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# Use of HPPD-inhibiting Herbicides for Control of Troublesome Weeds in the Midsouthern United States

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## Abstract

Transgenic crops provide cotton and soybean producers additional weed control options for many of the most problematic weeds in midsouthern United States (U.S.). production systems. The expected commercialization of 4-hydroxyphenylpyruvate dioxygenase (HPPD)-resistant soybean in 2017 and cotton in 2020 will provide producers the option to apply HPPD-inhibiting herbicides that will offer an alternative mechanism of action for previously hard-to-control weeds. Experiments were conducted in 2010 and 2011 to determine the efficacy of HPPD-inhibiting herbicides applied preemergence (PRE) or postemergence (POST) for control of problematic weeds of cotton and soybean in the mid southern US. PRE experiments were conducted to understand the length and degree of control of Palmer amaranth and barnyardgrass that could be expected with HPPD-inhibiting herbicides compared with current standards on silt loam and clay soil textures. The HPPD herbicides evaluated included mesotrione, tembotrione, and isoxaflutole compared to several standards currently labeled in soybean. In the POST experiment, applications of isoxaflutole, tembotrione, glyphosate, and two rates of glufosinate applied alone and both HPPD herbicides combined with glyphosate or glufosinate were evaluated for control of Palmer amaranth, barnyardgrass, hemp sesbania, and yellow nutsedge. When herbicides were applied PRE, the HPPD-inhibiting herbicides and the current standard treatments all provided greater than 90% control of Palmer amaranth 4 weeks after treatment (WAT) on both soil textures. Barnyardgrass control with HPPD-inhibitors was generally weaker than the current standards with the exception of mesotrione which proved to be comparable to the standards 4 WAT. In the POST experiment, all treatments, except for glyphosate alone, provided excellent (>85%) control of Palmer amaranth less than 10-cm in height. Barnyardgrass, yellow nutsedge, and hemp sesbania were effectively controlled with HPPD-inhibiting herbicides with and without glufosinate or glyphosate.

**Keywords:** HPPD-inhibiting herbicides; Preemergence; Postemergence; Tank-mix

## Introduction

Options for weed control in midsouthern U.S. crops were broadened with the introduction of transgenic crops, specifically glyphosate-resistant soybean and cotton in 1996 and 1997, respectively. The adoption of glyphosate-resistant crops came with a dramatic shift in herbicide use patterns, most notably the almost sole reliance on glyphosate [1]. Glyphosate is a non-selective herbicide that inhibits the 5-enolpyruvylshikimate-3-photsphate synthase (EPSPS) within a plant. Producers were allowed to apply up to 3.3 kg ae $ha^{-1}$ $yr^{-1}$ over multiple application timings [2]. Due to the fact that glyphosate applications are cheap, effective, and simple [3], applications were being made multiple times per year in cotton and soybean and thus replaced tank mixtures of herbicides, tillage, and residual herbicides in the late 1990s and early 2000s [1,4,5]. Extensive and often exclusive use of glyphosate created an increasing number of glyphosate-resistant weeds [6]. In order to mitigate weed resistance to glyphosate, new mechanisms of action are being sought that can be integrated into current or future cropping systems. In a survey conducted by Norsworthy et al. [7] in Arkansas, cotton consultants overwhelmingly expressed the importance of a need for new tools for resistant weed management.

Another transgenic option for producers to apply an effective broad-spectrum herbicide in crop was the release of glufosinate-resistant crops. Glufosinate-resistant crops allow for over-the-top application of glufosinate, which inhibits glutamine synthetase in sensitive plants [8].

In 2017 and 2020, soybean and cotton are expected to be released that are resistant to a mechanism of action currently used in corn (*Zea mays* L.) and grain sorghum (*Sorghum bicolor* L.) production, 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides. HPPD-inhibiting herbicides prevent the formation of homogentisate in the formation of chloroplasts and carotenoids [9,10]. Enzymatic inhibition results in a bleaching effect in plants due to the absence of carotenoid biosynthesis [11]. HPPD-inhibiting herbicides are known to be broad spectrum, often controlling both grass and broadleaf species. This technology will provide soybean and cotton producers with another option for control of troublesome weeds. These HPPD-resistant crops will eventually possess resistance to glyphosate and glufosinate [12]. The combination of these traits will provide producers additional options to combat the resistant weeds currently infesting cotton and soybean fields.

In a survey of midsouthern U.S. cotton consultants in 2011, of the most problematic weeds in cotton, Palmer amaranth, hemp sesbania, yellow nutsedge, and barnyardgrass were ranked among the top 10 [13]. Palmer amaranth has evolved wide-spread resistance to glyphosate and ALS-inhibiting herbicides making POST over-the-top control impossible in glyphosate-resistant cotton [14]. Applications of glyphosate to control troublesome weeds, such as hemp sesbania and yellow nutsedge, have been marginal depending on rate and size of the

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plant at application [15,16]. Applications of glufosinate on both hemp sesbania and yellow nutsedge have proven very effective [16,17].

Barnyardgrass is a problematic weed due to its ability to germinate and grow under a wide variety of conditions [18]. It has been predicted that barnyardgrass will eventually evolve resistance to glyphosate [19]. The addition of HPPD-resistant cotton and soybean could be an additional tool that can be used to combat weed resistance. The weed spectrum shift caused by glyphosate-resistant crops has affected the entire southern US. where cotton and soybean are two of the principle crops [20]. The objectives of this research were to evaluate alternative options in the use of HPPD-inhibiting herbicides for crops likely to be labeled in the near future. This research also aims to explore the most efficient method of application to control four of the most troublesome weeds in Arkansas: Palmer amaranth, barnyardgrass, hemp sesbania, and yellow nutsedge.

