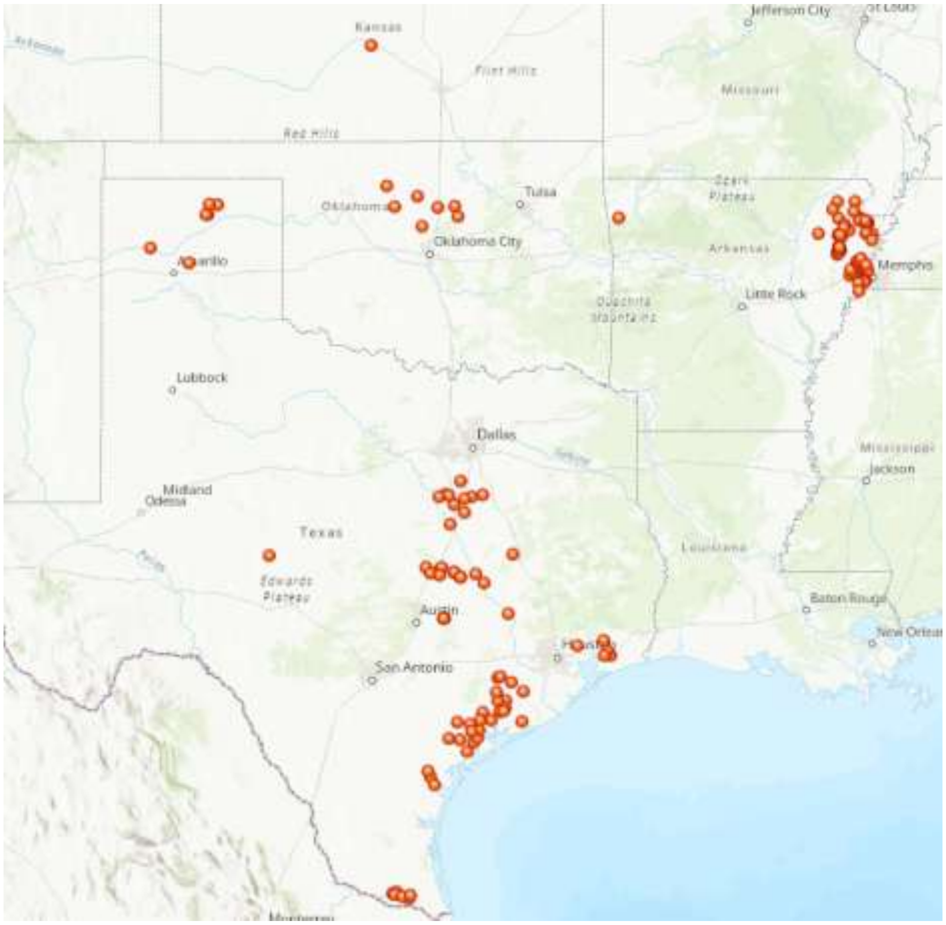

Figure 1. Johnsongrass sampling locations in Arkansas, Oklahoma, and Texas. Samples were also collected from sites in Kansas, but GPS coordinates are not available.

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