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WEED SCIENCE

Cotton Response and Palmer Amaranth Control with Pyroxasulfone Applied Preemergence and Postemergence

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ABSTRACT

Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) is a widespread problem in cotton (*Gossypium hirsutum* L.) production. Growers are encouraged to include residual herbicides applied preemergence (PRE) and postemergence (POST) in their management systems to control this weed adequately. Pyroxasulfone, an isoxazoline herbicide with the same mode of action as acetochlor and *S*-metolachlor, effectively controls Palmer amaranth in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.]. The objective of this study was to compare cotton tolerance and Palmer amaranth control with pyroxasulfone, acetochlor, and *S*-metolachlor applied PRE and POST to cotton. Treatments in a field study at four locations included pyroxasulfone at 60, 90, and 120 g a.i. ha^{-1} applied PRE or mixed with glyphosate and applied POST; an encapsulated formulation of acetochlor at 1260 g a.i. ha^{-1} applied PRE or POST with glyphosate; and *S*-metolachlor at 1070 g a.i. ha^{-1} applied POST with glyphosate. Pyroxasulfone PRE increased late-season Palmer amaranth control 14 to 27% and increased yield in one of two years. Similar results were observed with pyroxasulfone and acetochlor applied PRE. Pyroxasulfone, acetochlor, and *S*-metolachlor applied POST with glyphosate did not increase Palmer amaranth control compared with glyphosate alone. Cotton was less tolerant of pyroxasulfone applied PRE or POST than acetochlor applied PRE or POST or *S*-metolachlor applied POST. Cotton growth was reduced 14 to 17% by pyroxasulfone applied PRE and stand was reduced 10 to 25%. Acetochlor PRE reduced cotton growth 6% but did not affect stand. Pyroxasulfone applied POST caused 23 to 36% necrosis 7 d after application and reduced cotton growth 21 to 39% at 14 d after application compared with 6 to 17% necrosis and 3 to 8% growth reduction caused by acetochlor and *S*-metolachlor. Yields were not reduced by any treatment.

Palmer amaranth (*Amaranthus palmeri* S. Wats.) is one of the most common and problematic weeds in cotton (*Gossypium hirsutum* L.) and other agronomic crops in the southern U.S. (Webster, 2013). The biology of this weed, its impact on cotton yield, and the difficulty of control in cotton were reviewed by Culpepper et al. (2010). Prior to commercialization of herbicide-resistant cotton, effective Palmer amaranth control required multiple applications of preplant, preemergence (PRE), and postemergence (POST)-directed herbicides (Wilcut et al., 1995). Cultivation usually supplemented chemical control. These programs were effective if PRE herbicides received timely rainfall for activation and POST-directed herbicides were applied to small weeds (Culpepper and York, 1997). However, the height differential necessary for POST-directed application was difficult to achieve due to rapid growth of Palmer amaranth. Herbicide options for topical POST application were limited. Pyrithiobac, an acetolactate synthase (ALS)-inhibiting herbicide, could be applied POST to control small Palmer amaranth (Branson et al., 2005; Corbett et al., 2004). However, ALS-resistant Palmer amaranth is now common in North Carolina and across the southern U.S. (Heap, 2014; Poirier et al., 2014; Sosnoskie et al., 2011). Fluometuron is registered for topical POST application to cotton (Anonymous, 2014a), but it is not adequately effective on Palmer amaranth (Barnett et al., 2013) and it can substantially injure cotton and reduce yield when applied in this manner (Byrd and York, 1987).

Glyphosate-resistant (GR) cotton was commercialized in 1997, allowing growers to effectively control Palmer amaranth with glyphosate (Culpepper and York, 1998, 1999; Scott et al., 2002). However, with widespread planting of GR crops

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and extensive reliance on glyphosate, resistant biotypes evolved. Resistance to glyphosate has been confirmed in 31 weed species (Heap, 2014). The first confirmation of resistance to glyphosate in an *Amaranthus* species occurred with Palmer amaranth in Georgia in 2005 (Culpepper et al., 2006). By the end of 2014, GR Palmer amaranth had been confirmed in Alabama, Arizona, Arkansas, Delaware, Florida, Georgia, Illinois, Indiana, Kansas, Kentucky, Louisiana, Maryland, Michigan, Mississippi, Missouri, New Jersey, New Mexico, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Texas, and Virginia (Heap, 2014). Multiple resistance to glyphosate and ALS-inhibiting herbicides is also common (Heap, 2014; Poirier et al., 2014; Sosnoskie et al., 2011). Many growers in the southeastern U.S. are now planting glufosinate-resistant cultivars in an effort to control GR Palmer amaranth (USDA-AMS, 2014).