## Materials and Methods

### Length and degree of control with pre-applied HPPD-inhibiting herbicides compared to current herbicide standards

Experiments were conducted during the summers of 2010 and 2011 to determine the length of residual control with HPPD-inhibiting herbicides compared to the current PRE-applied herbicides commonly used in midsouthern US. soybean production systems. Experiments were conducted at the University of Arkansas Northeast Research and Extension Center (NEREC) in Keiser, AR in 2010 on a Sharkey (very fine, smectitic, thermic Chromic Epiaquerts, pH 6.5, OM 3.8%) and 2011 on a Sharkey-Steele (very fine, smectitic, thermic Chromic Epiaquerts, pH 6.7, OM 3.3%). Experiments were also conducted at the University of Arkansas Agricultural Research and Extension Center (AAREC) in Fayetteville, AR in 2010 on a Captina silt loam (fine-silty, siliceous, active, mesic, Typic Fragiudults, pH 6.4, OM 1.8%), in 2011 on a Johnsburg silt loam (fine-silty, mixed active, mesic, Aquic Fragiudults, pH 6.5, OM 1.4%), and in 2011 at the University of Arkansas Pine Tree Branch Experiment Station (PTBES) near Colt, AR on a Calloway silt loam (fine-silty, mixed active thermic Aquic Fraglossudalfs, pH 6.5, OM 2.2%). Soil samples from the top 10 cm were analyzed from all locations to determine soil properties on all five experimental sites (Table 1). Soil organic matter (OM) was determined using loss on ignition [21].

Experiments conducted in 2010 and 2011 at the AAREC and in 2010 at the NEREC where plots were overhead irrigated. The trials were conducted during the spring and early summer at times that would be typical for crop production in the region. In 2011 at NEREC and PTBES, the experiment was surface irrigated. Surface irrigation involved building a levee around the field and applying enough water inside the levee to saturate the soil in the experimental site to activate treatments and germinate weed seeds. The experimental design was a randomized complete block with four replications with the herbicide treatments evaluated within each soil texture. The experimental plots were 1 m wide by 2 m long separated by 2 m alleys between the plots and four replications at all locations. The front 1 by 1 m of each plot was sown with 3,000 barnyardgrass seeds and the remaining 1 by 1 $m^2$ was sown with approximately 5,000 Palmer amaranth seeds prior to applying the herbicides. All seeds were lightly incorporated with a rake to approximately a 1.5-cm depth. Barnyardgrass seed was obtained from Azlin Seed Service (Leland, MS 38756), and Palmer amaranth seed was collected from an infested field at AAREC the previous fall. Herbicide treatments for the clay and silt loam soils are shown in Tables 2 and 3, respectively. Phytotoxicity was visually rated on a scale of 0 to 100%,

| Location | Year | Sand | Silt | Clay | Soil organic matter | Soil texture | Soil pH |
|---|---|---|---|---|---|---|---|
| | | | ------------- $g\ g^{-1}$ -------- | | --%-- | | |
| Fayetteville | 2010 | 0.23 | 0.49 | 0.28 | 1.8 | Silt loam | 6.4 |
| | 2011 | 0.27 | 0.50 | 0.23 | 1.4 | Silt loam | 6.5 |
| Keiser | 2010 | 0.09 | 0.22 | 0.69 | 3.8 | Clay | 6.5 |
| | 2011 | 0.18 | 0.20 | 0.62 | 3.3 | Clay | 6.7 |
| Pine Tree | 2011 | 0.05 | 0.67 | 0.28 | 2.2 | Silt loam | 6.5 |

**Table 1:** Soil properties from a 0- to 10-cm depth at Fayetteville, Keiser, and Pine Tree, Arkansas in 2010 and 2011.

| | | Palmer amaranth Control[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2010 | | | | 2011 | | | |
| Herbicide treatment | Rate | 4 WAT | | 8 WAT | | 4 WAT | | 8 WAT | |
| | g ai $ha^{-1}$ | | | | ——————%—————— | | | | |
| Isoxaflutole | 105 | 93 | a | 75 | cd | 98 | ab | 69 | ab |
| Tembotrione | 92 | 94 | a | 82 | abc | 90 | c | 55 | abc |
| Thiencarbazone + isoxaflutole | 37 + 92 | 96 | a | 92 | abc | 100 | a | 89 | ab |
| Mesotrione | 210 | 96 | a | 80 | bc | 100 | a | 99 | a |
| *S*-metolachlor | 1784 | 99 | a | 89 | abc | 100 | a | 70 | ab |
| Pendimethalin | 1704 | 98 | a | 55 | d | 93 | bc | 23 | c |
| Fomesafen | 280 | 95 | a | 98 | ab | 93 | bc | 52 | bc |
| Sulfentrazone + metribuzin[b] | 202 + 303 | 99 | a | 100 | a | 100 | a | 99 | a |
| *S*-metolachlor + metribuzin | 1987 + 473 | 99 | a | 100 | a | 100 | a | 97 | a |
| *S*-metolachlor + fomesafen | 1217 + 266 | 99 | a | 100 | a | 97 | abc | 66 | ab |
| Flumioxazin | 71 | 97 | a | 90 | abc | 100 | a | 73 | ab |
| *S*-metolachlor + mesotrione | 1873 + 185 | 95 | a | 99 | a | 100 | a | 99 | a |
| Chlorimuron + flumioxazin + thifensulfuron | 23 + 72 + 7 | 95 | a | 88 | abc | 100 | a | 93 | a |

[a]Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD (P ≤ 0.05).

