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Nomenclature:
isoxaflutole; broadleaf signalgrass; *Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster; entireleaf morningglory; *Ipomoea hederacea* var. *integriuscula*; johnsongrass; *Sorghum halepense* (L.) Pers.; Palmer amaranth; *Amaranthus palmeri* (S.) Wats.; corn; *Zea mays* L.; cotton; *Gossypium hirsutum* L.; soybean; *Glycine max* (L.) Merr.

Keywords:
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Utility of isoxaflutole-based herbicide programs in HPPD-tolerant cotton production systems

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Abstract

Palmer amaranth has developed resistance to at least seven herbicide sites of action in the Cotton Belt of the United States, leaving producers with fewer options to manage this weed. Previous research with corn and newly commercially released soybean systems have found the use of 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides such as isoxaflutole (IFT) to be effective at managing Palmer amaranth. Consequently, a new transgenic cultivar of cotton is being developed with tolerance to IFT, allowing for in-crop applications of the herbicide. Two separate studies were conducted near Marianna, AR, in 2019 and replicated in 2020, to investigate the crop safety and utility of IFT when added to cotton herbicide programs. Herbicide programs featured IFT as a preemergence or early-postemergence option, residual herbicides in subsequent postemergence applications, and the presence or absence of a layby application. The use of IFT did not significantly impact cotton injury or yield, whereas the use of layered residual herbicides, including IFT, increased Palmer amaranth control compared to those without. Regardless of earlier use of IFT, layby applications were needed for season-long control of Palmer amaranth, entireleaf morningglory, broadleaf signalgrass, and johnsongrass, as evidenced by greater than a 20 percentage point improvement in control of all weeds when a layby application was made. Overall, findings from these studies indicate IFT to be a suitable tool for managing Palmer amaranth and will provide an additional site of action for cotton herbicide programs. Sequential herbicide applications and overlaying residuals were found to be paramount for managing Palmer amaranth throughout the season.

Introduction

The ability of Palmer amaranth to adapt and invade cropping systems (Sauer 1972) has enabled it to become the dominant weed of concern in cotton production systems across the mid-South United States over the past 50 yr (Sauer 1972; Van Wychen 2019). Management concerns with Palmer amaranth have been exacerbated throughout the mid-South, where resistant populations have evolved to many of the available herbicide options for weed control in cotton production systems. Currently, Palmer amaranth has developed resistance to microtubule-inhibiting herbicides such as pendimethalin (Gossett et al. 1992), acetolactate synthase (ALS)-inhibiting herbicides such as trifloxysulfuron (Burgos et al. 2001; Norsworthy et al. 2008), synthetic auxin herbicides such as dicamba (Heap 2021; Shyam et al. 2021; Steckel 2020), 5-enolpyruvyl-shikimate-3-phosphate (EPSPS)-inhibiting herbicides such as glyphosate (Norsworthy et al. 2008), protoporphyrinogen oxidase (PPO)-inhibiting herbicides such as fomesafen (Varanasi et al. 2018), 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides such as mesotrione (Jhala et al. 2014), and very-long-chain fatty acid (VLCFA)-inhibiting herbicides such as *S*-metolachlor (Brabham et al. 2019).

Economically, Palmer amaranth can cause dramatic reductions in cotton yield, reducing lint production by 59% at Palmer amaranth densities of 1.1 plants m^{-2} (Morgan et al. 2001). As weed densities increase, cotton lint yield has been found to linearly decrease by 5.9% to 11% with each additional plant per meter row (Rowland et al. 1999). In addition to causing direct yield losses, heavy infestations also may reduce cotton harvest efficiencies. Palmer amaranth densities of 3,260 weeds ha^{-1} have been shown to increase the time to harvest a hectare of cotton by 3 h (Smith et al. 2000). Reduced harvest efficacy can result in significant economic loss, costing producers additional fuel, time, and wear on equipment. The development of herbicide resistance also has exposed the true costs of herbicide-resistant weeds in more expensive herbicide programs, technology fees for herbicide-resistant crops, and the addition of other management practices such as tillage and hand weeding (DeVore et al. 2012).

To offer more herbicide options for cotton producers, the BASF company has developed a genetically modified line of cotton that is tolerant to glyphosate, glufosinate, and isoxaflutole (IFT). The introduction of IFT to cotton production systems offers producers an additional site of action that previously had not been available for use (Barber et al. 2021). Isoxaflutole is in the isoxazole chemical family. The addition of IFT provides producers an additional pigment-inhibiting herbicide alongside fluridone, a phytoene desaturase inhibitor. Typically, IFT has been labeled for use in corn production as a preemergence (PRE) or early postemergence (EPOST) herbicide for the control of small-seeded broadleaf weeds and grasses (Anonymous 2019; Pallett et al. 1998). It has been previously reported that IFT is an effective tank-mixture partner with photosystem II (PSII)-inhibiting herbicides for the control of glyphosate-resistant Palmer amaranth when used as a part of a glufosinate-based herbicide programs (Chahal et al. 2019; Chahal and Jhala 2018; Jhala et al. 2014; Stephenson and Bond 2012).