Residual soil-applied herbicides are recommended in cotton management programs for Palmer amaranth (Culpepper et al., 2013; Scott and Smith, 2011; Wilson et al., 2011; York, 2014). The most effective soil-applied herbicides for Palmer amaranth control in cotton in the southeastern U.S. have been flumioxazin and fomesafen (Whitaker et al., 2011b). The chloroacetamide herbicide, *S*-metolachlor, applied PRE, is also effective on Palmer amaranth (Geier et al., 2006; Steele et al., 2005) but PRE application is not recommended on sandy soils typical of southeastern cotton production because of crop injury. In addition to soil-applied residual herbicides, residual herbicides mixed with glyphosate or glufosinate and applied POST are recommended also to extend residual control later into the season (Culpepper et al., 2013; Scott and Smith, 2011; York, 2014). Growers commonly use *S*-metolachlor in this manner (Sosnoskie and Culpepper, 2012), and improvements in Palmer amaranth control have been reported (Clewis et al., 2006; Culpepper et al., 2006; Whitaker et al., 2011a). An additional benefit is smaller weeds at the time of layby herbicide application and, hence, greater control (Clewis et al., 2006). *S*-metolachlor applied POST can injure cotton, but the injury is typically minor and transient, and yields are not adversely affected (Clewis et al., 2006; Culpepper et al., 2009; Dodds et al., 2010; Stephenson et al., 2013; Whitaker et al., 2011a).

Acetochlor, another chloroacetamide herbicide, controls Palmer amaranth and other *Amaranthus* species when applied prior to weed emergence (Bullington et al., 2012; Knezevic et al., 2009; Riar et al., 2012; Steckel et al., 2002; Steele et al., 2005; York et al., 2012). Acetochlor, in an emulsifiable concentrate formulation, applied POST is highly injurious to cotton (A. C. York, unpublished data). However, an encapsulated formulation of acetochlor (Warrant® herbicide, Monsanto Company, St. Louis, MO) was commercially introduced in 2009 (Anonymous, 2014b). Cotton tolerance of this encapsulated acetochlor applied POST has been reported to be similar to tolerance of *S*-metolachlor applied POST (Eure et al., 2013; Miller et al., 2012; Riar et al., 2012). Beginning in 2013, this encapsulated acetochlor was available for PRE application to cotton (Anonymous, 2014b).

Pyroxasulfone, an isoxazoline herbicide, has the same mode of action as chloroacetamide herbicides (Tanetani et al., 2009). Pyroxasulfone, applied PRE to weeds, is effective on Palmer amaranth and other *Amaranthus* species (Bullington et al., 2012; Geier et al., 2006; Knezevic et al., 2009; Olson et al., 2011; Steele et al., 2005). Corn and soybean are tolerant of pyroxasulfone (Geier et al., 2006; Hardwick et al., 2013; Knezevic et al., 2009), and the herbicide is registered for use in those crops (Anonymous, 2014c). Research on cotton tolerance of pyroxasulfone has been limited, and the results have been contradictory. Dodds et al. (2007) and Koger et al. (2008) reported little to no injury to cotton from pyroxasulfone applied PRE at 250 and 208 g ha^{-1}, respectively, on silt loam soils. Doherty et al. (2014) reported that pyroxasulfone applied PRE on a silt loam soil at rates up to 120 g ha^{-1} caused little injury and no impact on yield; pyroxasulfone applied PRE at 240 g ha^{-1}, the maximum rate suggested for corn on fine-textured soils, reduced yield in one of two years. Koger et al. (2008) observed only 13 to 17% injury when pyroxasulfone at 208 g ha^{-1} was applied POST to four-leaf cotton. Collie et al. (2014) reported up to 44% injury with pyroxasulfone at 240 g/ha^{-1} applied POST to 4- to 6-leaf cotton but yield was unaffected. However, on loamy sand soils, Eure et al. (2013) reported that pyroxasulfone at 60 to 180 g ha^{-1} injured cotton 38 to 61%, reduced stand 35 to 76%, and reduced yield 24 to 69%. Pyroxasulfone at the same rates applied POST injured cotton 30 to 40%, and pyroxasulfone at 75 to 180 g ha^{-1} reduced yield 19 to 25%.

The objective of our research was to compare cotton tolerance and Palmer amaranth control with pyroxasulfone, encapsulated acetochlor, and *S*-

metolachlor applied POST and also to determine cotton response and Palmer amaranth control with pyroxasulfone and encapsulated acetochlor applied PRE on coarse-textured soils typical of cotton production in North Carolina.

MATERIALS AND METHODS

The experiment was conducted in two fields, 1.2 km apart, on the Central Crops Research Station near Clayton, NC in 2011. Soils included Wedowee sandy loam (fine, kaolinitic, thermic Typic Kanhapludults) with 0.71% humic matter and pH 5.3 in field 1 and Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with 0.41% humic matter and pH 5.9 in field 2. The experiment was repeated in a different field at the Central Crops Research Station in 2012 and at the Upper Coastal Plains Research Station near Rocky Mount, NC. Soils in 2012 included Norfolk loamy sand with 0.36% humic matter and pH 5.9 at Clayton and Aycock sandy loam (fine-silty, siliceous, subactive, thermic Typic Paleudults) with 0.51% humic matter and pH 5.8 at Rocky Mount. Soils were characterized by the Agronomic Services Division of the North Carolina Department of Agriculture and Consumer Services. Humic matter was determined according to Mehlich (1984).

Each site was naturally infested with Palmer amaranth. Palmer amaranth densities in the non-treated controls, recorded about 1 month after planting, averaged 19 and 47 plants m^{-2} in fields 1 and 2, respectively, at Clayton in 2011. In 2012, Palmer amaranth was present at 8 and 9 plants m^{-2} at Clayton and Rocky Mount, respectively. Large crabgrass (*Digitaria sanguinalis* L.) was present at each location at densities of 15 and 31 plants m^{-2} in fields 1 and 2, respectively, in 2011, and 15 and 5 plants m^{-2} at Clayton and Rocky Mount, respectively, in 2012.

