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Diuron; fluometuron; fluridone; *p*-hydroxyphenylpyruvate dioxygenase; isoxaflutole; *S*-metolachlor; pendimethalin; large crabgrass; *Digitaria sanguinalis* L.; morningglory; *Ipomoea* spp.; Palmer amaranth; *Amaranthus palmeri* S. Wats.; cotton; *Gossypium hirsutum* L.; soybean; *Glycine max* (L.) Merr.

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Performance of tank-mix partners with isoxaflutole across the Cotton Belt

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Abstract

BASF Corp. has developed *p*-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor–resistant cotton and soybean that will allow growers to use isoxaflutole in future weed management programs. In 2019 and 2020, a multi-state non-crop research project was conducted to examine weed control following isoxaflutole applied preemergence alone and with several tank-mix partners at high and low labeled rates. At 28 d after treatment (DAT), Palmer amaranth was controlled ≥95% at six of seven locations with isoxaflutole plus the high rate of diuron or fluridone. These same combinations provided the greatest control 42 DAT at four of seven locations. Where large crabgrass was present, isoxaflutole plus the high rate of diuron, fluridone, pendimethalin, or *S*-metolachlor or isoxaflutole plus the low rate of fluometuron controlled large crabgrass ≥95% in two of three locations 28 DAT. In two of three locations, isoxaflutole plus the high rate of pendimethalin or *S*-metolachlor improved large crabgrass control 42 DAT when compared to isoxaflutole alone. At 21 DAT, morningglory was controlled ≥95% at all locations with isoxaflutole plus the high rate of diuron and at three of four locations with isoxaflutole plus the high rate of fluometuron. At 42 DAT at all locations, isoxaflutole plus diuron or fluridone and isoxaflutole plus the high rate of fluometuron improved morningglory control compared to isoxaflutole alone. These results suggest that isoxaflutole applied preemergence alone or in tank mixture is efficacious on a number of cross-spectrum annual weeds in cotton, and extended weed control may be achieved when isoxaflutole is tank-mixed with several soil-residual herbicides.

Introduction

From the onset to the peak of the Roundup Ready® (glyphosate-resistant crops) era, the use of soil-residual herbicides decreased, because postemergence-topical applications of glyphosate effectively controlled most weed species (Faircloth et al. 2001; Young 2006). The increased use of glyphosate without other modes of action and tillage provided the selection pressure for glyphosate-resistant weeds. Glyphosate-resistant weeds began appearing in 2001 in Tennessee when horseweed [*Conyza canadensis* (L.) Cronq.] was confirmed as the first glyphosate-resistant weed in cotton (*Gossypium hirsutum* L.) (Heap 2021; Steckel and Gwathmey 2009). Soil-active herbicides are important tools for cotton growers because of their broad-spectrum efficacy and ability to control herbicide-resistant Palmer amaranth plants before they become troublesome (Price et al. 2008).

There are 502 unique cases of herbicide-resistant weeds in the United States (Heap 2021). The most recent herbicide class of chemistry developed were the *p*-hydroxyphenylpyruvate dioxygenase inhibitors, also known as HPPD inhibitors, which were first patented in the United States in the 1980s (Michaely and Kratz 1988). HPPD inhibitors are part of a larger group of carotenoid biosynthesis inhibitors. Herbicides in this group deplete plastoquinone, an essential electron acceptor in the carotenoid-biosynthetic pathway (Norris et al. 1995; Pallett et al. 1998). Carotenoids are essential for plant life, as they protect chlorophyll molecules from photooxidation. This generates an abundance of singlet oxygen in the absence of carotenoids

Table 1. Location, year, GPS coordinates, altitude, average rainfall, soil type, pH, organic matter content, and application date of isoxaflutole tank-mix partner field experiments in 2019 and 2020.

Location	Year	Latitude	Longitude	Altitude	Average annual rainfall	Soil type	pH	Organic matter	Application date
		°N	°W	m	mm			%	
Attapulgus, GA	2019	30.764509	84.47989	77	1,194	Faceville sandy loam	6.2	1.1	May 15
Bixby, OK	2019	35.96529	95.8632737	185	1,036	Radley silt loam	6.4	0.6	June 12
Bixby, OK	2020	35.96529	95.8632737	185	1,036	Radley silt loam	6.4	0.6	June 2
College Station, TX	2019	30.509199	96.4212093	67	1,019	Belk clay	8.4	1.25	May 29
College Station, TX	2020	30.5074	96.4185	67	1,019	Weswood silty clay loam	8.1	2	May 6
Dundee, MS	2019	34.32962	90.282511	56	907	Sharky clay	7.0	2.5	June 3
Dundee, MS	2020	34.32962	90.282511	56	907	Sharky clay	7.0	2.5	May 20
Halfway, TX	2019	34.186101	101.946055	1,072	521	Pullman clay loam	8.4	<1	May 14
Halfway, TX	2020	34.186101	101.946055	1,072	521	Pullman clay loam	8.4	<1	May 18
Ideal, GA	2019	32.423478	84.128571	135	1,168	Dothan loamy sand	6.3	1.9	April 23
Ideal, GA	2020	32.423478	84.128571	135	1,168	Dothan loamy sand	6.3	1.9	May 5
Jackson, TN	2019	35.630803	88.855149	112	1,372	Lexington silt loam	6.4	2	May 2
Jackson, TN	2020	35.631734	88.856941	112	1,372	Lexington silt loam	6.4	2	May 14
Marianna, AR	2019	34.726739	90.735393	67	1,295	Convent silt loam	7.0	1	May 15
Marianna, AR	2020	34.726739	90.735393	67	1,295	Convent silt loam	7.0	1	May 12
San Angelo, TX	2019	31.605664	100.651133	609	506	Rioconcho clay loam	8.2	1.5	May 30
San Angelo, TX	2020	31.549781	100.507398	600	506	Angelo clay loam	7.8	1.6	July 9
Stillwater, OK	2019	36.130614	97.106572	272	965	Norge loam	6.5	1.6	June 10
Stillwater, OK	2020	36.130614	97.106572	272	965	Norge loam	6.5	1.6	June 11