When applied postemergence (POST), the combination of HPPD- and PSII-inhibiting herbicides has been shown to have a synergistic effect, whereas PRE applications of similar tank-mixtures were additive in nature (Chahal and Jhala 2018; Kohrt and Sprague 2017; Meyer et al. 2016). Although HPPD-resistant populations of Palmer amaranth have been documented, the pairing of HPPD-inhibiting herbicides such as IFT with PSII-inhibiting herbicides has been shown to be effective at overcoming resistance to either site of action (Chahal et al. 2019; Chahal and Jhala 2018). In IFT-tolerant cotton, producers will have the flexibility to apply IFT PRE or EPOST.

In 2019 and 2020, field experiments were established to investigate the utility of IFT-tolerant cotton herbicide programs in terms of weed control and crop safety. The objectives of these studies were to determine the effectiveness of different IFT-based herbicide programs on weed control and to evaluate crop safety and tolerance of IFT-tolerant cotton to different IFT-based herbicide programs in Arkansas.

Materials and Methods

Crop Safety

Stewarded field trials were conducted in the summers of 2019 and 2020 to determine the crop safety of various IFT-based herbicide programs in IFT-tolerant cotton. Field trials were conducted at the Lon Mann Cotton Research and Extension Center near Marianna, AR (34.73°N, 90.74°W), on a Convent silt loam soil with 1% organic matter, 7% clay, 1% sand, and 92% silt (USDA-NRCS 2020). Each plot measured 3.9 m wide and 9.1 m long with 96-cm row spacings, allowing for four rows per plot with the two center rows being used for data collection and the outside rows acting as a buffer between applied treatments. Prior to planting, the experimental area was tilled and bedded. The trial was seeded with a four-row cone planter (Almaco, Nevada, IA) at a rate of 114,000 seeds ha^{-1} to a glufosinate, glyphosate, and IFT-tolerant cotton experimental line (BASF, Research Triangle, NC) The experiment was designed as a single-factor, randomized complete block design with four replications. The entire study and associated buffer area were fertilized on the basis of typical cotton production practices for Arkansas (Robertson et al. 2021). Supplemental irrigation was provided via in-furrow irrigation when rainfall was not sufficient.

Treatments consisted of different herbicide programs using IFT either PRE or EPOST along with a herbicide program that lacked IFT and a nontreated control for comparison (Tables 1 and 2). Herbicide treatments were applied at 140 L ha^{-1} using a CO_2-pressurized backpack sprayer with TeeJet® AIXR 110015 nozzles (TeeJet Technologies, Springfield, IL), and layby applications were made using a single-nozzle boom with a TeeJet® XR8002E even flat-fan nozzle. Herbicides were applied according to standard cotton production practices with the PRE applications applied at planting (0 d after planting), EPOST at 21 d after planting, mid-POST (MPOST) at 42 d after planting, and layby applications made prior to canopy closure (approximately 63 d after planting). In addition to herbicide applications, plots were hand-weeded as needed to prevent weed interference with cotton. A 20-m buffer of Deltapine 1518XF (Bayer Crop Science, St. Louis, MO) cotton was planted in all directions from the trial and destroyed prior to harvest to prevent outcrossing from the experimental seed.

To evaluate phytotoxic crop injuries, visual estimations of crop injury (ratings) based on chlorosis, necrosis, and stunting were taken weekly until 28 d after the layby application. Ratings were based on a 0 to 100 scale, with 0 representing no injury and 100 representing plant death. Stand counts were taken at 14 d after planting from 2 m of row in each plot. Days to 70% boll opening were taken prior to maturity and were made relative to the nontreated check in each block. Seed cotton yield was determined at cotton maturity using a two-row cotton picker, and 40 representative bolls collected per plot for fiber quality analysis (Kothari et al. 2017). Fiber quality analysis was conducted at the west Tennessee Research and Extension Center in Jackson, TN, and resulted in measurements for micronaire, fiber length, uniformity, fiber strength, and elongation.

Weed Control

To evaluate the efficacy of the addition of IFT into cotton herbicide programs, studies were conducted during the summers of 2019 and 2020 at the Lon Mann Cotton Research and Extension Center near Marianna, AR, on a Convent silt loam soil similar to the crop tolerance study. In both site-years, herbicide programs were applied in bare ground conditions, which were tilled and bedded prior to PRE applications. Plots measured 1.9 m wide by 6.1 m long. The treatments and treatment structure were the same as the crop safety study (Table 2), and all applications were made at the same time as in the crop safety study. Applications were made with a CO_2-pressurized backpack sprayer using TeeJet® AIXR 110015 nozzles at 140 L ha^{-1}. Visual estimations of control of a natural population of weeds were taken every 7 d following the first application until 28 d after the layby application. In 2019, Palmer amaranth, entireleaf morningglory, johnsongrass, and broadleaf signalgrass were rated. In 2020, Palmer amaranth and entireleaf morningglory were rated. Groundcover was measured with drone imagery from a height of 55 m taken 14 d after the EPOST and MPOST applications in 2020 and 14 d after the layby application in 2019 using a DGI Phantom 4 PRO (DGI, Shenzhen, China). Percent groundcover was calculated from field imagery using the Field Analyzer software (Turf Analyzer, Fayetteville, AR) to compare groundcover coverage between treatments.