Cotton cultivar PHY 375WRF (Dow AgroSciences, Indianapolis, IN) was planted in both fields on 12 May 2011. In 2012, cotton cultivar FM 1944GLB2 (Bayer CropScience, Research Triangle Park, NC) was planted 1 May and 2 May at Rocky Mount and Clayton, respectively. Cotton was planted on conventionally prepared seedbeds at all Clayton sites. Cotton was planted strip-till into a desiccated wheat (*Triticum aestivum* L.) cover crop at Rocky Mount. All plots at Rocky Mount received a preplant application of glyphosate potassium salt (Roundup POWERMAX® herbicide, Monsanto Co., St. Louis, MO) at 866 g a.e. ha^{-1} plus dimethylamine salt of 2,4-D (Weedar® 64 herbicide, Nufarm, Inc., Burr Ridge, IL) at 532 g a.e. ha^{-1} approximately 3 wk ahead of planting. Additionally, paraquat dichloride (Parazone® 3SL herbicide, Makhteshim Agan of North America, Inc., Raleigh, NC) at 840 g a.e. ha^{-1} plus a crop oil concentrate at 1.0% (v/v) was applied at planting at Rocky Mount. Aldicarb insecticide (Temik® 15G, Bayer CropScience, Research Triangle Park, NC) at 840 g a.i. ha^{-1} was applied in the seed furrow at all locations, and seed were planted 2 to 2.5 cm deep. The experimental design was a randomized complete block with treatments replicated four times. Plot size was four rows by 9 m, with row spacing of 91 cm at Rocky Mount and 97 cm at Clayton.

Treatments in both years included the following: pyroxasulfone (Zidua® herbicide, BASF Corp., Research Triangle Park, NC) applied PRE at 60, 90, and 120 g ha^{-1}; pyroxasulfone at 60, 90, and 120 g ha^{-1}applied POST to two-leaf cotton; pyroxasulfone at 60 g ha^{-1} applied POST to two-leaf cotton and repeated on six-leaf cotton; encapsulated acetochlor at 1260 g ha^{-1} applied POST to two-leaf cotton; encapsulated acetochlor at 1260 g ha^{-1} applied POST to two-cotton and repeated on six-leaf cotton; and *S*-metolachlor (Dual Magnum® herbicide, Syngenta Crop Protection, LLC, Greensboro, NC) at 1070 g ha^{-1} applied POST to two-leaf cotton. An additional treatment in 2012 included acetochlor at 1260 g ha^{-1} applied PRE. A non-treated check was included each year. All plots except the non-treated check received glyphosate POST at 866 g ha^{-1} when cotton had 2, 6, and 12 leaves. A treatment with only glyphosate POST was also included. Acetochlor, *S*-metolachlor, and pyroxasulfone were mixed with the glyphosate in plots scheduled to receive those herbicides POST. Herbicides were applied using CO_2-pressurized backpack sprayers equipped with flat-fan nozzles (DG TeeJet® Drift Guard Flat Spray Tips, TeeJet Technologies, Wheaton, IL) delivering 140 L ha^{-1} at 165 kPa.

Cotton injury and weed control were estimated visually on a 0 to 100 scale according to Frans et al. (1986). Cotton growth reduction and necrosis were determined 14, 25, and 40 DAPRE (d after PRE application) in 2011 or 21, 35, and 50 DAPRE in 2012. Cotton necrosis was recorded 7 and 14 DAPOST1 (d after first POST application) and 7 and 14 DAPOST2 (d after second POST application), and cotton growth reduction was recorded

14 DAPOST1 and 14 DAPOST2. Cotton stands were determined 21 DAPRE. Height of 20 cotton plants per plot was determined 43 and 94 DAPRE in 2011 and 60 and 104 DAPRE in 2012. The recording dates for height corresponded to 14 and 60 DAPOST2. Weed control was estimated visually 14 and 21 DAPRE in 2011 and 2012, respectively, 14 DAPOST1, 14 DAPOST2, and late in the season. Weed fresh weight was determined late in the season by collecting above-ground biomass from a 1-m^2 area in non-treated checks and from three row middles (25 to 26 m^2) in treated plots. Cotton was mechanically harvested to determine seed cotton yield. Non-treated checks were not harvestable due to severe weed infestations, and yield was assumed to be zero. A seed cotton sample was collected from each harvested plot, ginned to determine lint percentage, and subjected to high volume instrument (HVI) analysis to determine fiber length, fiber length uniformity, fiber strength, and micronaire (Sasser, 1981). The HVI analysis was performed by Cotton Incorporated in Cary, NC.

Data were analyzed separately by year because of the additional treatment in 2012. Data were subjected to analysis of variance using the PROC MIXED procedure of SAS (version 9.2; SAS Institute Inc., Cary, NC). Herbicide treatments were a fixed factor, whereas locations and replications were treated as random. Means were separated using Fisher's Protected LSD at $p = 0.05$. Visual estimates of cotton growth reduction, cotton necrosis, and weed control were arcsine square root transformed before analysis (Grafen and Hails, 2002). Weed fresh weights were subjected to the square root (n + 0.5) transformation prior to analysis (Grafen and Hails, 2002). Non-treated checks were excluded from the analysis of variance for all variables except weed fresh weight.