Table 2. Location, year, spray volume, nozzles, pressure, speed, plot size, and precipitation for field experiments in 2019 and 2020.[a]

Location	Year	Volume	Spray tips		Pressure	Speed	Plot size	Activation rainfall/ irrigation		Total moisture 14 d following application
		L ha^{-1}			kPa	km h^{-1}	m^2	DAT	mm	mm
Attapulgus, GA	2019	140	TTI	110015	276	4.8	17	1	13	45
Bixby, OK	2019	112	TTI	110015	241	4.8	23	4	6	64
Bixby, OK	2020	112	TTI	110015	241	4.8	23	6	13	13
Carlsbad, TX	2019	140	TT	8002	207	5.5	9.3	0	7	39
College Station, TX	2019	140	TTI	110015	317	4.8	19	2	22	32
College Station, TX	2020	140	DG	11003	248	4.8	19	6	41	57
Dundee, MS	2019	140	XR	110015	331	4.8	18	3	30	30
Dundee, MS	2020	140	XR	110012	331	4.8	47	2	10	40
Halfway, TX	2019	140	XR	11002	221	4.8	37	1	13	100
Halfway, TX	2020	140	XR	11002	207	4.8	37	1	16	48
Ideal, GA	2019	140	TTI	110015	276	4.8	17	2	13	62
Ideal, GA	2020	140	TTI	110015	276	4.8	17	4	13	45
Jackson, TN	2019	140	XR	11003	207	4.8	18	1	9	53
Jackson, TN	2020	140	XR	11003	193	4.8	28	4	28	62
Marianna, AR	2019	140	XR	110015	276	4.8	12	4	25	119
Marianna, AR	2020	140	XR	110015	276	4.8	12	5	11	38
San Angelo, TX	2020	140	TT	8002	207	5.5	9.3	13	8	8
Stillwater, OK	2019	140	XR	8002	138	4.8	20	5	11	42
Stillwater, OK	2020	140	XR	8002	138	4.8	20	8	53	66

[a]Abbreviations: DAT, days after treatment; DG, drift guard; TTI, Turbo TeeJet Induction; TT, Turbo TeeJet; XR, extended-range.

(Beaudegnies et al. 2009). Once the carotenoid biosynthesis pathway is blocked and the formation of new carotenoids stopped, all new plant growth exhibits symptomology that resembles "bleaching" or albino colored meristematic tissue (Lee et al. 1997).

Isoxaflutole received Federal 3 label status in the United States in 1998 and has been an effective herbicide at controlling a number of annual grass and broadleaf weed species in field corn (*Zea mays* L.) (Environmental Protection Agency 1998; Grichar et al. 2005; Stephenson and Bond 2012). When used as part of a preemergence herbicide program in soybean, isoxaflutole provided up to 95% Palmer amaranth control for 3 wk in bare-ground experiments (Meyer et al. 2016). Johnson et al. (2012) also observed a similar response in corn, with 87% to 99% Palmer amaranth control for 8 wk. Mixtures of other residual herbicides with isoxaflutole have the potential to broaden the spectrum of weeds controlled based on experiments with other HPPD inhibitors (Abendroth et al. 2006; Woodyard et al. 2009), extend the length of residual weed control, and lessen the potential for resistance development––especially when considering that two *Amaranthus* species have been confirmed to mount resistance to HPPD inhibitors (Diggle et al. 2003; Duke 2011; Heap 2021; Mitchell et al. 2001).

Adding a new mode of action to a weed management program such as isoxaflutole, a Group 27 herbicide (Herbicide Resistance Action Committee 2020), will help delay the development of herbicide-resistant weeds against the new auxinic-resistant systems recently developed in cotton (Gould 1995; Orson 1999; Peever and Milgroom 1995). Although current cotton varieties do not tolerate HPPD inhibitors, BASF Corp. has developed HPPD-resistant cotton that will allow growers to use isoxaflutole in future weed management programs. Growers are currently able to use isoxaflutole in both corn and HPPD-resistant soybean weed management programs. According to the WSSA's 2019 survey of most common and troublesome weeds in broadleaf crops, Palmer amaranth and morningglory (*Ipomoea* spp.) ranked number 1 and 2, respectively, in cotton production (Van Wychen 2019). Other weeds on those lists include horseweed, crabgrass (*Digitaria* spp.), and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv]. Isoxaflutole has been studied alone and in mixture with many corn and soybean herbicides (Grichar et al. 2005; Steckel et al. 2003; Stephenson and Bond 2012; Wicks et al. 2007), but not with cotton herbicides. Therefore, the objective of this study was to determine the most effective tank-mix partners with isoxaflutole to enhance and extend soil-residual control of the most common and troublesome weeds across the Cotton Belt.