[b]Industry standards for soybean that were included in this trial were sulfentrazone + metribuzin, *S*-metolachlor + metribuzin, *S*-metolachlor + fomesafen, flumioxazin, and chlorimuron + flumioxazin + thifensulfuron.

**Table 2:** Palmer amaranth control with residual herbicides at 4 and 8 weeks after treatment (WAT) on a clay soil at Keiser, AR in 2010 and 2011.

| Herbicide treatment | Rate | Palmer amaranth Control[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2 WAT | | 4 WAT | | 6 WAT | | 10 WAT | |
| | g ai ha$^{-1}$ | ------------------------------- % ------------------------ | | | | | | | |
| Isoxaflutole | 88 | 91 | a | 98 | a | 66 | cd | 74 | abc |
| Tembotrione | 92 | 90 | ab | 93 | ab | 55 | d | 55 | c |
| Thiencarbazone + isoxaflutole | 37 + 92 | 100 | a | 100 | a | 69 | bcd | 50 | c |
| Mesotrione | 210 | 100 | a | 100 | a | 82 | abc | 87 | ab |
| *S*-metolachlor | 1335 | 100 | a | 99 | a | 85 | abc | 85 | ab |
| Pendimethalin | 1119 | 79 | b | 86 | b | 77 | abcd | 56 | c |
| Fomesafen | 280 | 99 | a | 99 | a | 98 | a | 91 | a |
| Sulfentrazone + metribuzin[b] | 151 + 227 | 96 | a | 99 | a | 91 | ab | 87 | ab |
| *S*-metolachlor + metribuzin | 1545 + 368 | 100 | a | 99 | a | 91 | ab | 88 | ab |
| *S*-metolachlor + fomesafen | 1217 + 266 | 100 | a | 100 | a | 99 | a | 92 | a |
| Flumioxazin | 71 | 99 | a | 99 | a | 93 | ab | 65 | bc |
| *S*-metolachlor + mesotrione | 1873 + 185 | 100 | a | 100 | a | 95 | a | 91 | a |
| Chlorimuron + flumioxazin + thifensulfuron | 23 + 72 + 7 | 99 | a | 99 | a | 94 | ab | 89 | a |

[a]Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD ($P \leq 0.05$).

[b]Industry standards for soybean that were included in this trial were sulfentrazone + metribuzin, S-metolachlor + metribuzin, S-metolachlor + fomesafen, flumioxazin, and chlorimuron + flumioxazin + thifensulfuron.

**Table 3:** Palmer amaranth control with residual herbicides at 2, 4, 6, and 10 weeks after treatment (WAT) on a silt loam soil at Fayetteville, AR averaged over 2010 and 2011.

with 0 being no plant injury and 100 complete control. Weed control in plots was rated weekly for 8 to 10 weeks after application, which is the length of time generally needed for soybean and cotton to achieve a dense crop canopy [22-24]. Barnyardgrass and Palmer amaranth seedlings m$^{-2}$ were counted in 2010 and 2011. At Pine Tree, adequate Palmer amaranth failed to emerge in 2011. All Palmer amaranth and barnyardgrass counts were reported as a percent of the total relative to the non treated control to compensate for variation differences in germination from seed sources between years. Data were analyzed across years within a soil texture or locations within a soil texture for both weed species using JMP V. 9.0.0. Means were then separated using Fisher's protected LSD.

## POST HPPD-inhibiting herbicides applied alone and in combinations with glufosinate or glyphosate

Field studies were conducted in 2010 and 2011 at the AAREC during the spring and early summer at times that would be typical for crop production in the region. For both years, the experimental area was tilled, bedded, and then the beds were knocked down to a 30-cm wide surface using a bed conditioner. The row width of the implements used at the AAREC was changed in the winter of 2010; therefore, the summer of 2010 row centers were 1 m apart and in 2011 row centers were 0.9 m. These trails were conducted in fields that had a history of small-plot weed control research evaluations. After conducting a trial, the following year the field is fallowed before conducting additional evaluations. The experiment was conducted as a randomized complete block with factorial treatment structure arrangement of 4 POST herbicide timings and 11 herbicide treatments with four replications both years. Plot dimensions were 30 cm by 3.5 m with a non-planted row separating the plots and a 1 m alley between replications. In 2010, the beds were hand-sown to glyphosate-resistant (GR) Palmer amaranth, hemp sesbania, and barnyardgrass. Each plant species were sown in two 1 m length rows on the left and right side of the bed separated by 15 cm to minimize competition among weeds. Glyphosate-susceptible (GS) Palmer amaranth, hemp sesbania, and barnyardgrass were planted in the same manner in 2011 as in 2010. The GR Johnsongrass did not germinate in 2010 and therefore was not included in the 2011 planting. GS Palmer amaranth was used in 2011 due to lack of sufficient GR seed for this experiment. The hemp sesbania and barnyardgrass seed sown both years was purchased from Azlin Seed Service and was not resistant to any herbicide used in this experiment based on a previous resistance screen. The GR Palmer amaranth used in 2010 was collected from a known GR accession at the AAREC in Washington County, AR. A natural population of yellow nutsedge was present both years. Plots were planted in fields with access to overhead irrigation to provide adequate moisture for weed seed germination both years.