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Table 1. Herbicide information for all products used in both experiments.

Common name	Product name	Manufacturer	Location
Acetochlor	Warrant	Bayer Crop Science	Research Triangle Park, NC
Dimethenamid-P	Outlook	BASF	Research Triangle Park, NC
Diuron	Direx	Adama	Raleigh, NC
Flumioxazin	Valor	Valent	Walnut Creek, CA
Fluometuron	Cotoran	Syngenta Crop Protection LLC	Greensboro, NC
Fluridone	Brake	SePRO Corp.	Carmel, IN
Glufosinate	Liberty	BASF	Research Triangle Park, NC
Glyphosate	Roundup PowerMax	Bayer Crop Science	Research Triangle Park, NC
Isoxaflutole	ALITE 27	BASF	Research Triangle Park, NC
MSMA	MSMA	Drexel Chemical Co.	Memphis, TN
Pendimethalin	Prowl H2O	BASF	Research Triangle Park, NC
S-metolachlor	Dual Magnum	Syngenta Crop Protection LLC	Greensboro, NC

Table 2. Treatment structure for both experiments in 2019 and 2020.[a]

Program	Timing	Common name	Product name	Rate
				g ai or ae ha–[1]
1	None	—————	——————	—————
2	PRE	Fluometuron	Cotoran	1,120
	EPOST	Glufosinate + *S*-metolachlor	Liberty + Dual Magnum	656 + 1,068
	MPOST	Glyphosate + Glufosinate +Acetochlor	Roundup Powermax + Liberty + Warrant	1,260 + 656 + 1,052
	Layby	Diuron + MSMA	Direx + MSMA	560 + 1,963
3	PRE	Isoxaflutole + Diuron	ALITE 27 + Direx	105 + 560
	EPOST	Dimethenamid-P + Glufosinate	Outlook + Liberty	840 + 880
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup Powermax	880 + 1,740
4	PRE	Isoxaflutole + Pendimethalin	ALITE 27 + Prowl H20	105 + 1,065
	EPOST	Dimethenamid-P + Glufosinate	Outlook + Liberty	840 + 880
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup Powermax	880 + 1,740
5	PRE	Isoxaflutole + Diuron + Pendimethalin	ALITE 27 + Direx + Prowl H20	105 + 560 + 1,065
	EPOST	Dimethenamid-P + Glufosinate	Outlook + Liberty	840 + 880
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup Powermax	880 + 1,740
6	PRE	Isoxaflutole + Prometryn	ALITE 27 + Caparol	105 + 1,120
	EPOST	Glufosinate + *S*-metolachlor	Liberty + Dual Magnum	880 + 1,068
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup Powermax	880 + 1,740
	Layby	Flumioxazin + MSMA	Valor + MSMA	72 + 1,963
7	PRE	Isoxaflutole + Fluometuron	ALITE 27 + Cotoran	105 + 1,120
	EPOST	Glufosinate + *S*-metolachlor	Liberty + Dual Magnum	880 + 1,068
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup Powermax	880 + 1,740
	Layby	Flumioxazin + MSMA	Valor + MSMA	72 + 1,963
8	PRE	Isoxaflutole + Fluridone	ALITE 27 Brake	105 + 168
	EPOST	Glufosinate + *S*-metolachlor	Liberty + Dual Magnum	880 + 1,068
	MPOST	Glufosinate + Glyphosate	Liberty + Roundup Powermax	880 + 1,740
	Layby	Flumioxazin + MSMA	Valor + MSMA	72 + 1,963
9	PRE	Fluometuron	Cotoran	1,120
	EPOST	Isoxaflutole + Glufosinate + Glyphosate	ALITE 27 + Liberty + Roundup Powermax	105 + 880 + 1,740
	MPOST	*S*-metolachlor + Glufosinate + Glyphosate	Dual Magnum + Liberty + Roundup Powermax	1,068 + 880+ 1,740
	Layby	Flumioxazin + MSMA	Valor + MSMA	72 + 1,963
10	PRE	Fluridone + Fluometuron	Brake + Cotoran	168 + 1,120
	EPOST	Isoxaflutole + Glufosinate + Glyphosate	ALITE 27 + Liberty + Roundup Powermax	105 + 880 + 1,740
	MPOST	*S*-metolachlor + Glufosinate + Glyphosate	Dual Magnum + Liberty + Roundup Powermax	1,068 + 880+ 1,740
	Layby	Flumioxazin + MSMA	Valor + MSMA	72 + 1,963

[a]Abbreviations: PRE, preemergence; EPOST, first postemergence application; MPOST, second postemergence application.