Materials and Methods

Field Studies

Non-crop field experiments were conducted at 10 locations in 2019 and 9 locations in 2020 across the Cotton Belt; site information (pH, organic matter, etc.) is provided in Table 1. Applications were made to bare-ground plots with a CO_2-pressurized backpack sprayer, and all locations received at least 6 mm rainfall or sprinkler irrigations for activation within 6 d of application, except for Stillwater, OK, 2020 (8 d) and San Angelo, TX, 2020 (13 d) (Table 2). All sites were conventionally tilled, except for the Jackson, TN, location, where no-till practices are implemented. Treatments included isoxaflutole applied alone and in tank mix with high and low rates of commonly used preemergence herbicides labeled for use in cotton (Table 3). Treatments were arranged in a randomized complete block design with four replications at each location.

Evaluations

Weed control by species was evaluated on a 0 to 100% scale (0 being no control and 100% being no presence of the target weed) (Frans et al. 1986) every 7 d starting 14 d after treatment (DAT) and concluding 49 DAT. Palmer amaranth was present at the following sites: Halfway, TX, Marianna, AR, Bixby, OK, College Station, TX, Ideal, GA, Jackson, TN, and Dundee, MS; large crabgrass (*Digitaria sanguinalis* L.) was present at Marianna, AR, Ideal, GA, and Bixby, OK; and morningglory was present at Bixby, OK [ivyleaf morningglory (*Ipomoea hederacea* Jacq.)] and Marianna, AR, College Station, TX, and Jackson, TN [pitted morningglory (*Ipomoea lacunosa* L.)]. Weed density by species was recorded in two 0.5-m quadrats, except at Ideal, GA, where the entire 17-m^2 plot was counted, in each plot 28 to 35 DAT at six locations. Data from 28 and 42 DAT evaluations are presented.

Data Analysis

Data were separated by location, but year was considered a random effect to broaden the inference and account for environmental variability; therefore, data were pooled across years (Blouin et al. 2011; Carmer et al. 1989; Moore and Dixon 2014). Data were analyzed using the GLIMMIX procedure (2014 Version 9.4, SAS Institute Inc., Cary, NC) for ANOVA and Tukey's HSD at $\alpha = 0.05$. Single degree-of-freedom contrast statements were conducted to examine the difference in control between the high and low rates of tank-mix partners.

Table 3. Preemergence treatments and herbicide rates used in weed control experiments across the Cotton Belt in 2019 and 2020.

Treatment	Rate
	kg ai ha^{-1}
Nontreated control	–
Isoxaflutole	0.11
Isoxaflutole + acetochlor	0.11 + 1.26
Isoxaflutole + acetochlor	0.11 + 0.63
Isoxaflutole + diuron	0.11 + 1.12
Isoxaflutole + diuron	0.11 + 0.56
Isoxaflutole + fluometuron	0.11 + 1.12
Isoxaflutole + fluometuron	0.11 + 0.56
Isoxaflutole + fluridone	0.11 + 0.17
Isoxaflutole + fluridone	0.11 + 0.08
Isoxaflutole + fomesafen	0.11 + 0.28
Isoxaflutole + fomesafen	0.11 + 0.14
Isoxaflutole + pendimethalin	0.11 + 1.12
Isoxaflutole + pendimethalin	0.11 + 0.56
Isoxaflutole + prometryn	0.11 + 1.35
Isoxaflutole + prometryn	0.11 + 0.67
Isoxaflutole + pyrithiobac	0.11 + 0.058
Isoxaflutole + pyrithiobac	0.11 + 0.029
Isoxaflutole + *S*-metolachlor	0.11 + 1.4
Isoxaflutole + *S*-metolachlor	0.11 + 0.7

Results and Discussion

Palmer Amaranth

At Bixby, OK, at 28 DAT, isoxaflutole provided 82% control and all tank-mix partners improved control by at least 12% except for pyrithiobac and the low rate of pendimethalin (Table 4). By 42 DAT, isoxaflutole provided 31% control, and the addition of fluometuron, pendimethalin, or prometryn at the low rate or pyrithiobac at either rate were the only tank-mix partners not improving control. Mixtures including the high rate of prometryn, diuron, or acetochlor provided ≥75% control. This site had a large population of Palmer amaranth that is resistant to acetolactate synthase–inhibiting herbicides (Heap 2021).

At College Station, TX, the only treatments that failed to control Palmer amaranth >90% at 28 DAT were isoxaflutole and isoxaflutole plus the low rate of fomesafen (Table 4). By 42 DAT, isoxaflutole provided 79% control, whereas mixtures with the high rate of fluridone or *S*-metolachlor or either rate of diuron improved control to ≥98%. Density in the nontreated control was 346,900 plants ha^{-1} at 28 DAT, and all herbicide treatments reduced the population similarly by at least 92% (Table 5).