All herbicides were applied with a $CO_2$-pressurized backpack sprayer calibrated to deliver 140 L ha$^{-1}$ with Teejet 110015XR flat-fan nozzles (TeeJet XR110015 flat-fan nozzle, Spraying Systems Co., Wheaton, IL 60189) spaced 48 cm apart at a pressure of 276 kPa. Herbicide rates were chosen based on recommendations in the Arkansas 2010 Weed and Brush Control MP-44 [25]. Application timings were based on size of the fastest growing weed in the plot, which was Palmer amaranth. Both years the applications were applied between the hours of 10:00 AM and 4:00 PM based on work done by Sellers et al. [26] determined that between 4 hours following sunrise to 4 hours prior to sunset is optimum time for application of glufosinate. In 2010, Palmer amaranth sizes were 2.5- to 7.5-, 25- to 38-, and 38- to 50-cm tall at application. In 2011, Palmer amaranth size at application was 2.5 to 10-, 30- to 45-, and 45 to 65-cm. Yellow nutsedge, hemp sesbania, and barnyardgrass were all 2.5 to 7.5 cm for both years at the first application timing.

Treatments applied for both years were isoxaflutole plus a methylated seed oil (MSO) at 105 g ai ha$^{-1}$ + 1% v/v, respectively, tembotrione plus a MSO at 92 g ai ha$^{-1}$ + 1% v/v, respectively, two rates of glufosinate (450 and 595 g ai ha$^{-1}$), and glyphosate at 860 g ae ha$^{-1}$. Isoxaflutole and tembotrione were also applied with both rates of glufosinate and the single rate of glyphosate for a total of 11 herbicide treatments. Additionally, a non treated control was included to allow weed control to be visually assessed on a 0 to 100% scale, with 0 representing no control and 100 being plant death. Weed control was evaluated 3 weeks after each application. The timing of application across years differed slightly; therefore, data were analyzed separately by year. Fisher's protected LSD was used to separate means across herbicide treatments and timings.

## Results and Discussion

### Length and degree of control with pre-applied HPPD-inhibiting herbicides compared to current herbicide standards

The effect of year and location and their interaction with herbicide was non significant for Palmer amaranth and barnyardgrass control for the silt loam soil; thus, the control data were pooled over years and locations. Control for both Palmer amaranth and barnyardgrass on the clay soil differed by year; therefore, means were separated by year.

Under overhead irrigation, thiencarbazone + isoxaflutole, a standard in corn, and *S*-metolachlor + mesotrione controlled Palmer amaranth equal to all non-HPPD-containing treatments at 8 WAT (Table 2). In 2010, tembotrione, mesotrione, and isoxaflutole provided 82, 80, and 75% control, respectively; however, all were well below the industry standards, which provided ≥ 90% control on the clay soil 8 WAT (0.62 g $g^{-1}$ clay). When surface irrigation was used to activate the herbicides in 2011 at Keiser, control for all treatments 4 WAT were greater than 90%. At 8 WAT, control differed considerably by treatment; mesotrione, *S*-metolachlor+mesotrione, thiencarbazone + isoxaflutole, and isoxaflutole were all comparable to the industry standards. Tembotrione alone was the only HPPD-inhibiting herbicide that did not provide control of Palmer amaranth comparable to the industry standards. Tembotrione is currently recommended as a POST product in corn; hence, the lack of extensive residual control was not surprising. The combination of *S*-metolachlor + mesotrione provided 91% control or above for both years. The high control is likely from the *S*-metolachlor portion of the combination since when applied alone *S*-metolachlor provided at least 90% control both years.

All treatments were able to provide at least 4 weeks of >90% control of Palmer amaranth on the silt loam soil at Fayetteville (Table 3). Palmer amaranth control with the HPPD-inhibiting herbicides isoxaflutole and mesotrione were comparable to the non-HPPD-inhibiting herbicides at 10 WAT on the silt loam soil. When mesotrione was applied with *S*-metolachlor, effective Palmer amaranth control (>90%) was obtained through 10 WAT. Tembotrione alone did not provide comparable Palmer amaranth control to the industry standards at 10 WAT. The addition of thiencarbazone to isoxaflutole did not increase control or length of control of Palmer amaranth likely because the population of Palmer amaranth evaluated in this experiment is resistant to ALS-inhibiting herbicides.

When end-of-season counts were conducted, the Palmer amaranth densities differed tremendously among treatments (Table 4). This is to be expected as there was no crop competition to provide a canopy to assist the herbicides in preventing late-season emergence. The fact that some treatments provided a high level of control through 10 WAT is evidence that season-long control may occur in some instances when some of the herbicides evaluated here are used in HPPD-resistant soybean or cotton.

Isoxaflutole and tembotrione did not provide adequate residual control of barnyardgrass through 4 WAT when applied alone (Table 5). Barnyardgrass control with mesotrione, isoxaflutole, and tembotrione on the clay soil ranged from 53 to 75% in 2010 at 4 WAT. Mesotrione was among the herbicide treatments supplying the highest level of barnyardgrass control at 4 WAT in 2010 and at 4 and 8 WAT in 2011.