Statistical Analysis

Data were analyzed using R Statistical Software v 4.0.3 (R Foundation, Vienna, Austria). Prior to final model selection, data were evaluated for normality using Shapiro-Wilks tests, and equal variance was determined by plotting the residuals of the model (Kniss and Streibig 2018). Variables that met both normality and homogeneity of variance assumptions were evaluated with linear models using base functions. Variables that failed normality or variance assumptions were analyzed using a nonparametric factorial model using the RANKFD package (Brunner et al. 1997, 2019) to test for year-by-treatment interactions, which were not significant for all experimental variables. Treatment effects across year and replication were determined with a Friedmans test using the PGIRMESS package (Giraudoux et al. 2018). The effect of year was determined through a nonparametric Kruskal-Wallis test (Kruskal and Wallis 1952; Shah and Madden 2004) using the PGIRMESS package. Orthogonal contrast analyses were conducted to evaluate Palmer amaranth control to compare the use of IFT to the nontreated, the use of IFT PRE to EPOST, the use of residual herbicides at MPOST, and the use of layby applications. Following model selection, data were subjected to a Type I ANOVA, and means were separated using LSD with Tukey's adjustment at $\alpha = 0.05$.

Table 3. P-values for cotton crop safety by treatment and year for cotton injury.[a,b]

Source	Cotton injury						
	14 DAP	14 DAEP	14 DAMP	14 DA Layby	Stand	Boll opening	Yield
	P-values						
Treatment	**0.0067**	0.5110	0.5204	0.6678	0.7827	0.3007	0.7843
Year	0.8401	<**0.0001**	<**0.0001**	<**0.0001**	0.3054	**0.0380**	0.1069
Treatment*Year	0.4977	0.7374	**0.0353**	0.6660	0.9376	0.5430	0.8485

[a]Abbreviations: DAP, days after preemergence; DAEP, days after first postemergence application; DAMP, days after second postemergence application; DA Layby, days after layby application.
[b]Bolded values are statistically significant at α < 0.05 based on LSD with Tukey's adjustment.

Table 4. P-values for cotton fiber quality by treatment and year.[a]

Source	Micronaire	Fiber length	Uniformity	Fiber strength	Fiber elongation
	P-values				
Treatment	0.8964	0.8667	0.9535	0.9716	0.8719
Year	0.1276	<**0.0001**[a]	**0.0342**	0.4197	0.1016
Treatment*Year	0.9612	0.9551	0.9321	0.6994	0.6331

[a]Bolded values are statistically significant at α <0.05 based on LSD with Tukey's adjustment.

Table 5. Injury to isoxaflutole-tolerant cotton at 14 d after preemergence applications, averaged over 2019 and 2020 and injury 14 days after mid-POST application in 2019.[a,b]

Herbicide program	Cotton injury	
	14 DAP	14 DAMP 2019
	%	
2: Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu+Ace MPOST fb Diuron+MSMA Layby	1 b	2 ab
3: IFT+Diuron PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	2 ab	0 b
4: IFT+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	3 ab	0 b
5: IFT+Diuron+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	4 ab	0 b
6: IFT+Prometryn PRE fb Glu+Smoc EPOST fb Glu+Ggly MPOST fb Flum+MSMA Layby	3 ab	0 b
7: IFT+Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	5 ab	0 b
8: IFT+Fluridone PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	5 ab	0 b
9: Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	1 b	3 a
10: Fluridone+Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	6 a	1 ab

[a]Abbreviations: Ace, acetochlor; DAMP, days after second postemergence application; DAP, days after preemergence; dim, dimethenamid-P; EPOST, first postemergence application; fb, followed by; flum, flumioxazin; fluo, fluometuron; glu, glufosinate; gly, glyphosate; ift, isoxaflutole; MPOST, second postemergence application; PRE, preemergence; smoc, *S*-metolachlor.
[b]Means followed by the same letter within a column are not statistically different based on LSD with Tukey's adjustment (α=0.05)

Results and Discussion

Crop Safety

Differences in cotton tolerance were observed over the course of the two site-years for the study (Tables 3 and 4). Preemergence treatments were determined to have a significant influence on cotton injury at 14 d after treatment (Table 3). Across both site-years, stand-alone PRE applications of fluometuron resulted in the lowest crop injury (1%). In contrast, PRE applications of fluridone resulted in higher crop injury in both site-years (6%), though this program was not different than any other program besides the programs that used only fluometuron PRE. Crop injury caused by PRE-applied IFT-containing programs was not higher or lower in either site-year to that of other programs (2% to 5% crop injury; Table 5). All PRE herbicide programs resulted in ≤10% crop injury, which has been used as a standard injury threshold in cotton (Jordan et al. 1993). At 14 d after EPOST, crop safety was similar for all herbicide programs averaged over site-years (Table 3), although averaged over treatments, differences were observed between site-years (Table 3). Injury was lower in 2019 than in 2020 (Table 6), presumably due to differences in environmental conditions following application between the two site-years, with more rainfall following application in 2020 than 2019 (Figure 1).