At Ideal, GA, Palmer amaranth control and density were recorded in 2019 and 2020, but control at 42 DAT was evaluated only in 2019. Visible control exceeded 99% by all treatments at 14 DAT (data not shown); however, isoxaflutole controlled Palmer amaranth 61% by 28 DAT. The addition of diuron, fluridone, fomesafen, *S*-metolachlor, or acetochlor at either rate or the high rate of pendimethalin improved control to at least 90%. By 42 DAT in 2019, isoxaflutole plus the high rate of fluometuron (80%), prometryn (87%), fomesafen (96%), and both rates of diuron (91% to 99%), fluridone (92% to 98%), pendimethalin (80% to 92%), *S*-metolachlor (86% to 96%), and acetochlor (96% to 97%) controlled Palmer amaranth better than isoxaflutole alone (64%). Density in the control consisted of 928,000 plants ha^{-1} at 28 DAT. Isoxaflutole alone reduced the population by

Table 4. Palmer amaranth control as affected by herbicide combination and rate 28 and 42 DAT at seven locations in 2019 and 2020.[a,b]

		Halfway, TX		Marianna, AR		Bixby, OK		College Station, TX		Ideal, GA		Jackson, TN		Dundee, MS	
Treatment	Rate	28 DAT[c]	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT
	kg ai ha^{-1}	———	———	———	———	———	———	%	———	———	———	———	———	———	———
Isoxaflutole	0.11	99	93	98	91 ab	82 c	31 f	82 b	79 bc	61 f	64 f	76	25 ab	73	26 b
IFT + acetochlor	0.11 + 1.26	100	98	99	89 ab	99 a	75 abc	99 ab	96 ab	95 ab	97 a	92	43 ab	92	55 ab
IFT + acetochlor	0.11 + 0.63	100	97	97	94 ab	95 ab	70 a–d	100 a	97 ab	91 a–d	96 a	89	45 ab	89	44 ab
IFT + diuron	0.11 + 1.12	99	96	97	91 ab	99 a	79 ab	99 ab	98 a	95 ab	99 a	87	43 ab	95	53 ab
IFT + diuron	0.11 + 0.56	100	96	98	91 ab	97 a	70 a–d	99 ab	98 a	90 a–d	91 ab	86	30 ab	91	64 a
IFT + fluometuron	0.11 + 1.12	99	96	99	94 ab	95 ab	64 a–d	96 ab	82 abc	83 a–e	80 b–e	81	30 ab	92	61 a
IFT + fluometuron	0.11 + 0.56	100	96	99	95 ab	95 ab	48 c–f	100 a	96 ab	72 def	67 ef	83	28 ab	92	44 ab
IFT + fluridone	0.11 + 0.17	98	96	99	97 a	98 a	71 a–d	100 a	100 a	96 a	98 a	87	50 ab	95	56 ab
IFT + fluridone	0.11 + 0.08	99	94	97	91 ab	96 ab	61 a–e	99 ab	96 ab	92 abc	92 ab	75	28 ab	90	49 ab
IFT + fomesafen	0.11 + 0.28	99	98	99	96 ab	97 a	74 abc	99 ab	94 ab	97 a	96 a	93	57 a	89	64 a
IFT + fomesafen	0.11 + 0.14	100	98	99	93 ab	94 ab	66 a–d	88 ab	75 c	90 a–d	79 b–f	87	36 ab	91	59 ab
IFT + pendimethalin	0.11 + 1.12	98	94	98	94 ab	94 ab	55 a–f	98 ab	89 abc	90 a–d	92 ab	88	36 ab	91	53 ab
IFT + pendimethalin	0.11 + 0.56	100	94	98	89 ab	84 c	33 f	100 a	93 abc	75 b–f	80 b–e	80	33 ab	93	46 ab
IFT + prometryn	0.11 + 1.35	98	93	98	94 ab	99 a	80 a	100 a	97 ab	79 a–f	87 abc	79	21 b	91	37 ab
IFT + prometryn	0.11 + 0.67	97	92	98	92 ab	95 ab	52 b–f	96 ab	88 abc	67 ef	74 c–f	80	24 ab	87	49 ab
IFT + pyrithiobac	0.11 + 0.058	100	98	97	91 ab	87 bc	45 def	99 ab	84 abc	73 c–f	75 c–f	82	33 ab	73	36 ab
IFT + pyrithiobac	0.11 + 0.029	99	99	94	85 b	83 c	35 ef	99 ab	89 abc	73 c–f	71 def	80	34 ab	90	45 ab
IFT + *S*-metolachlor	0.11 + 1.4	100	99	95	91 ab	99 a	71 a–d	99 ab	99 a	93 ab	96 a	81	33 ab	91	62 a
IFT + *S*-metolachlor	0.11 + 0.7	100	97	99	93 ab	96 ab	66 a–d	99 ab	94 ab	87 a–e	86 a–d	84	35 ab	90	45 ab
P values		0.3723	0.0055	0.3774	0.083	<0.0001	<0.0001	0.0383	<0.0001	<0.0001	<0.0001	0.0392	0.0428	0.0623	0.0039

[a]Abbreviations: DAT, d after treatment; IFT, isoxaflutole.
[b]Palmer amaranth control was combined across 2019 and 2020 at all locations.
[c]Treatment means within a column followed by the same or no letter do not statistically differ according to Tukey's HSD test at $\alpha = 0.05$.

