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Cotton tolerance to halauxifen-methyl applied preplant

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Research Article

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Abstract

Auxin herbicides are used in combinations to control glyphosate-resistant horseweed preplant burndown. Herbicide labels for 2,4-D–containing products require a 30-d rotation interval for planting cotton cultivars not resistant to 2,4-D. Dicamba labels require an accumulation of 2.5 cm of rain plus 21 d per 280 g ae ha^{-1} rotation interval for planting cotton cultivars not resistant to dicamba. Previous research has shown that cotton injury caused by dicamba applied 14 d before planting was transient with little effect on cotton yield, whereas 2,4-D has little effect on cotton when applied 7 d prior to planting. Injury caused by dicamba and 2,4-D is inversely related to rainfall received between herbicide application and cotton planting. Experiments were conducted to evaluate cotton tolerance to halauxifen-methyl, a new Group 4 herbicide, applied at intervals shorter than labeled requirements. Experiments were established near Painter and Suffolk, VA, and Belvidere, Clayton, Eure, Lewiston, and Rocky Mount, NC, during the 2017 and 2018 growing seasons. Herbicide treatments included halauxifen, dicamba, and 2,4-D applied 4, 3, 2, 1, and 0 wk before planting (WBP). Visible estimates of cotton growth reduction and total injury were collected 1, 2, and 4 wk after cotton emergence (WAE). Cotton stand and percentage of plants with distorted leaves were recorded 2 and 4 WAE. Cotton plant heights were recorded 4 and 8 WAE. Halauxifen was less injurious (9%) than dicamba (26%) or 2,4-D (21%) 2 WAE when herbicides were applied 0 WBP. Cotton stand reduction 2 WAE by halauxifen was less than 2,4-D and dicamba when applied 0 WBP. Injury observed from herbicides applied 1, 2, 3, and 4 WBP was minor, and no significant differences in cotton stand were observed. Early-season cotton injury was transient, and seed cotton yield was unaffected by any treatment.

Introduction

Since conservation compliance provisions were implemented in the 1985 farm bill (Gillespie et al. 1990), conservation tillage has been widely adopted. During 2008, nearly 35% of US cotton was in conservation or reduced-tillage systems (CTIC 2008). With decreasing tillage, preplant herbicides have become essential (York et al. 2004). Glyphosate and paraquat have traditionally been relied upon to control most weeds preplant. Prior to selection for resistance, glyphosate provided excellent horseweed control (87% to 100%) (Bruce and Kells 1990; Scott et al. 1998). Paraquat adequately controls smaller horseweed; however, paraquat-resistant biotypes have been identified (Eubank et al. 2008; Heap 2018; Keeling et al. 1989). In response to horseweed resistant to glyphosate, acetolactate synthase (ALS)–inhibitors, and photosystem II inhibitors, cotton producers turned to synthetic auxin herbicides to control this troublesome weed preplant (Bruce and Kells 1990; Wilson and Worsham 1988; York et al. 2004). Dicamba and 2,4-D are the most widely used synthetic auxins for herbicide-resistant horseweed control prior to planting cotton (Byker et al. 2013; Flessner et al. 2015; Kruger et al. 2010). In the southeastern United States, these herbicides are typically applied 3 to 4 wk prior to cotton planting in combination with glyphosate for control of emerged horseweed and other winter annual weeds and with flumioxazin for residual weed control (Cahoon et al. 2014). However, 2,4-D does not consistently control horseweed that has bolted and is taller than 10 cm (Keeling et al. 1989).

Halauxifen-methyl is a new Group 4, synthetic auxin herbicide and a member of the pyridine-2-carboxylate (or arylpicolinate) herbicide family (Epp et al. 2016; WSSA 2018). Other members of the pyridine-2-carboxylate family include picloram, clopyralid, and aminopyralid (Epp et al. 2016). Halauxifen is marketed for use preplant burndown targeting broadleaf annual weeds (Anonymous 2018a). Halauxifen is also being marketed in a premix with florasulam, an

Table 1. Locations, soil descriptions, planting dates, and harvest dates at the North Carolina and Virginia research locations, 2017 and 2018.

Location	Year	Soil series	Soil texture	pH	Humic matter[i]	Plot length	Planting date	Harvest date
						m		
Painter, VA	2017	Bojac[a]	Sandy loam	6.4	0.50	9.1	May 9	November 20
Suffolk, VA	2017	Kenansville[b]	Sandy loam	6.3	0.45	9.1	May 17	November 7
Clayton, NC	2017	Dothan[c]	Loamy sand	6.4	0.27	9.1	May 9	October 27
Rocky Mount, NC	2017	Aycock[d]	Sandy loam	5.9	0.36	15.2	May 9	October 3
Belvidere, NC	2018	Seabrook[e]	Loamy sand	5.7	1.08	7.6	May 16	October 10
Eure, NC	2018	Conetoe[f]	Loamy sand	6.2	0.27	7.6	May 24	October 30
Lewiston, NC	2018	Goldsboro[g]	Sandy loam	5.8	1.14	9.1	May 10	October 30
Rocky Mount, NC	2018	Norfolk[h]	Loamy sand	6.0	0.51	15.2	May 9	October 18

[a] Coarse-loamy, mixed, semiactive, thermic Typic Hapludults.
[b] Loamy, siliceous, subactive, thermic Arenic Hapludults.
[c] Fine-loamy, kaolinitic, thermic Plinthic Kandiudults.
[d] Fine-silty, siliceous, subactive, thermic Typic Paleudults.
[e] Loamy-sand, mixed, thermic Aquic Udipsamments.
[f] Loamy, mixed, semiactive, thermic Arenic Hapludults.
[g] Fine-loamy, siliceous, subactive, thermic Aquic Paleudults.
[h] Fine-loamy, kaolinitic, thermic Typic Kandiudults.
[i] Humic matter determined according to Mehlich (1984).