At 14 d after the MPOST (DAMP), there was a significant treatment–by–site-year interaction (Table 3). In 2019, cotton injury was influenced by herbicide treatment. Three programs caused up to 3% injury to cotton in 2019; fluometuron followed by glufosinate plus *S*-metolachlor followed by glyphosate, glufosinate, acetochlor; fluometuron followed by IFT, glufosinate; and glyphosate followed by *S*-metolachlor, glufosinate, and glyphosate; and fluridone with fluometuron followed by IFT, glufosinate, and glyphosate followed by *S*-metolachlor, glufosinate, and glyphosate. However, the injury that resulted from either the program containing fluometuron followed by glufosinate, *S*-metolachlor followed by glyphosate, glufosinate, acetochlor or the program containing fluridone with fluometuron followed by IFT, glufosinate, and glyphosate followed by *S*-metolachlor, glufosinate, and glyphosate were not found to be different than those programs that did not

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express any injury (Table 5). Injury observed in these programs was most likely due to the addition of chloroacetamide herbicides in the MPOST application. Applications of chloroacetamide herbicides and glufosinate have been shown to be injurious to glufosinate-tolerant cotton, but well within commercial tolerance and not detrimental to yield (Culpepper et al. 2009). Injury in 2019 also was within acceptable levels. In 2020, there were no differences among the programs, and all injury was less than the 10% acceptable injury threshold. There also was not a program effect at 14 d following the layby application in either year, although there was a difference between the two site-years of the study. Cotton injury was greater in 2020 than in 2019, presumably due to higher temperatures in 2020 after application compared with 2019 (Figure 1).

Cotton stand at 14 d after planting was not different for herbicide program and site-year (Table 3). Cotton boll opening also was not affected by treatment. Seventy percent boll opening was different between site-years, with 2020 reaching 70% boll opening 1 d later than in 2019 (Table 6). This may be because two hurricanes passed over the trial area, causing defoliation in 2020. Despite the hurricanes and any observed injury in the field, there were no differences in yield among the treatments or between years. Fiber quality measurements did not differ among treatments (Table 4). There was a year effect on fiber length and uniformity, with lower fiber length and uniformity in 2020 (Table 6). These differences are attributed to the environmental conditions after desiccation, primarily due to the hurricane events.

The results reported above support that the addition of IFT to cotton weed management herbicide programs is suitable for IFT-tolerant cotton systems. Crop injury measured throughout the growing season in both site-years was within the range of acceptable crop safety. Most injury appeared to be transient and dissipated throughout the season, and did not have any impact on cotton yield. Fiber quality was not influenced by the presence or absence of IFT in the herbicide programs either.

Weed Control

At 21 d following planting, Palmer amaranth control among the herbicide programs did not differ, although there was a difference between site-years (Table 7). The difference in year showed that there was greater overall control in 2020 than in 2019 in all programs, potentially because of differences in weed population dynamics and environment, as the experiment were not conducted in the same area of the field in consecutive years (Table 8). At 21 d after EPOST (DAEP), weed control among herbicide treatments did not differ for entireleaf morningglory, broadleaf signalgrass, or johnsongrass (Tables 7 and 9). There was, however, a treatment-by-year interaction at 21 DAEP for Palmer amaranth (Table 7). Treatment had an effect on Palmer amaranth control in 2019, whereas all herbicide programs provided similar control in 2020. In 2019, treatments that used IFT PRE in combination with fluridone or fluometuron were found to be the most efficacious (Table 10). These findings are similar to those reported by Chalal and Jhala (2018), when there was greater Palmer amaranth control when IFT was mixed with a PSII herbicide such as fluometuron. Groundcover analysis following the EPOST application was not different across herbicide program (Table 9). Contrast analyses determined that there was not a difference between the use of IFT PRE or EPOST at 21 DAEP (P = 0.189) as well as between the presence or absence of IFT in the program (P = 0.841; data not shown). While the addition of IFT did not enhance Palmer amaranth control at this location, IFT did add an additional site of action without detriment to weed control, potentially aiding in the delay of herbicide-resistance evolution. In production areas where Palmer amaranth may be resistant to HPPD, PSII, or both sites of action, the use of IFT with a PSII herbicide such as fluometuron may still be able to provide some control where fluometuron alone may not, due to the synergistic behavior that has been shown to overcome resistance to these sites of action (Chahal and Jhala 2018; Chahal et al. 2019).