Barnyardgrass on a silt loam soil treated with thiencarbazone+isoxaflutole and *S*-metolachlor+mesotrione resulted in greater than 90% control 2 WAT and residual control continued to remain high through 10 WAT (Table 6). The extended control may have been partially a result of control provided by the ALS-inhibitor thiencarbazone and the chloroacetamide *S* metolachlor that are marketed as a premix with these HPPD herbicides. Barnyardgrass control with the HPPD-inhibiting herbicides alone ranged from 13 to 53% at 10 WAT, which was markedly less than the level of control obtained with many of the industry standards.

There was a tremendous amount of variability in the barnyardgrass counts among plots on both soil textures, resulting in less detectable differences among herbicide treatments than observed with control data (Table 7). Late season barnyardgrass densities in plots treated with HPPD-inhibiting herbicides alone did not differ from the non treated control, and barnyardgrass densities in HPPD-treated plots

| | | Palmer amaranth Density[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Keiser (clay) | | | | Fayetteville (silt loam) | | | |
| Herbicide treatment | Rate[b] | 2010 | | 2011 | | 2010 | | 2011 | |
| | g ai $ha^{-1}$ | ---------------------------- % of nontreated -------------------- | | | | | | | |
| Isoxaflutole | 105/88* | 50 | cde | 13 | cd | 38 | a | 28 | a |
| Tembotrione | 92 | 100 | a | 40 | ab | 35 | a | 14 | bc |
| Thiencarbazone + isoxaflutole | 37 + 92 | 23 | bcd | 12 | d | 18 | bc | 8 | d |
| Mesotrione | 210 | 44 | abc | 7 | d | 7 | d | 32 | a |
| *S*-metolachlor | 1784/1335* | 54 | bcd | 10 | d | 13 | cd | 7 | d |
| Pendimethalin | 1704/1119* | 8 | ef | 44 | a | 24 | b | 8 | d |
| Fomesafen | 280 | 50 | def | 5 | d | 17 | bcd | 1 | d |
| Sulfentrazone + metribuzin[c] | 202/151 + 303/227* | 0 | f | 0 | d | 10 | cde | 11 | c |
| *S*-metolachlor + metribuzin | 1987/1545 + 473/368* | 0 | f | 3 | d | 8 | de | 5 | d |
| *S*-metolachlor + fomesafen | 1217+266 | 4 | ef | 20 | c | 1 | e | 2 | d |
| Flumioxazin | 75 | 9 | ef | 0 | d | 4 | e | 17 | bc |
| *S*-metolachlor + mesotrione | 1873 + 185 | 8 | def | 1 | d | 6 | e | 11 | c |
| Chlorimuron + flumioxazin + thifensulfuron | 23 + 72 + 7 | 67 | def | 2 | d | 3 | e | 10 | cd |

[a] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD (P ≤ 0.05).

[b] '*' Represents different rate for clay or silt loam soil texture where the higher rate is for the clay soil texture.

[c] Industry standards for soybean that were included in this trial were sulfentrazone + metribuzin, *S*-metolachlor + metribuzin, *S*-metolachlor + fomesafen, flumioxazin, and chlorimuron + flumioxazin + thifensulfuron.

**Table 4:** Late season Palmer amaranth density relative to the nontreated control as influenced by choice of residual herbicide in 2010 and 2011 at Keiser and Fayetteville, AR.[a]

| | | Barnyardgrass Control[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2010 | | | | 2011 | | | |
| Herbicide treatment | Rate | 4 WAT | | 8 WAT | | 4 WAT | | 8 WAT | |
| | g ai ha$^{-1}$ | % | | | | | | | |
| Isoxaflutole | 105 | 55 | bc | 34 | e | 73 | d | 80 | abc |
| Tembotrione | 92 | 53 | c | 39 | e | 19 | f | 30 | d |
| Thiencarbazone + isoxaflutole | 37 + 92 | 72 | abc | 59 | e | 90 | abc | 97 | ab |
| Mesotrione | 210 | 75 | abc | 65 | cde | 86 | abcd | 99 | a |
| *S*-metolachlor | 1784 | 97 | a | 93 | abcd | 89 | abcd | 89 | abc |
| Pendimethalin | 1704 | 96 | a | 93 | abcd | 91 | abc | 40 | d |
| Fomesafen | 280 | 93 | a | 96 | ab | 40 | e | 60 | bcd |
| Sulfentrazone + metribuzin[b] | 202 + 303 | 99 | a | 96 | a | 79 | cd | 98 | a |
| *S*-metolachlor + metribuzin | 1987 + 473 | 97 | a | 95 | abc | 95 | a | 99 | a |
| *S*-metolachlor + fomesafen | 1217 + 266 | 96 | a | 95 | ab | 83 | bcd | 60 | dc |
| Flumioxazin | 71 | 83 | ab | 68 | bcde | 80 | bcd | 81 | abc |
| *S*-metolachlor + mesotrione | 1873 + 185 | 94 | a | 93 | abcd | 91 | ab | 99 | a |
| Chlorimuron + flumioxazin + thifensulfuron | 23 + 72 + 7 | 61 | bc | 60 | de | 83 | bcd | 94 | abc |

[a]Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD ($P \leq 0.05$).