Table 5. Palmer amaranth density as affected by herbicide combination and rate 28 and 35 DAT at six locations in 2019 and 2020.[a,b]

Treatment	Rate	Halfway, TX 35 DAT[c]	College Station, TX 28 DAT	Marianna, AR 28 DAT	Ideal, GA 28 DAT	Jackson, TN 28 DAT	Dundee, MS 28 DAT
	kg ai ha^{-1}	plants ha^{-1}	100 plants ha^{-1}	——1,000 plants ha^{-1}——			10,000 plants ha^{-1}
Nontreated control	–	31,673 a	3,469 a	52 a	928 a	268	137 a
Isoxaflutole	0.11	1,344 b	246 b	0 b	311 b	504	86 ab
IFT + acetochlor	0.11 + 1.26	134 b	8 b	4 b	11 e	161	26 b
IFT + acetochlor	0.11 + 0.63	201 b	8 b	19 ab	18 e	40	36 b
IFT + diuron	0.11 + 1.12	201 b	124 b	7 ab	2 e	195	24 b
IFT + diuron	0.11 + 0.56	134 b	0 b	12 ab	48 de	248	24 b
IFT + fluometuron	0.11 + 1.12	403 b	279 b	0 b	113 cde	732	19 b
IFT + fluometuron	0.11 + 0.56	67 b	122 b	0 b	228 bcd	585	66 ab
IFT + fluridone	0.11 + 0.17	739 b	0 b	0 b	6 e	87	18 b
IFT + fluridone	0.11 + 0.08	268 b	8 b	2 ab	9 e	275	31 b
IFT + fomesafen	0.11 + 0.28	336 b	41 b	12 ab	6 e	40	24 b
IFT + fomesafen	0.11 + 0.14	134 b	531 b	0 b	66 cde	262	24 b
IFT + pendimethalin	0.11 + 1.12	672 b	88 b	0 b	33 e	161	36 b
IFT + pendimethalin	0.11 + 0.56	134 b	37 b	0 b	146 b–e	289	21 b
IFT + prometryn	0.11 + 1.35	537 b	0 b	9 ab	127 cde	457	26 b
IFT + prometryn	0.11 + 0.67	874 b	21 b	0 b	242 bc	416	34 b
IFT + pyrithiobac	0.11 + 0.058	67 b	303 b	9 ab	169 b–e	531	58 ab
IFT + pyrithiobac	0.11 + 0.029	403 b	0 b	0 b	178 b–e	363	26 b
IFT + *S*-metolachlor	0.11 + 1.4	0 b	37 b	14 ab	11 e	490	23 b
IFT + *S*-metolachlor	0.11 + 0.7	67 b	0 b	0 b	60 cde	504	28 b
P values		<0.0001	<0.0001	0.0268	<0.0001	0.4618	0.0002

[a]Abbreviations: DAT, days after treatment; IFT, isoxaflutole.
[b]Palmer amaranth density was combined across 2019 and 2020 at all locations except for Marianna, AR, where density was only recorded in 2019.
[c]Treatment means within a column followed by the same or no letter do not statistically differ according to Tukey's HSD test at α = 0.05.

Table 6. Contrast statements comparing high vs low rates of tank-mix partners on Palmer amaranth control.[a,b]

Herbicide rate	Halfway, TX 28 DAT	Halfway, TX 42 DAT	Marianna, AR 28 DAT	Marianna, AR 42 DAT	Bixby, OK 28 DAT	Bixby, OK 42 DAT	College Station, TX 28 DAT	College Station, TX 42 DAT	Ideal, GA 28 DAT	Ideal, GA 42 DAT	Jackson, TN 28 DAT	Jackson, TN 42 DAT	Dundee, MS 28 DAT	Dundee, MS 42 DAT
	———						%							———
High	99	96	98	93	96	68	99	94	89	91	85	38	90	53
Low	99	96	98	91	93	56	98	91	82	82	83	32	90	50
P values	0.4029	0.3303	.8856	0.1520	0.0014	0.0002	0.1608	0.2432	0.0018	0.0005	0.1329	0.0914	0.8752	0.2955

[a]Single degree-of-freedom contrast statements were conducted to examine the difference in control between the high and low rates of tank-mix partners.
[b]Abbreviations: DAT, d after treatment.

67%. Tank-mix partners reduced the population by 86% to 99% compared to the control except for the low rate of fluometuron, pendimethalin, or prometryn and both rates of pyrithiobac. Palmer amaranth densities were <10,000 plants ha^{-1} with isoxaflutole plus the high rate of diuron or fomesafen and with either rate of fluridone.

At Halfway, TX, and Marianna, AR, Palmer amaranth control and density was evaluated in 2019 and 2020. All treatments provided ≥93% at 28 DAT (Table 4). By 42 DAT, isoxaflutole alone provided 91% to 93% control, which was similar to that observed with all tank mixtures (85% to 99%). Plant density recorded in the control exceeded 31,000 plants ha^{-1} in Halfway wherein isoxaflutole alone or in mixtures reduced the population similarly by >95% (Table 5). In Marianna, AR, plant density was 52,000 plants ha^{-1} in the control, and treatments reduced the population similarly and at least 64%.

Palmer amaranth control with isoxaflutole in Jackson, TN, was 76% and 25% at 28 and 42 DAT, respectively. At Dundee, MS, Palmer amaranth control with isoxaflutole was 73% and 26% at 28 DAT and 42 DAT, respectively. The addition of tank-mix partners did not improve control during any evaluation date, nor did they influence plant population. At Attapulgus, GA, control was 100% in treated plots, regardless of herbicide treatment (data not shown).