RESULTS AND DISCUSSION

Weed Control. The PRE herbicides received adequate rainfall for activation during both years. In 2011, 2.0 cm of rainfall were received during the first 8 DAPRE (data not shown). In 2012, 5.7 and 4.1 cm of rainfall were received during the first 8 DAPRE at Clayton and Rocky Mount, respectively.

Data for Palmer amaranth and large crabgrass control and fresh weight were averaged over locations within years. At 14 DAPRE, prior to the first glyphosate POST application, pyroxasulfone controlled Palmer amaranth completely in 2011 (Table 1). At 21 DAPRE in 2012, acetochlor applied PRE controlled Palmer amaranth 98% (Table 2). Similar control was noted with pyroxasulfone applied PRE at 90 and 120 g ha^{-1}. Pyroxasulfone at 60 g ha^{-1} was 2 to 4% less effective than acetochlor or the higher rates of pyroxasulfone.

Approximately 10 to 15% of the Palmer amaranth population in 2011 consisted of a GR biotype. Glyphosate alone controlled Palmer amaranth 91, 87, and 85% at 14 DAPOST1, 14 DAPOST2, and late in the season, respectively (Table 1). Pyroxasulfone applied PRE increased control to 99 to 100% at each of these evaluations. A similar trend was noted with Palmer amaranth fresh weight in late season. Palmer amaranth fresh weight was reduced 76% by glyphosate alone and at least 99% by pyroxasulfone PRE followed by glyphosate POST.

A GR biotype comprised a greater percentage of the Palmer amaranth populations in 2012. Glyphosate alone controlled Palmer amaranth only 69, 57, and 66% 14 DAPOST1, 14 DAPOST2, and late in the season, respectively (Table 2). Similar to results in 2011, pyroxasulfone applied PRE increased control at each evaluation. Late-season control by pyroxasulfone applied PRE followed by glyphosate POST was 85 to 93% compared with 66% control by glyphosate alone. A rate response with pyroxasulfone was generally noted. Control by acetochlor applied PRE followed by glyphosate POST was similar to that with pyroxasulfone PRE followed by glyphosate POST. Glyphosate alone did not reduce Palmer amaranth fresh weight (8620 kg ha^{-1} with glyphosate compared with 9585 kg ha^{-1} in the non-treated check). Pyroxasulfone at 60 or 90 g ha^{-1} applied PRE followed by glyphosate reduced fresh weight 65 to 68%, whereas acetochlor or pyroxasulfone at 120 g ha^{-1} followed by glyphosate reduced fresh weight 82 to 84%.

Acetochlor and *S*-metolachlor applied POST in combination with glyphosate or glufosinate are commonly recommended for cotton, especially for fields with GR Palmer amaranth (Culpepper et al., 2013; Scott and Smith, 2011; York, 2014). Neither of these chloroacetamide herbicides mixed with glyphosate or glufosinate would be expected to increase control of emerged weeds. Rather, the objective of using acetochlor or *S*-metolachlor in this manner is to extend residual control of susceptible species, especially Palmer amaranth, farther into the growing season (York, 2014).

Table 1. Palmer amaranth control and fresh weight in 2011 with pyroxasulfone applied preemergence and acetochlor, *S*-metolachlor, and pyroxasulfone applied postemergence[z]

Herbicides and time of application			Application rate			Control				Fresh Weight[w]
PRE[y]	First POST[y]	Second POST[x]	PRE	First POST	Second POST	14 DAPRE[y]	14 DAPOST1[y]	14 DAPOST2[y]	Late-season	
			--------- g ha^{-1} ---------			---------------------- % ----------------------				kg ha^{-1}
None	Glyphosate	Glyphosate		866	866	---	91 b	87 b	85 b	5300 a
Pyroxasulfone	Glyphosate	Glyphosate	60	866	866	100 a	99 a	99 a	99 a	165 bc
Pyroxasulfone	Glyphosate	Glyphosate	90	866	866	100 a	100 a	100 a	99 a	35 c
Pyroxasulfone	Glyphosate	Glyphosate	120	866	866	100 a	100 a	100 a	100 a	15 c
None	Acetochlor + glyphosate	Glyphosate		1260 + 866	866		91 b	91 b	91 b	3155 ab
None	Acetochlor + glyphosate	Acetochlor + glyphosate		1260 + 866	1260 + 866			91 b	85 b	7050 a
None	*S*-Metolachlor glyphosate	Glyphosate		1070 + 866	866		92 b	91 b	91 b	4900 a
None	Pyroxasulfone + glyphosate	Glyphosate		60 + 866	866		89 b	88 b	80 b	8345 a
None	Pyroxasulfone + glyphosate	Glyphosate		90 + 866	866		93 b	90 b	90 b	3690 ab
None	Pyroxasulfone + glyphosate	Glyphosate		120 + 866	866		91 b	88 b	80 b	10,770 a
None	Pyroxasulfone + glyphosate	Pyroxasulfone + glyphosate		60 + 866	60 + 866			87 b	85 b	8360 a

[z] Data averaged over two locations. Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at $p = 0.05$.

[y] Abbreviations: PRE, preemergence; POST, postemergence; DAPRE, days after PRE application; DAPOST1, days after first POST application; DAPOST2, days after second POST application.