[b]Industry standards for soybean that were included in this trial were sulfentrazone + metribuzin, *S*-metolachlor + metribuzin, *S*-metolachlor + fomesafen, flumioxazin, and chlorimuron + flumioxazin + thifensulfuron.

**Table 5:** Barnyardgrass control with residual herbicides at 4 and 8 weeks after treatment (WAT) on a clay soil at Keiser, AR in 2010 and 2011.

| | | Barnyardgrass Control[a] | | | | | |
|---|---|---|---|---|---|---|---|
| Herbicide treatment | Rate | 2 WAT | | 6 WAT | | 10 WAT | |
| | g ai ha$^{-1}$ | % | | | | | |
| Isoxaflutole | 88 | 51 | d | 34 | c | 55 | cd |
| Tembotrione | 92 | 70 | c | 0 | d | 13 | f |
| Thiencarbazone + isoxaflutole | 37 + 92 | 98 | a | 94 | a | 91 | a |
| Mesotrione | 210 | 92 | ab | 29 | c | 30 | ef |
| *S*-metolachlor | 1335 | 99 | a | 90 | a | 83 | a |
| Pendimethalin | 1119 | 93 | a | 74 | ab | 59 | bcd |
| Fomesafen | 280 | 84 | b | 20 | cd | 16 | f |
| Sulfentrazone + metribuzin[b] | 151 + 227 | 97 | ab | 73 | ab | 76 | abc |
| *S*-metolachlor + metribuzin | 1545 + 368 | 99 | a | 89 | a | 90 | a |
| *S*-metolachlor + fomesafen | 1217 + 266 | 100 | a | 98 | a | 90 | a |
| Flumioxazin | 71 | 97 | ab | 48 | bc | 50 | de |
| *S*-metolachlor + mesotrione | 1873 + 185 | 93 | ab | 85 | a | 79 | ab |
| Chlorimuron + flumioxazin + thifensulfuron | 23 + 72 + 7 | 94 | ab | 39 | c | 53 | d |

[a]Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD ($P \leq 0.05$).

[b]Industry standards for soybean that were included in this trial were sulfentrazone + metribuzin, *S*-metolachlor + metribuzin, *S*-metolachlor + fomesafen, flumioxazin, and chlorimuron + flumioxazin + thifensulfuron.

**Table 6:** Barnyardgrass control with residual herbicides at 2, 6, and 10 weeks after treatment (WAT) on a silt loam soil in 2011 averaged over Fayetteville, AR and Pine Tree, AR.

alone were often greater than those in plots treated with the herbicides currently labeled for use in soybean. Therefore, it is likely that some of the herbicides that are currently being used in soybean today will continue to be needed once HPPD-resistant soybean or cotton is commercialized.

## POST HPPD-inhibiting herbicides applied alone and in combinations with glufosinate or glyphosate

The accession of Palmer amaranth used in 2010 was different than that used in 2011. While both were expected to have resistance, the 2011 accession was, in fact, susceptible to glyphosate at 860 g ha$^{-1}$, which was later confirmed in a greenhouse trial (data not shown). When plants began to emerge, Palmer amaranth quickly overtook most of the natural weed population and other planted weeds. Following trial establishment, it was soon apparent that in addition to the Palmer amaranth that was planted in the 1-m rows, both fields had an abundance of a natural Palmer amaranth population. It has been well documented that *Amaranthus* has a very prolific growth habit, especially Palmer amaranth [27,28]. The excess Palmer amaranth in the field soon outgrew the other planted weed species, eventually shading them. Hence, the first application at the smallest weed size timing was the only application that provided effective spray coverage to all four of the planted weed species.

## Palmer amaranth control

Palmer amaranth control differed by weed size each year; therefore, data are presented separately by year. Within each year, there was a herbicide treatment by timing interaction for Palmer amaranth. In 2010, glyphosate at 860 g ae ha$^{-1}$ was the only treatment to provide less than 85% control of Palmer amaranth when the size was 2.5- to 7.5-cm tall (Table 8). The lack of a control with glyphosate was a result of the Palmer amaranth being from a resistant population. Isoxaflutole and tembotrione alone provided ≥ 94% control when applied alone in both 2010 and 2011 (Table 9). In 2010, the addition of glyphosate to either isoxaflutole or tembotrione did not increase glyphosate-resistant Palmer amaranth control over tembotrione or isoxaflutole alone when the plants were 2.5-

| | | Barnyardgrass Density (m[-2]) | | | |
|---|---|---|---|---|---|
| | | clay[a] | | silt loam[b] | |
| Herbicide treatment | Rate | Keiser | | Fayetteville and Pine Tree | |
| | g ai ha[-1] | ————%———— | | | |
| Isoxaflutole | 105 | 86 | ab | 85 | a-d |
| Tembotrione | 92 | 100 | a | 81 | a-d |
| Thiencarbazone + isoxaflutole | 37 + 92 | 62 | ab | 53 | d |
| Mesotrione | 210 | 91 | ab | 72 | bcd |
| *S*-metolachlor | 1780 | 12 | c | 85 | a-d |
| Pendimethalin | 1700 | 16 | c | 55 | cd |
| Fomesafen | 280 | 9 | c | 100 | a |
| Sulfentrazone + metribuzin[c] | 25 + 38 | 8 | c | 76 | a-d |
| *S*-metolachlor + metribuzin | 1990 + 473 | 17 | c | 92 | ab |
| *S*-metolachlor + fomesafen | 1220 + 266 | 13 | c | 100 | a |
| Flumioxazin | 71 | 62 | b | 50 | a-d |
| *S*-metolachlor + mesotrione | 1870 + 185 | 10 | c | 71 | bcd |
| Chlorimuron + flumioxazin + thifensulfuron | 23 + 72 + 7 | 73 | ab | 97 | ab |

[a]Barnyardgrass density was not assessed at Keiser in 2011.