At 28 DAT, Palmer amaranth control improved at three locations with the addition of the high rate of diuron or fluridone and the low rate of acetochlor. By 42 DAT, the addition of both rates of diuron and the high rates of fluometuron, fomesafen, and fluridone improved control at three locations, and the addition of the high rate of *S*-metolachlor improved control at four locations. Contrast statements comparing high vs low rates of tank-mix partners indicated no differences at 28 or 42 DAT at all locations except for Bixby, OK, and Ideal, GA, where tank-mixing high rates of another residual herbicide with isoxaflutole increased Palmer amaranth control (Table 6). Although the metabolite of isoxaflutole alone is active on Palmer amaranth, control increased when tank-mixing isoxaflutole with another soil-residual herbicide. These results are similar to those reported by Stephenson and Bond (2012), where isoxaflutole alone controlled Palmer amaranth 83% at the end of the season and tank-mixing isoxaflutole with thiencarbazone-methyl and/or atrazine increased Palmer amaranth control to 92%.

Table 7. Large crabgrass control as affected by herbicide combination and rate 28 and 42 DAT at three locations in 2019 and 2020.[a,b]

		Marianna, AR		Ideal, GA		Bixby, OK	
Treatment	Rate	28 DAT[c]	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT
	kg ai ha^{-1}	%					
Isoxaflutole	0.11	81 ab	75	77 f	76 f	90 ab	55 cd
IFT + acetochlor	0.11 + 1.26	93 ab	81	92 a–d	95 abc	90 ab	59 a–d
IFT + acetochlor	0.11 + 0.63	84 ab	75	87 a–f	93 a–d	89 ab	57 cd
IFT + diuron	0.11 + 1.12	88 ab	81	96 a	96 abc	98 a	83 ab
IFT + diuron	0.11 + 0.56	90 ab	86	90 a–f	91 a–e	97 a	64 a–d
IFT + fluometuron	0.11 + 1.12	91 ab	86	89 a–f	88 b–e	96 a	70 abc
IFT + fluometuron	0.11 + 0.56	96 a	87	83 b–f	82 ef	97 a	65 a–d
IFT + fluridone	0.11 + 0.17	93 ab	86	95 ab	97 ab	97 a	68 a–d
IFT + fluridone	0.11 + 0.08	90 ab	87	91 a–e	90 a–e	95 a	58 bcd
IFT + fomesafen	0.11 + 0.28	88 ab	84	91 a–e	96 abc	88 ab	53 cd
IFT + fomesafen	0.11 + 0.14	83 ab	74	78 ef	86 c–f	84 ab	52 cd
IFT + pendimethalin	0.11 + 1.12	95 a	91	94 abc	98 a	95 a	65 a–d
IFT + pendimethalin	0.11 + 0.56	85 ab	77	90 a–f	94 a–d	91 ab	55 cd
IFT + prometryn	0.11 + 1.35	89 ab	85	94 abc	94 a–d	97 a	82 ab
IFT + prometryn	0.11 + 0.67	86 ab	83	85 a–f	86 c–f	97 a	54 cd
IFT + pyrithiobac	0.11 + 0.058	78 b	71	78 ef	82 ef	79 b	61 a–d
IFT + pyrithiobac	0.11 + 0.029	86 ab	75	79 def	82 ef	79 b	45 d
IFT + *S*-metolachlor	0.11 + 1.4	91 ab	86	97 a	97 abc	99 b	84 a
IFT + *S*-metolachlor	0.11 + 0.7	93 ab	83	82 c–f	84 def	97 a	66 a–d
P values		0.0044	0.4108	<0.0001	<0.0001	<0.0001	<0.0001

[a]Abbreviations: DAT, d after treatment; IFT, isoxaflutole.
[b]Large crabgrass control was combined across 2019 and 2020 at all locations except for Marianna, AR, where large crabgrass was only present in 2019.
[c]Treatment means within a column followed by the same or no letter do not statistically differ according to Tukey's HSD test at α = 0.05.

Table 8. Large crabgrass and morningglory density as affected by herbicide combination and rate 28 DAT at two and three locations, respectively, in 2019 and 2020.[a,b]

		Large crabgrass[b]		Morningglory[c]		
Treatment	Rate	Marianna, AR[d]	Ideal, GA	Marianna, AR	College Station, TX	Jackson, TN
	kg ai ha^{-1}	1,000 plants ha^{-1}				
Nontreated control		958 a	415 a	40	65	54
Isoxaflutole	0.11	325 b	105 b–d	30	39	40
IFT + acetochlor	0.11 + 1.26	257 b	22 fg	50	81	67
IFT + acetochlor	0.11 + 0.63	360 ab	42 d–g	68	81	108
IFT + diuron	0.11 + 1.12	345 b	21 fg	3	17	81
IFT + diuron	0.11 + 0.56	360 ab	41 d–g	5	42	202
IFT + fluometuron	0.11 + 1.12	35 b	55 c–g	53	38	175
IFT + fluometuron	0.11 + 0.56	26 b	106 bcd	23	47	148
IFT + fluridone	0.11 + 0.17	35 b	19 fg	8	5	202
IFT + fluridone	0.11 + 0.08	167 b	34 efg	23	55	81
IFT + fomesafen	0.11 + 0.28	82 b	30 fg	20	100	108
IFT + fomesafen	0.11 + 0.14	132 b	82 b–f	20	68	94
IFT + pendimethalin	0.11 + 1.12	147 b	22 fg	30	65	13
IFT + pendimethalin	0.11 + 0.56	357 ab	35 d–g	58	57	81
IFT + prometryn	0.11 + 1.35	50 b	24 fg	35	15	108
IFT + prometryn	0.11 + 0.67	40 b	74 b–g	30	39	121
IFT + pyrithiobac	0.11 + 0.058	420 ab	126 b	23	93	81
IFT + pyrithiobac	0.11 + 0.029	220 b	125 bc	35	48	27
IFT + *S*-metolachlor	0.11 + 1.4	142 b	10 g	48	76	81
IFT + *S*-metolachlor	0.11 + 0.7	230 b	53 d–g	38	46	40
P values		0.0003	<0.0001	0.4928	0.1626	0.9192