There were differences among herbicide programs and between site-years at 14 DAMP for Palmer amaranth control (Table 7). Fluometuron PRE followed by glufosinate and *S*-metolachlor EPOST followed by glyphosate, glufosinate, and acetochlor MPOST as well as fluometuron PRE followed by IFT, glufosinate, and glyphosate EPOST followed by *S*-metolachlor, glufosinate, and

Table 6. Cotton injury and quality factors in 2019 and 2020.[a,b]

Year	Cotton injury 14 DAEP	Cotton injury 14 DA Layby	Relative 70% boll opening	Relative fiber length	Relative fiber uniformity
	%	Days		%	
2019	3 b	0 b	+1 b	100 a	100 a
2020	18 a	4 a	+2 a	97 b	99 b

[a]Abbreviations: DAEP, days after first postemergence application; DA Layby, days after layby application.
[b]Means followed by the same letter within a column are not statistically different based on LSD with Tukey's adjustment (α = 0.05).

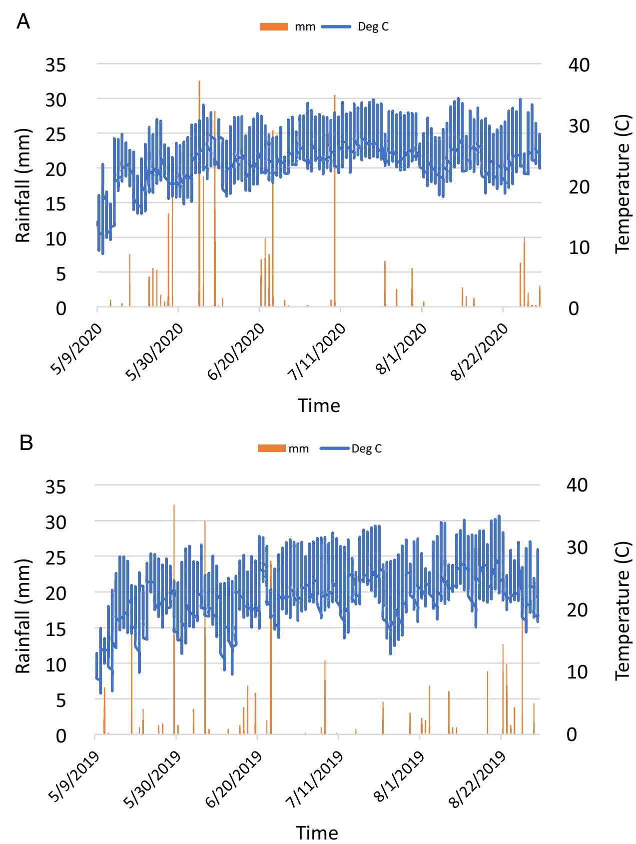

Figure 1. Rainfall and temperature data over the growing season at the Lon Mann Cotton Research Center near Marianna, AR in 2019 (A) and 2020 (B).

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Table 7. P-values for Palmer amaranth and entireleaf morningglory control in 2019 and 2020[a,b]

	Palmer amaranth control				Entireleaf morningglory control		
Source	21 DAP	21 DAEP	14 DAMP	28 DA Layby	21 DAEP	14 DAMP	28 DA Layby
	P-values						
Treatment	0.2018	0.4529	**0.0002**	**<0.0001**	0.3172	**0.0234**	**<0.0001**
Year	**0.0002**	**<0.0001**	**0.0003**	0.1786	**<00.001**	**<0.0001**	0.0931
Treatment*Year	0.3713	**0.0233**	0.5064	0.2536	0.4192	0.4392	0.5840

[a]Abbreviations: DAP, days after preemergence; DAEP, days after first postemergence application; DAMP, days after second postemergence application.
[b]Bolded values are statistically significant at α = 0.05 based on LSD with Tukey's adjustment.

Table 8. Palmer amaranth and entireleaf morningglory control averaged over treatment.[a,b]

	Palmer amaranth control		Entireleaf morningglory control	
Year	21 DAP	14 DAMP	14 DAEP	14 DAMP
	%			
2019	84 b	86 a	93 a	75 a
2020	95 a	72 b	72 b	65 b

[a]Abbreviations: DAP, days after preemergence application; DAEP, days after first postemergence application; DAMP, days after second postemergence application; PRE, preemergence.
[b]Means followed by the same letter within a column are not statistically different based on LSD with Tukey's adjustment (α = 0.05).

glyphosate MPOST both resulted in the greatest Palmer amaranth control at 91% (Table 10). These two programs resulted in similar weed control compared to all other programs aside from the program that used IFT and fluometuron PRE followed by glufosinate and *S*-metolachlor EPOST followed by glyphosate and glufosinate MPOST, which resulted in only 68% Palmer amaranth control (Table 10). Based on contrast analyses comparing programs that included a residual chloroacetamide herbicide at MPOST to those that did not, those programs that included a residual resulted in greater Palmer amaranth control at 14 DAMP and 28 d after layby (Table 11). At 14 DAMP, Palmer amaranth control for those plots that contained residual herbicides was 89% on average, whereas those that did not resulted in 73% control on average. These results are likely due to the residual weed control activity that chloroacetamide herbicides have, prolonging the control of weeds such as Palmer amaranth (Culpepper et al. 2009; Norsworthy et al. 2012; Riar et al. 2013). Although differences were in observed weed control, there were no differences in weed groundcover at the MPOST timing (Tables 8 and 9).