[x] The second POST application was made 14 d after the first POST application.

[w] Fresh weight of non-treated control was 22,030 kg ha^{-1}, which was different from all herbicide treatments.

Acetochlor, *S*-metolachlor, and pyroxasulfone, mixed with glyphosate and applied POST, did not increase control of Palmer amaranth nor decrease fresh weight in 2011 (Table 1). Rainfall for herbicide activation was inadequate following the first POST application; only 0.2 cm of rainfall was received between the two POST applications in 2011 (data not shown). Additionally, few Palmer amaranth emerged during the dry conditions following the first POST application.

In contrast to 2011, rainfall was adequate for activation of the residual herbicides applied POST in 2012. At Clayton, 0.4 cm was received within a few hours of the first POST application, and rainfall totaled 7.4 cm in the first 6 d after the first POST application (data not shown). At Rocky Mt, 1.3 and 5.5 cm of rainfall were received on day 1 and day 2, respectively, following the first POST application. In spite of adequate rainfall for activation, the residual herbicides mixed with glyphosate and applied POST did not increase Palmer amaranth control 14 DAPOST2 or late in the season nor reduce weed fresh weight in 2012 compared with glyphosate alone (Table 2). These residual herbicides increased control 8% or less at 14 DAPOST1. Most of the weeds emerged prior to the first glyphosate POST application. Control by the first POST application was mediocre (69 to 77%) because of the GR individuals in the population. Residual herbicides mixed with glyphosate are of little benefit when emerged plants are not controlled by glyphosate (Culpepper et al., 2009).

Large crabgrass was controlled well in 2011 (data not shown). Complete control was observed with all treatments at 14 DAPRE, 14 DAPOST1, and 14 DAPOST2. At the late-season evaluation, control by the glyphosate-only treatment (95%) was statistically less than control by all other treatments. Treatments containing pyroxasulfone PRE at 60 g ha^{-1} and *S*-metolachlor in the first POST application controlled large crabgrass 97%. All other treatments controlled large crabgrass 99 to 100%. No differences in large crabgrass fresh weight were noted among herbicide treatments. Compared to fresh weight in the non-treated control, all herbicide treatments reduced large crabgrass fresh weight at least 99%.

Large crabgrass was also controlled well in 2012 (data not shown). Complete control was obtained 21 DAPRE. Large crabgrass was controlled 93 to 100% 14 DAPOST1, with no differences among treatments. Minor differences were noted at 14 DAPOST2. Compared to control by the glyphosate-only treatment (95%), no improvement in control was noted with PRE herbicides. All residual herbicides applied POST except pyroxasulfone at 60 g ha^{-1} and *S*-metolachlor increased control to at least 98%. The glyphosate-only treatment controlled large crabgrass 97% late in the season, with no differences among herbicide treatments. Compared to fresh weight in the non-treated check (11,813 g ha^{-1}), all herbicide treatments reduced fresh weight at least 99% and there were no differences among herbicide treatments.

Cotton Response. Data for cotton stands, necrosis, height, growth reduction, and yield were averaged over locations within years. Visible injury by pyroxasulfone applied PRE appeared as stand reduction and growth reduction; no necrosis was noted from pyroxasulfone applied PRE. Pyroxasulfone applied PRE at all rates in 2011 reduced stands 13 to 25%; pyroxasulfone at 90 and 120 g ha^{-1} in 2012 reduced cotton stands 10 to 12% (Table 3). Eure et al. (2013) also reported stand reduction by pyroxasulfone applied PRE. Acetochlor applied PRE in 2012 did not impact stands.

Table 2. Palmer amaranth control and fresh weight in 2012 with acetochlor and pyroxasulfone applied preemergence and acetochlor, *S*-metolachlor, and pyroxasulfone applied postemergence[z]

Herbicides and time of application			Application rate			Control				Fresh weight[w]
PRE[y]	First POST[y]	Second POST[x]	PRE	First POST	Second POST	21 DAPRE[y]	14 DAPOST1[y]	14 DAPOST2[y]	Late-season	
			--------- g ha^{-1} ---------			---------------------- % ----------------------				kg ha^{-1}
None	Glyphosate	Glyphosate		866	866	---	69 e	57 c	66 bc	8620 ab
Acetochlor	Glyphosate	Glyphosate	1260	866	866	98 a	96 b	88 ab	91 a	1695 cd
Pyroxasulfone	Glyphosate	Glyphosate	60	866	866	96 b	95 b	78 b	85 a	3390 c
Pyroxasulfone	Glyphosate	Glyphosate	90	866	866	99 a	96 b	83 ab	89 a	3055 cd
Pyroxasulfone	Glyphosate	Glyphosate	120	866	866	100 a	100 a	91 a	93 a	1530 d
None	Acetochlor + glyphosate	Glyphosate		1260 + 866	866		74 cd	55 c	60 bc	7585 ab
None	Acetochlor + glyphosate	Acetochlor + glyphosate		1260 + 866	1260 + 866			58 c	55 c	8210 ab
None	*S*-metolachlor + glyphosate	Glyposate		1070 + 866	866		74 cd	66 c	71 b	5985 b
None	Pyroxasulfone + glyphosate	Glyphosate		60 + 866	866		72 de	60 c	61 bc	9780 a
None	Pyroxasulfone + glyphosate	Glyphosate		90 + 866	866		75 cd	62 c	61 bc	10,200 a
None	Pyroxasulfone + glyphosate	Glyphosate		120 + 866	866		77 c	62 c	66 bc	9615 ab
None	Pyroxasulfone + glyphosate	Pyroxasulfone + glyphosate		60 + 866	60 + 866			55 c	59 bc	9645 ab

[z] Data averaged over two locations. Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at $p = 0.05$.