[a]Abbreviations: DAT, d after treatment; IFT, isoxaflutole.
[b]Large crabgrass density was combined across 2019 and 2020 at all locations except for Marianna, AR, where large crabgrass was only present in 2019.
[c]Morningglory density was only recorded in 2020 at all locations.
[d]Treatment means within a column followed by the same or no letter do not statistically differ according to Tukey's HSD test at α = 0.05.

Large Crabgrass

Large crabgrass was present at Marianna, AR, in 2019. At 28 and 42 DAT, isoxaflutole provided 75% to 81% control, and no tank-mix partner improved control. However, >90% control was observed at both evaluation dates when isoxaflutole was mixed with the high rate of pendimethalin and both rates of *S*-metolachlor (Table 7). At 28 DAT, large crabgrass density in the nontreated control was 958,000 plants ha^{-1} (Table 8). All treatments decreased large crabgrass density at least 66% except for isoxaflutole plus the low rate of diuron, pendimethalin, or acetochlor, and the high rate of pyrithiobac.

At Ideal, GA, large crabgrass control and density were evaluated in 2019 and 2020. At 28 DAT, isoxaflutole plus the high rate of prometryn (94%), diuron (96%), fomesafen (91%), pendimethalin (94%), *S*-metolachlor (97%), acetochlor (92%), and both rates of

Table 9. Contrast statements comparing high vs low rates of tank-mix partners on large crabgrass and morningglory control.[a,b]

	Large crabgrass						Morningglory							
	Marianna, AR		Bixby, OK		Ideal, GA		Marianna, AR		Bixby, OK		College Station, TX		Jackson, TN	
Herbicide rate	28 DAT	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT	21 DAT	35 DAT
	%													
High	89	84	93	69	92	94	73	23	85	76	70	77	92	70
Low	88	81	92	57	85	88	68	19	80	67	69	75	89	67
P values	0.3969	0.2759	0.3236	<0.0001	<0.0001	<0.0001	0.1161	0.4213	0.0402	0.006	0.762	0.5448	0.5146	0.4516

[a]Single degree-of-freedom contrast statements were conducted to examine the difference in control between the high and low rates of tank-mix partners.
[b]Abbreviations: DAT, d after treatment.

Table 10. Morningglory control as affected by herbicide combination and rate 21, 28, 35, and 42 DAT at four locations in 2019 and 2020.[a,b]

		Marianna, AR		Bixby, OK		College Station, TX		Jackson, TN	
Treatment	Rate	28 DAT[c]	42 DAT	28 DAT	42 DAT	28 DAT	42 DAT	21 DAT	35 DAT
	kg ai ha^{-1}	%							
Isoxaflutole	0.11	50 b	18	76	66 a–d	80 ab	81 ab	89	77
IFT + acetochlor	0.11 + 1.26	61 ab	5	83	68 a–d	54 b	68 abc	81	66
IFT + acetochlor	0.11 + 0.63	66 ab	11	76	67 a–d	53 b	70 abc	80	60
IFT + diuron	0.11 + 1.12	88 a	40	94	89 a	83 ab	89 a	99	79
IFT + diuron	0.11 + 0.56	81 ab	34	91	83 abc	74 ab	84 a	89	65
IFT + fluometuron	0.11 + 1.12	76 ab	26	87	79 a–d	80 ab	82 ab	99	72
IFT + fluometuron	0.11 + 0.56	74 ab	35	87	68 a–d	80 ab	80 ab	92	63
IFT + fluridone	0.11 + 0.17	85 a	49	84	80 a–d	94 a	94 a	94	62
IFT + fluridone	0.11 + 0.08	70 ab	19	78	76 a–d	75 ab	83 a	80	71
IFT + fomesafen	0.11 + 0.28	71 ab	31	80	74 a–d	58 ab	45 c	87	71
IFT + fomesafen	0.11 + 0.14	61 ab	14	79	64 a–d	55 ab	53 bc	93	69
IFT + pendimethalin	0.11 + 1.12	66 ab	36	83	73 a–d	62 ab	67 abc	89	84
IFT + pendimethalin	0.11 + 0.56	63 ab	14	71	49 d	70 ab	80 ab	99	73
IFT + prometryn	0.11 + 1.35	75 ab	14	90	88 ab	73 ab	85 a	96	64
IFT + prometryn	0.11 + 0.67	74 ab	23	89	80 a–d	78 ab	74 abc	89	68
IFT + pyrithiobac	0.11 + 0.058	74 ab	11	95	75 a–d	63 ab	83 a	86	68
IFT + pyrithiobac	0.11 + 0.029	65 ab	8	80	61 a–d	66 ab	77 ab	99	73
IFT + *S*-metolachlor	0.11 + 1.4	59 ab	6	71	57 bcd	68 ab	81 ab	93	67
IFT + *S*-metolachlor	0.11 + 0.7	59 ab	13	66	56 cd	68 ab	78 ab	84	63
P values		0.0035	0.1986	0.0285	0.0001	0.0115	<0.0001	0.7616	0.9784