[b]Barnyardgrass data did not differ within soil textures; thus the silt loam locations data were pooled. Letters of separation were calculated by the counts of total barnyardgrass emergence at the end of the season. Means within a column followed by the same letter are not significantly different.

[c]Industry standards for soybean that were included in this trial were sulfentrazone + metribuzin, *S*-metolachlor + metribuzin, *S*-metolachlor + fomesafen, flumioxazin, and chlorimuron + flumioxazin + thifensulfuron.

**Table 7:** Percent of total barnyardgrass emergence as influenced by choice of residual herbicide at Keiser, AR in 2010 and 2011[b] and at Fayetteville and Pine Tree, AR in 2011.

| | | Control | | | | | |
|---|---|---|---|---|---|---|---|
| | | Plant height (cm)[b] | | | | | |
| Herbicide treatment | Rate | 2.5 to 7.5 | | 25 to 38 | | 38 to 50 | |
| | g ai or ae ha[-1] | ------------------------%------------------------ | | | | | |
| Isoxaflutole | 105 | 94 | a | 53 | b-f | 43 | b-g |
| Tembotrione | 92 | 98 | a | 62 | b | 35 | d-g |
| Glufosinate | 450 | 90 | a | 51 | b-f | 30 | fg |
| Glufosinate | 595 | 85 | a | 51 | b-f | 37 | c-g |
| Glyphosate | 860 | 33 | fg | 61 | b | 33 | efg |
| Isoxaflutole + glufosinate | 105 + 450 | 95 | a | 55 | b-e | 42 | b-g |
| Isoxaflutole + glufosinate | 105 + 595 | 99 | a | 48 | b-f | 25 | g |
| Isoxaflutole + glyphosate | 105 + 860 | 98 | a | 53 | b-f | 43 | b-g |
| Tembotrione + glufosinate | 92 + 450 | 96 | a | 56 | bcd | 49 | b-f |
| Tembotrione + glufosinate | 92 + 595 | 89 | a | 59 | bc | 38 | c-g |
| Tembotrione + glyphosate | 92 + 860 | 86 | a | 50 | b-f | 44 | b-g |

[a]Control was assessed at 3 wk after treatment for each herbicide application timing.

[b]Means across all plant height columns followed by the same letter did not differ significantly when using Fisher's protected LSD ($P \leq 0.05$).

**Table 8:** Palmer amaranth control in 2010 at Fayetteville, AR with POST applications of herbicides at three timings.[a]

| | | Control | | | | | |
|---|---|---|---|---|---|---|---|
| | | Plant height (cm)[b] | | | | | |
| Herbicide treatment | Rate | 2.5-10 | | 30-45 | | 45-65 | |
| | g ai or ae ha[-1] | ------------------------%------------------------ | | | | | |
| Isoxaflutole | 105 | 96 | a | 51 | def | 35 | ef |
| Tembotrione | 92 | 95 | a | 59 | cde | 58 | def |
| Glufosinate | 450 | 96 | a | 49 | def | 48 | def |
| Glufosinate | 595 | 97 | a | 51 | def | 36 | ef |
| Glyphosate | 860 | 100 | a | 88 | ab | 33 | f |
| Isoxaflutole + glufosinate | 105 + 450 | 99 | a | 52 | def | 60 | cde |
| Isoxaflutole + glufosinate | 105 + 595 | 99 | a | 38 | ef | 44 | ef |
| Isoxaflutole + glyphosate | 105 + 860 | 100 | a | 84 | abc | 36 | ef |
| Tembotrione + glufosinate | 92 + 450 | 100 | a | 50 | def | 48 | def |
| Tembotrione + glufosinate | 92 + 595 | 100 | a | 47 | def | 61 | cde |
| Tembotrione + glyphosate | 92 + 860 | 100 | a | 53 | def | 70 | bcd |

[a]Control was assessed at 3 wk after treatment for each herbicide application timing.

[b]Means within columns and across all plant height columns followed by the same letter did not differ significantly when using Fisher's protected LSD ($P \leq 0.05$).

**Table 9:** Palmer amaranth control in 2011 with POST herbicides applied three timings.[a]

to 7.5 cm. Reduced activity of glufosinate on small Palmer amaranth (<7.5 cm) in 2010 can be attributed to reduced absorption due to a low relative humidity (38%) at application as shown by Coetzer et al. [29]. At the larger sizes of Palmer amaranth, neither HPPD herbicides alone or in combination with glyphosate or glufosinate resulted in acceptable control. Since this research was conducted there has been a study that shows there is no antagonism from glufosinate and tembotrione at a 1x field rate when applied to 7-cm tall Palmer amaranth [30]. Applications to Palmer amaranth plants larger than 25 cm, in either 2010 or 2011, resulted in insufficient levels of control. No herbicide or combination of herbicides in either year provided >70% Palmer amaranth control when plants were at least 25 to 30 cm tall at application, except for glyphosate alone and in combination with isoxaflutole in 2011 on the glyphosate-susceptible biotype. Based on the Palmer amaranth control provided by the combination of glyphosate or glufosinate with each of HPPD herbicide it appears that combination may be antagonistic on Palmer amaranth because the levels of control with the combination are similar to the control when each herbicide was applied alone.