[y] Abbreviations: PRE, preemergence; POST, postemergence; DAPRE, days after PRE application; DAPOST1, days after first POST application; DAPOST2, days after second POST application.

[x] The second POST application was made 21 d after the first POST application.

[w] Fresh weight of non-treated control was 9585 kg ha^{-1}; only treatments that included acetochlor or pyroxasulfone applied PRE were different from the control.

Table 3. Cotton stand, growth reduction, and height with acetochlor and pyroxasulfone applied preemergence[z]

PRE[y] herbicides	Application rate	Stand[x]		Growth reduction						Height			
				2011			2012			2011		2012	
				DAPRE[y]			DAPRE			DAPRE		DAPRE	
		2011	2012	14	25	40	21	35	50	43	94	60	104
	g ha^{-1}	-- plants 10 m^{-1} --		---------------------- % ----------------------						------------------ cm ------------------			
Acetochlor	1260		117 a				6 b	1 c	0 c			57 a	88 a
Pyroxasulfone	60	92 b	112 ab	14 a	6 b	1 b	15 a	6 b	3 b	31 ab	62 a	53 abc	92 a
Pyroxasulfone	90	83 bc	106 bc	16 a	9 ab	3 ab	14 a	6 b	3 b	29 b	65 a	55 ab	87 ab
Pyroxasulfone	120	79 c	104 c	17 a	11 a	6 a	16 a	12 a	8 a	30 b	67 a	50 c	89 a
None		106 a	118 a							34 a	64 a	52 bc	82 b

[z] Data averaged over two locations in each year. Means within a column followed by the same letter are not different according to Fisher's Protected LSD at $p = 0.05$.

[y] Stand recorded 21 DAPRE.

[x] Abbreviations: PRE, preemergence; DAPRE, days after PRE application.

Cotton growth reduction generally increased as the rate of pyroxasulfone applied PRE increased. Pyroxasulfone reduced growth 14 to 17% at 14 DAPRE in 2011 (Table 3). The amount of growth reduction decreased over time, with 6 to 11% and 1 to 6% reduction noted 25 and 40 DAPRE, respectively. Compared to no PRE herbicide (glyphosate POST only), pyroxasulfone at 90 and 120 g ha^{-1} reduced cotton height 12 to 15% 43 DAPRE, but no height reduction was noted 94 DAPRE. Similar results were observed in 2012. Pyroxasulfone applied PRE reduced cotton growth 14 to 16% 21 DAPRE, 6 to 12% 35 DAPRE, and 3 to 8% 50 DAPRE. Only 6% growth reduction was noted with acetochlor PRE at 21 DAPRE, and little to no reduction was noted at later evaluations. Regardless of the injury observed earlier in the season, pyroxasulfone applied PRE did not reduce cotton height 60 DAPRE. Acetochlor increased cotton height 60 DAPRE relative to no PRE herbicide. This is a reflection of greater weed control (Table 2), but only minor injury with this treatment. At 104 DAPRE, all herbicides applied PRE increased cotton height (Table 3), again a reflection of weed control.

Both necrosis and growth reduction were observed with acetochlor, *S*-metolachlor, and pyroxasulfone applied POST, with pyroxasulfone having the greatest effect. Pyroxasulfone included with the first POST glyphosate application caused 23 to 36% necrosis at 7 DAPOST1 (Table 4). This was greater than the 9 to 17% and 6 to 16% necrosis noted 7 DAPOST1 with acetochlor and *S*-metolachlor, respectively. The necrosis caused by pyroxasulfone became less obvious over time as the cotton continued to grow and develop new foliage. By 28 DAPOST1 (14 DAPOST2 in 2011, 7 DAPOST2 in 2012), only 3 to 6% necrosis was noted with pyroxasulfone mixed with glyphosate in the first POST application.

Significant growth reduction was noted with pyroxasulfone applied POST. Pyroxasulfone mixed with glyphosate at the first POST application caused 32 to 39% growth reduction 14 DAPOST1 in 2011 (Table 5). Growth reduction by pyroxasulfone was likely an indirect effect caused by necrosis of the foliage and the slower growth that resulted from loss of leaf surface area for photosynthesis. The cotton was slow to recover from the initial pyroxasulfone injury. Growth was still reduced 27 to 38% at 14 DAPOST2 and height was reduced 26 to 29%. In contrast, cotton growth was reduced only 3 to 8% at 14 DAPOST1 by acetochlor or *S*-metolachlor, and no growth reduction or height reduction was noted 14 DAPOST2. In 2012, pyroxasulfone mixed with glyphosate at the first POST application caused 21 to 29% growth reduction 14 DAPOST1 compared to 3 to 6% growth reduction by acetochlor or *S*-metolachlor. The cotton recovered from the initial injury somewhat better in 2012 as compared with 2011, likely due to more optimum growing conditions in 2012. Cotton growth was reduced only 11 to 14% at 14 DAPOST2 in 2012. Cotton height 14 DAPOST2 was reduced 15 to 17% by pyroxasulfone, but no height reduction was noted with acetochlor or *S*-metolachlor.