Entireleaf morningglory control was influenced by herbicide program at 14 DAMP. Three programs (fluometuron PRE followed by glufosinate and S-metolachlor EPOST followed by glyphosate, glufosinate, and acetochlor MPOST; IFT and fluometuron PRE followed by glufosinate, and S-metolachlor EPOST followed by glyphosate and glufosinate MPOST; and fluometuron PRE followed by IFT, glufosinate, and glyphosate EPOST followed by S-metolachlor, glufosinate, and glyphosate MPOST) all resulted in 89% control. These three programs were similar to all other programs besides the program that used isoxaflutole with diuron followed by dimethenamid-P with glufosinate followed by glyphosate with glufosinate and the program that used fluridone with fluometuron followed by IFT, glufosinate, and glyphosate followed by *S*-metolachlor, glufosinate, and glyphosate with 73% and 68% control, respectively (Table 10). Lack of control was likely the result of newly emerged weeds at this time period as the residuals in these two programs at PRE and EPOST are not completely effective at controlling morningglory species, particularly fluometuron (Anonymous 2019), isoxaflutole (Stephenson and Bond 2012), and diuron (Anonymous 2021). Unlike Palmer amaranth, contrast analysis of the use of residual herbicides in the MPOST applications were not significant for entireleaf morningglory, as the addition of chloroacetamide herbicides did not provide any additional benefit for morningglory control (Table 11). This is expected, as morningglory species are not controlled by chloroacetamide herbicides (Anonymous 2018, 2020). Control for the two grass species, johnsongrass and broadleaf signalgrass, were not impacted by herbicide program or by the inclusion of a residual at the MPOST application at 14 DAMP as control for all programs was greater than 95% (Table 12).

The observed Palmer amaranth, entireleaf morningglory, johnsongrass, and broadleaf signalgrass control following the layby applications was different among treatments. Programs that used a layby application had the greatest Palmer amaranth control ranging from 67% to 85%, while Palmer amaranth control in programs without layby applications ranged from 35% to 36% (Table 10). Similar trends were observed in broadleaf signalgrass, johnsongrass (Table 11), and entireleaf morningglory (Table 10). Contrast analysis comparing the use of layby applications to not resulted in a significant increase in average weed control for all species evaluated. With the addition of a layby application, Palmer amaranth control increased from 36% to 78%, entireleaf morningglory control increased from 49% to 80%, broadleaf signalgrass control increased from 64% to 88%, and johnsongrass control increased from 47% to 83% at 28 d after layby applications (Table 11).

Aerial imagery data suggest that the weedy groundcover was influenced by treatment following the layby application. Just as with the observed Palmer amaranth control, the treatments that used a layby application decreased weedy groundcover relative to no layby application (Table 12). The use of the additional herbicide application provided plots with greater weed control primarily due the longer residual activity of the herbicides applied as well as additional POST weed control. Although the study was conducted in a bare-ground setting, similar results would likely be observed in a row-crop environment, though potentially to a lesser extent due to the added benefit of crop canopy closure. Despite this limitation, use of additional successful herbicide applications and layered residuals have been shown previously to improve weed control in cotton (Price et al. 2008).

The findings from these studies indicate that the integration of IFT into cotton herbicide programs provide comparable control of weeds such as Palmer amaranth without sacrificing yield or fiber quality in IFT-tolerant cotton systems. The addition of IFT will provide an additional herbicide site of action for cotton production

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Table 9. P-values for weed groundcover, johnsongrass control, and broadleaf signalgrass control.[a,b]

Source	Groundcover			Johnsongrass			Broadleaf signalgrass		
	14 DAEP 2020	14 DAMP 2019	14 DA Layby 2019	21 DAEP 2019	14 DAMP 2019	28 DA Layby 2019	21 DAEP 2019	14 DAMP 2019	28 DA Layby 2019
	P-values								
Treatment	0.3350	0.3863	**0.0001**	0.4613	0.2654	<**0.0001**	0.4735	**0.0289**	**0.0044**

[a]Abbreviations: DAEP, days after first postemergence application; DAMP, days after second postemergence application; DA Layby, days after layby application.
[b]Bolded values are statistically significant at α = 0.05 based on LSD with Tukey's adjustment.