## Barnyardgrass control

Barnyardgrass control was only rated at the first application timing of 2.5- to 7.5-cm in 2010 and 2.5- to 10-cm in 2011 because of shading by Palmer amaranth at later timings. The year by treatment interaction was significant; therefore, data are presented by year. In 2010, isoxaflutole, tembotrione, isoxaflutole + glufosinate at both rates, isoxaflutole + glyphosate, and tembotrione + glufosinate at both rates provided ≥ 80% barnyardgrass control (Table 10). Glufosinate at either 450 or 595 g $ha^{-1}$ did not provide more than 70% control. In 2011, all herbicide treatments provided 96 to 99% barnyardgrass control. Based on this research, isoxaflutole and tembotrione appear to be good post emergence options for controlling barnyardgrass if applications are made according to manufacturer's recommendations only.

## Yellow nutsedge and hemp sesbania control

The year by treatment interaction for both yellow nutsedge and hemp sesbania was not significant; hence, data were pooled over years. There were no differences among herbicide treatments for yellow nutsedge or hemp sesbania control, with yellow nutsedge control ranging from 74 to 90% and hemp sesbania control ranging from 91 to 99% (Table 10). Hence, it is does not appear that the addition of tembotrione or isoxaflutole to glyphosate or glyphosate will improve yellow nutsedge or hemp sesbania control. However, it should be noted that mixing two mechanisms of action that provide effective weed control is a strategy that is commonly recommended to reduce the risk of herbicide resistance evolving [31]. While no herbicide-resistant hemp sesbania has ever been documented, ALS-resistant yellow nutsedge was recently confirmed in Arkansas [32]. Although all treatments provided adequate control, the additional HPPD-inhibiting mechanism of action could be integrated into many integrated weed management systems to help delay resistance.

## Summary

The objectives of this research were to determine the length and degree of weed control with HPPD-inhibiting herbicides that could eventually be used in HPPD-resistant cotton and soybean as an alternative or additional mechanism of action for control of problematic and resistant weeds. Results showed that there are still multiple options for the effective control of some of the most problematic weeds of mid southern US. row crops. Palmer amaranth, barnyardgrass, and hemp sesbania can be effectively controlled with the correct combination of herbicides and alternating mechanisms of action. Since this was a non-crop study, there was no weed-crop competition and it is likely that the addition of a crop to these experiments would have resulted in even greater weed suppression.

Although the adoption rate of HPPD-resistant crops by producers remains to be seen, it is an effective option for control of both resistant and susceptible weeds if applied at the correct timing. When used in the correct manner and with the right combination of herbicides, HPPD inhibitors will bring an extra effective mechanism of action to crops to combat an ever increasing problem of herbicide resistance. While HPPD-inhibiting herbicide use is limited in the Mid south, the need for expanded use of these herbicides in more crops will help to mitigate current resistance challenges. The commercialization of HPPD-resistant crops will not be the sole answer to the problematic and resistant weeds currently inundating Mid south production fields; however, it will be an option for producers who have been limited in their herbicide options.

| | | Control | | | | | |
|---|---|---|---|---|---|---|---|
| | | Barnyardgrass[b] | | | | Yellow nutsedge[d] | Hemp sesbania[d] |
| Herbicide treatment | Rate | 2010 | | 2011 | | | |
| | g ai/ae $ha^{-1}$ | ----------------------------%---------------------------- | | | | | |
| Isoxaflutole | 105 | 97 | a | 96 | c | 84 | 96 |
| Tembotrione | 92 | 88 | ab | 98 | b | 74 | 99 |
| Glufosinate | 450 | 69 | bc | 99 | a | 75 | 97 |
| Glufosinate | 595 | 26 | d | 99 | a | 80 | 91 |
| Glyphosate | 860 | 66 | c | 99 | a | 83 | 96 |
| Isoxaflutole + glufosinate | 105 + 450 | 96 | a | 99 | a | 87 | 99 |
| Isoxaflutole + glufosinate | 105 + 595 | 99 | a | 99 | a | 87 | 99 |
| Isoxaflutole + glyphosate | 105 + 860 | 99 | a | 99 | a | 87 | 99 |
| Tembotrione + glufosinate | 92 + 450 | 84 | abc | 99 | a | 90 | 99 |
| Tembotrione + glufosinate | 92 + 595 | 80 | abc | 99 | a | 89 | 98 |
| Tembotrione + glyphosate | 92 + 860 | 65 | c | 99 | a | 90 | 95 |

[a]Weed species of plants at application were 2.5 to 7.5 cm and 1 to 2 lf for all three species.

[b]The year by herbicide treatment interaction was significant for barnyardgrass control; hence, data are presented by year.

[c]Means are separated using Fisher's protected LSD (P ≤ 0.05).

[d]Means for yellow nutsedge and hemp sesbania were not significant based on ANOVA (α=0.05).

**Table 10:** Yellow nutsedge, barnyardgrass, and hemp sesbania control 3 weeks after POST treatment at Fayetteville, AR.[a]

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