Table 4. Cotton necrosis following postemergence application of acetochlor, *S*-metolachlor, and pyroxasulfone[z]

POST herbicides		Application rate		Necrosis							
				2011				2012			
				DAPOST1[y]		DAPOST2[y]		DAPOST1		DAPOST2	
First POST[y]	Second POST[x]			7	14	7	14	7	14	7	14
		-------- g ha^{-1} --------		---------- % ----------							
Glyphosate	Glyphosate	866	866	0 f	0 d	0 f	0 e	0 e	0 d	0 d	0 c
Acetochlor + glyphosate	Glyphosate	1260 + 866	866	9 e	7 c	3 e	2 d	17 c	6 c	0 d	0 c
Acetochlor + glyphosate	Acetochlor + glyphosate	1260 + 866	1260 + 866			5 d	5 c			6 b	3 b
S-Metolachlor + glyphosate	Glyphosate	1070 + 866	866	16 d	6 c	3 e	2 d	6 d	3 c	0 d	0 c
Pyroxasulfone + glyphosate	Glyphosate	60 + 866	866	29 c	25 b	9 c	5 c	23 b	14 b	3 c	0 c
Pyroxasulfone + glyphosate	Glyphosate	90 + 866	866	33 b	27 b	10 c	5 c	27 ab	16 ab	3 c	0 c
Pyroxasulfone + glyphosate	Glyphosate	120 + 866	866	36 a	30 a	12 b	6 b	30 a	19 a	3 c	0 c
Pyroxasulfone + glyphosate	Pyroxasulfone + glyphosate	60 + 866	60 + 866			29 a	22 a			28 a	6 a

[z] Data averaged over two locations in each year. Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at $p = 0.05$.

[y] Abbreviations: POST, postemergence; DAPOST1, days after first POST application; DAPOST2, days after second POST application.

[x] The second POST application was made 14 and 21 d after the first POST application in 2011 and 2012, respectively.

Table 5. Cotton growth reduction and cotton height following postemergence application of acetochlor, *S*-metolachlor, and pyroxasulfone[z]

POST herbicides		Application rate		Growth reduction				Height			
				14 DAPOST1[y]		14 DAPOST2[y]		14 DAPOST2		60 DAPOST2	
First POST[y]	Second POST[x]			2011	2012	2011	2012	2011	2012	2011	2012
		-------- g ha^{-1} --------		---------- % ----------				---------- cm ----------			
Glyphosate	Glyphosate	866	866	0 d	0 d	0 f	0 c	34 a	52 a	64 a	82 ab
Acetochlor + glyphosate	Glyphosate	1260 + 866	866	3 cd	6 c	0 f	6 c	31 ab	47 ab	64 a	82 ab
Acetochlor + glyphosate	Acetochlor + glyphosate	1260 + 866	1260 + 866			0 f	6 c	30 b	46 b	61 a	79 b
S-Metolachlor + glyphosate	Glyphosate	1070 + 866	866	8 c	3 cd	0 f	4 c	33 ab	52 a	68 a	86 a
Pyroxasulfone + glyphosate	Glyphosate	60 + 866	866	33 b	21 b	27 d	11 b	24 c	44 b	62 a	80 b
Pyroxasulfone + glyphosate	Glyphosate	90 + 866	866	32 b	24 ab	33 c	12 b	25 c	43 b	62 a	80 b
Pyroxasulfone + glyphosate	Glyphosate	120 + 866	866	39 a	29 a	38 b	14 b	24 c	44 b	63 a	81 b
Pyroxasulfone + glyphosate	Pyroxasulfone + glyphosate	60 + 866	60 + 866			48 a	18 a	25 c	43 b	62 a	77 b

[z] Data averaged over two locations in each year. Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at $p = 0.05$.

[y] Abbreviations: POST, postemergence; DAPOST1, days after first POST application; DAPOST2, days after second POST application.

[x] The second POST application was made 14 and 21 d after the first POST application in 2011 and 2012, respectively.

Pyroxasulfone applied twice POST also had a greater impact on cotton than acetochlor applied twice. Pyroxasulfone applied twice caused 28 to 29% necrosis 7 DAPOST2 compared with 5 to 6% necrosis by acetochlor applied twice (Table 4). As noted earlier, the cotton was better able to recover from injury in 2012. Necrosis 14 DAPOST2 with pyroxasulfone applied twice was estimated at 22% in 2011 but only 6% in 2012. Cotton growth 14 DAPOST2 was reduced 48 and 18% in 2011 and 2012, respectively, and cotton height was reduced 26 and 17%, respectively (Table 5). Pyroxasulfone applied twice at 60 g ha^{-1} was more injurious than pyroxasulfone applied once at 120 g ha^{-1}. Eure et al. (2013) reported a similar effect.