Table 10. Observed control of Palmer amaranth and entireleaf morningglory averaged over 2019 and 2020.[a,b]

Herbicide program	Palmer amaranth control				Entireleaf morningglory control	
	21 DAEP 2019	21 DAEP 2020	14 DAMP	28 DA Layby	14 DAMP	28 DA Layby
	%					
2: Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu+Ace MPOST fb Diuron+MSMA Layby	79 b	70	91 a	84 a	89 a	85 a
3: IFT+Diuron PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	95 ab	60	72 ab	36 b	73 bc	53 bc
4: IFT+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	93 ab	55	74 ab	36 b	82 abc	48 c
5: IFT+Diuron+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	89 ab	62	75 ab	35 b	80 abc	47 c
6: IFT+Prometryn PRE fb Glu+Smoc EPOST fb Glu+Ggly MPOST fb Flum+MSMA Layby	74 b	50	70 ab	74 a	85 ab	79 a
7: IFT+Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	98 a	56	68 b	80 a	85 ab	81 a
8: IFT+Fluridone PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	98 a	60	79 ab	79 a	89 a	79 a
9: Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	84 ab	71	91 a	85 a	89 a	83 a
10: Fluridone+Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	92 ab	73	84 ab	67 a	68 c	76 ab

[a]Abbreviations: Ace, acetochlor; DAP, days after preemergence application; DAEP, days after postemergence application; DA Layby, days after layby application; DAMP, days after second postemergence application; dim, dimethenamid-P; fb, followed by; flum, flumioxazin; fluo, fluometuron; glu, glufosinate; gly, glyphosate; ift, isoxaflutole; PRE, preemergence, smoc, *S*-metolachlor.
[b]Means followed by the same letter within a column are not statistically different based on LSD with Tukey's adjustment (α = 0.05).

Table 11. Results of contrast analyses comparing the use of residuals or no residual in the mid-postemergence applications and the presence or absence of layby applications for Palmer amaranth, entireleaf morningglory, broadleaf signalgrass, and johnsongrass control averaged over year.[a,b,c]

Contrasts	Palmer amaranth control			Entireleaf morningglory control			Broadleaf signalgrass control			Johnsongrass control		
	With	Without	P-value	With	Without	P-value	With	Without	P-value	With	Without	P-value
	%			%			%			%		
MPOST residual–No MPOST residual 14 DAMP	89 a	73 b	<**0.001**	–	–	0.996	–	–	0.051	–	–	0.669
Layby–No Layby 28 DA Layby	78 a	36 b	<**0.001**	80 a	49 b	<**0.001**	88 a	64 b	**0.001**	83 a	47 b	<**0.001**

[a]Abbreviations: DA Layby, days after layby application; DAMP, days after second postemergence application; MPOST, mid-postemergence.
[b]Bolded values are statistically significant at α = 0.05 based on LSD with Tukey's adjustment.
[c]Values not shown due to insignificance.

acres while planted to cotton, which will be paramount for combating further herbicide resistance evolution. Even with HPPD-inhibiting herbicide resistance already present in Arkansas (Heap 2021) with resistance to mesotrione, combinations of HPPD-inhibiting herbicides such as IFT with PSII inhibiting herbicides, such as fluometuron in cotton, have been shown to overcome resistance to either HPPD- or PSII-inhibiting herbicides by Palmer amaranth (Chahal and Jhala 2018). It should be noted that successful, season-long weed control was attained only through the use of complete herbicide programs that used multiple effective sights of action, and these strategies, as well as the incorporation of holistic integrated weed management strategies, will need to be implemented to aid in the longevity of these new technologies (Norsworthy et al. 2012).

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Table 12. Visible estimates of broadleaf signalgrass control, johnsongrass control, and groundcover.[a,b]

	Broadleaf signalgrass control		Johnsongrass control	
Herbicide program	14 DAMP 2019	28 DA Layby 2019	28 DA Layby 2019	Layby groundcover
	%			
2: Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu+Ace MPOST fb Diuron+MSMA Layby	99 a	99 a	99 a	0.354 ab
3: IFT+Diuron PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	98 b	72 cd	50 c	11.215 a
4: IFT+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	99 a	59 d	41 c	8.539 a
5: IFT+Diuron+Pendimethalin PRE fb Dim+Glu EPOST fb Gly+Glu MPOST	98 b	64 d	50 c	11.164 a
6: IFT+Prometryn PRE fb Glu+Smoc EPOST fb Glu+Ggly MPOST fb Flum+MSMA Layby	99 a	71 cd	74 b	0.090 ab
7: IFT+Fluo PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	99 a	78 bcd	89 ab	0.000 b
8: IFT+Fluridone PRE fb Glu+Smoc EPOST fb Gly+Glu MPOST fb Flum+MSMA Layby	99 a	89 abc	75 b	0.000 b
9: Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+MSMA Layby	99 a	97 ab	79 b	0.000 b
10: Fluridone+Fluo PRE fb IFT+Glu+Gly EPOST fb Smoc+Glu+Gly MPOST fb Flum+ MSMA Layby	99 a	95 ab	83 ab	0.003 b

[a]Abbreviations: Ace, acetochlor; DA Layby, days after layby application; DAMP, days after second postemergence application; dim, dimethenamid-P; fb, followed by; flum, flumioxazin; fluo, fluometuron; glu, glufosinate; gly, glyphosate; ift, isoxaflutole; PRE, preemergence, smoc, *S*-metolachlor.
[b]Means followed by the same letter within a column are not statistically different based on LSD with Tukey's adjustment (α = 0.05).

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