[a]Abbreviations: DAT, d after treatment; IFT, isoxaflutole.
[b]Morningglory control was combined across 2019 and 2020 at all locations except for Marianna, AR, and Jackson, TN, where morningglory was only present in 2020.
[c]Treatment means within a column followed by the same or no letter do not statistically differ according to Tukey's HSD test at α = 0.05. 0.05.

fluridone (91% to 95%) improved large crabgrass control compared to isoxaflutole alone (77%) (Table 7). Plant density in the nontreated control was 415,000 plants ha^{-1}, and all treatments lowered populations by 70% to 98%. The addition of acetochlor, diuron, fomesafen, pendimethalin, and *S*-metolachlor at the high rate and fluridone at either rate with isoxaflutole reduced densities beyond that noted with isoxaflutole applied alone. By 42 DAT, isoxaflutole provided only 76% control, and all tank-mix partners controlled large crabgrass ≥90% 42 DAT except the low rate of prometryn (86%), fomesafen (86%), or *S*-metolachlor (84%), and both rates of pyrithiobac (82%) or fluometuron (82% to 88%).

Large crabgrass control was evaluated at Bixby, OK, in 2019 and 2020. Density was not measured at this site. At 28 DAT, no tank-mix partner improved control when compared to isoxaflutole applied alone. By 42 DAT, only isoxaflutole plus the high rate of diuron (83%), *S*-metolachlor (84%), and prometryn (82%) controlled large crabgrass better than isoxaflutole alone (55%).

At 28 DAT, isoxaflutole plus the high rate of diuron, fluridone, pendimethalin, or *S*-metolachlor, and isoxaflutole plus the low rate of fluometuron controlled large crabgrass ≥95% in two of three locations. Additionally, in two of three locations, isoxaflutole plus the high rate of pendimethalin or *S*-metolachlor improved large crabgrass control at 42 DAT when compared with isoxaflutole alone. Contrast statements comparing high and low rates of tank-mix partners on large crabgrass control indicated no differences at Marianna, AR, regardless of evaluation timing, and at Bixby, OK, at 28 DAT (Table 9). Tank-mixing isoxaflutole with the high rate of another residual herbicide compared to the low rate increased large crabgrass control at 42 DAT at Bixby, OK, and at 28 and 42 DAT at Ideal, GA. Brown and Masiunas (2002) also observed that large crabgrass was controlled 95% following isoxaflutole 21 DAT. Combinations of isoxaflutole plus metribuzin controlled large crabgrass 97% to 100% in studies conducted by Smith et al. (2019).

Morningglory

At Marianna, AR, morningglory control and density were recorded in 2020. At 28 DAT, isoxaflutole alone controlled morningglory

50%, and only the addition of the high rate of diuron (88%) or fluridone (85%) improved control (Table 10). Plant density in the control was 40,000 plants ha^{-1}, and there were no detectable differences in density between treatments. By 42 DAT, control was <50% with all treatments.

At Bixby, OK, morningglory control was evaluated in 2019 and 2020. Density was not measured at this site. At 28 DAT, control was 53% to 94% and did not differ among treatments. All tank-mix partners provided similar morningglory control when compared to isoxaflutole alone (66%) at 42 DAT.

At College Station, TX, morningglory control was evaluated in 2019 and 2020, and densities were recorded in 2019. At 28 DAT, no treatment control differed from isoxaflutole (80%). In 2019, morningglory density with isoxaflutole was 39,000 plants ha^{-1} 28 DAT, and no tank-mix partner decreased density. By 42 DAT, morningglory control ranged from 45% to 94%, and only isoxaflutole plus the high rate of fomesafen decreased control compared to isoxaflutole alone.

At Jackson, TN, morningglory control and density were recorded in 2020. Isoxaflutole provided 89% and 77% control at 21 and 35 DAT, respectively. The addition of tank-mix partners did not influence the level of control or densities observed. No differences were observed between the high and low rates of tank-mix partners on morningglory control except at Bixby, OK, where tank-mixing the high rate of another residual herbicide with isoxaflutole increased morningglory control compared to the low rate (Table 9).

Summary

Herbicides that consistently performed well with isoxaflutole across multiple locations and weed species were diuron, fluridone, and *S*-metolachlor. For broadleaf weed species, diuron, *S*-metolachlor, and fluridone were most effective when tank-mixed with isoxaflutole, whereas tank-mixing isoxaflutole with pendimethalin or *S*-metolachlor was most effective on grass species. Fluridone is an HRAC Group 27 herbicide and shares isoxaflutole's mode of action, although it binds to a different enzyme (phytoene desaturase); therefore, tank-mixing with this active ingredient would be considered similar to other herbicide modes of action and would help slow the development of weed resistance to HPPD-inhibiting herbicides (Sandmann et al. 1991). Diuron and *S*-metolachlor offer modes of action different from isoxaflutole, and tank-mixing with these two herbicides could help slow the spread of resistant weeds. Overall, weed control decreased more rapidly in environments that received higher amounts of average annual rainfall (National Weather Service 2021) (Table 1). Tank-mix partner recommendations will probably depend on several factors, such as environment, soil type, target weed species, and rotational crops. The opportunity to use isoxaflutole in cotton weed management systems not only will improve season-long control of a number of troublesome weeds but also will add a novel site of action for cotton growers, diversifying weed control programs.

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