No yield differences were observed among herbicide treatments in 2011 (Table 6). Palmer amaranth control by glyphosate alone was generally good in 2011 (Table 1), especially earlier in the season when weed competition would be expected to have the greatest impact, and the increase in Palmer amaranth control with pyroxasulfone applied PRE was not reflected in yield. Acetochlor, S-metolachlor, and pyroxasulfone applied POST did not increase Palmer amaranth control in 2011 (Table 1) but also did not impact cotton yield (Table 6). Compared with glyphosate alone in 2012, cotton yield was increased 30 to 40% when acetochlor or pyroxasulfone was applied PRE. This reflects less than adequate Palmer amaranth control by glyphosate alone due to a greater percentage of the GR biotype in the population in 2012 and the increase in control due to PRE herbicides (Table 2). Acetochlor, *S*-metolachlor, and pyroxasulfone applied POST had only minor effects on Palmer amaranth control in 2012 and no effect on yield (Table 6).

Table 6. Cotton lint yield as affected by pyroxasulfone and acetochlor applied preemergence and pyroxasulfone, acetochlor, and *S*-metolachlor applied postemergence[z]

Herbicides and time of application			Application rate			Yield	
PRE[y]	First POST[y]	Second POST[x]	PRE	First POST	Second POST	2011	2012
			------------------- g ha^{-1} -------------------			---------- kg ha^{-1} ----------	
None	Glyphosate	Glyphosate		866	866	1170 a	1280 cde
Acetochlor	Glyphosate	Glyphosate	1260	866	866	---	1790 a
Pyroxasulfone	Glyphosate	Glyphosate	60	866	866	1230 a	1670 a
Pyroxasulfone	Glyphosate	Glyphosate	90	866	866	1270 a	1670 a
Pyroxasulfone	Glyphosate	Glyphosate	120	866	866	1250 a	1710 a
None	Acetochlor + glyphosate	Glyphosate		1260 + 866	866	1230 a	1330 cd
None	Acetochlor + glyphosate	Acetochlor + glyposate		1260 + 866	1260 + 866	1160 a	1160 de
None	*S*-Metolachlor + glyphosate	Glyphosate		1070 + 866	866	1250 a	1430 bc
None	Pyroxasulfone + glyphosate	Glyphosate		60 + 866	866	1090 a	1150 de
None	Pyroxasulfone + glyphosate	Glyphosate		90 + 866	866	1090 a	1060 e
None	Pyroxasulfone + glyphosate	Glyphosate		120 + 866	866	1140 a	1250 cde
None	Pyroxasulfone + glyphosate	Pyroxasulfone + glyphosate		60 + 866	60 + 866	1050 a	1080 e

[z] Data averaged over two locations in each year. Means within a column followed by the same letter are not different according to Fisher's Protected LSD Test at $p = 0.05$.

[y] Abbreviations: PRE, preemergence; POST, postemergence.

[x] The second POST application was made 14 and 21 d after the first POST application in 2011 and 2012, respectively.

Cotton yield in this experiment was a function of both weed control and herbicide injury, and it is not possible to separate the effects of those two factors. An experiment conducted under weed-free conditions would be necessary to definitively determine the impact of pyroxasulfone on cotton yield. Crop injury by pyroxasulfone applied PRE might have offset the impact of greater Palmer amaranth control in 2011. However, pyroxasulfone applied POST caused considerable injury both years but had little to no effect on Palmer amaranth control. The cotton appeared to recover from injury caused by pyroxasulfone applied POST. No injury was visible late in the season (data not shown), and cotton height was not reduced 60 DPAPOST2 (Table 5). Recovery from injury is consistent with other reports (Koger et al. 2008; Collie et al., 2014).

Compared with glyphosate alone, acetochlor, *S*-metolachlor, and pyroxasulfone, regardless of time of application, did not impact fiber quality. There were no differences among herbicide treatments for the fiber quality parameters determined. Averaged over herbicide treatments, the respective fiber quality parameters in 2011 and 2012 included the following: micronaire, 5.2 and 4.5; fiber length, 268 and 295 mm; fiber length uniformity index, 81 and 83%; and fiber strength, 28.1 and 31.3 g tex^{-1} (data not shown). Herbicides seldom adversely affect fiber quality (Culpepper and York, 1998, 1999; Jordan et al., 1993; Snipes and Byrd, 1994; Whitaker et al., 2011a).

Pyroxasulfone can effectively control Palmer amaranth, as documented in this and other studies (Bullington et al., 2012; Doherty et al., 2014; Geier et al., 2006; Grey et al., 2014; Knezevic et al., 2009; Olson et al., 2011; Steele et al., 2005). However, even though pyroxasulfone did not negatively impact cotton yield in this experiment, the amount of crop injury caused by pyroxasulfone applied PRE or POST (Tables 3-5) on coarse-textured, low organic matter soils is commercially unacceptable (Eure et al., 2013). In light of the results of Dodds et al. (2007), Doherty et al. (2014), and Koger et al. (2008), where little to no injury was observed with pyroxasulfone applied PRE in Arkansas and Mississippi, more research is needed to determine the potential for PRE application of pyroxasulfone to cotton on medium- and fine-textured soils or soils with higher organic matter contents. Pyroxasulfone is currently registered only for POST-directed application to cotton after the five-leaf stage (Anonymous, 2014d). There is no published research on the herbicide used in this manner, but one might assume that cotton tolerance would be better with directed application and minimal contact with the cotton plant. Preliminary research in North Carolina (A. C. York, unpublished data) indicates good cotton tolerance with pyroxasulfone POST-directed.

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