ALS-inhibiting herbicide, for POST control of broadleaf weeds in wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and triticale (*Triticosecale rimpaui* C. Yen & J.L. Yang [*Secale cereal* × *Triticum aestivum*) (Anonymous 2018b).

In previous research, halauxifen controlled horseweed similarly to 2,4-D and dicamba (Ellis et al. 2017; McCauley and Young 2016; Zimmer et al. 2018a, 2018b). Askew (2018) reported that halauxifen controlled small (5 cm tall) and large (15 cm tall) horseweed 98% and 69%, respectively. In the same study, the researchers determined that halauxifen effectively controlled henbit (*Lamium amplexicaule* L.) and common vetch (*Vicia sativa* L.). Similar to these observations, Zimmer et al. (2018a, 2018b) observed 87% to 97% control of glyphosate-resistant horseweed from treatments containing halauxifen. In another study, halauxifen and dicamba controlled 30-cm-tall glyphosate-resistant horseweed 80%, whereas 2,4-D provided ≤50% control (McCauley and Young 2016).

Most labels for 2,4-D–containing products require preplant application 30 d prior to cotton planting (Anonymous 2018c, 2018d, 2018e; York and Cahoon 2018). Other 2,4-D products require 90 d between application and planting of a nonlabeled crop (Anonymous 2018f, 2018g; York et al. 2004). Enlist Duo™ and Enlist One™, products containing 2,4-D choline salt, are labeled for use in cotton with the Enlist™ trait and may be applied any time prior to or during planting of Enlist™ cotton cultivars (Anonymous 2018h, 2018i). Dicamba formulations labeled prior to planting cotton require 2.5 cm of rainfall or overhead irrigation and 21 d per 280 g acid equivalent (ae) ha^{-1} rotation interval prior to planting cotton that is not resistant to dicamba (Anonymous 2018j, 2018k, 2018l, 2018m; York et al. 2004). Low-volatility dicamba products are labeled for preplant, PRE, and POST use in dicamba-resistant cotton. In previous research, injury to cotton that is not resistant to dicamba from dicamba applied preplant burndown seemed to be inversely correlated with rainfall between application and planting (Ferguson 1996). No cotton injury was observed when at least 2.5 cm of rain fell between herbicide applications and cotton planting; however, dicamba injured cotton more than 2,4-D when <2.5 cm of rainfall was received between application and cotton planting (Guy and Ashcraft 1996). York et al. (2004) observed similar results; dicamba, regardless of rate, was more injurious than 2,4-D when applied sooner than 21 d prior to planting cotton. However, early-season injury caused by dicamba was transient and had little effect on cotton yield when applied ≥2 wk before planting (WBP). In the same study, 2,4-D injured cotton at only one of seven locations when applied 1 WBP. Similar to findings by Ferguson (1996) and Guy and Ashcraft (1996), York et al. (2004) noted that cotton injury from 2,4-D and dicamba applied preplant was inversely related to rainfall received between herbicide applications and cotton planting. Halauxifen currently has a 14-d rotational interval to corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) and a 30-d rotational interval to cotton (Anonymous 2018a). Although cotton response to 2,4-D and dicamba applied preplant burndown sooner than product labels allow is well understood, research is limited on cotton tolerance to halauxifen applied <30 d prior to planting. The objective of this study was to evaluate cotton tolerance to halauxifen when applied preplant burndown at intervals <30 d prior to planting.

Materials and Methods

Experiments were conducted at the Eastern Shore Agriculture Research and Extension Center near Painter, VA (37.5909°N, 75.8216°W), at the Tidewater Agriculture Research and Extension Center near Suffolk, VA (36.7282°N, 76.5836°W), at the Central Crops Research Station near Clayton, NC (35.6507°N, 78.4564°W), and at the Upper Coastal Plain Research Station near Rocky Mount, NC (35.9382°N, 77.7905°W) during the 2017 growing season. During the 2018 growing season, experiments were conducted at the Tidewater Agronomics Research Farm near Belvidere, NC (36.2688°N, 76.5358°W), a producer's field near Eure, NC (36.4202°N, 76.6875°W), at the Peanut Belt Research Station near Lewiston, NC (36.1229°N, 77.1766°W), and at the Upper Coastal Plain Research Station near Rocky Mount. Soils are described in Table 1. The experiment was arranged in a randomized complete block design with treatments replicated four times. Treatment structure was a four-by-five factorial arrangement of four herbicide treatments by five preplant burndown timings. Herbicide treatments included nontreated, 2,4-D dimethylamine salt applied at 1,060 g ae ha^{-1}, dicamba diglycolamine salt applied at 280 g ae ha^{-1}, and halauxifen-methyl applied at 5 g ae ha^{-1}. These herbicides were applied 4, 3, 2, 1, and 0 WBP. Applications at 0 WBP were made approximately 1 h before planting. Plots were four 91-cm wide rows by 8 to 15 m in length, depending upon location. Herbicide and adjuvant sources are listed in Table 2.

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Table 2. Herbicides and adjuvants used in experiments.[a]

Herbicides and adjuvants	Trade name	Formulation concentration	Application rate	Manufacturer
			g ae or ai ha^{-1}	
Halauxifen-methyl	Elevore	69 g ae L^{-1}	5	Corteva Agriscience
Dicamba diglycolamine salt	Clarity	480 g ae L^{-1}	280	BASF
2,4-D dimethylamine salt	Weedar 64	456 g ae L^{-1}	1,064	Nufarm Inc.
Halauxifen-methyl + florasulam	Quelex	10.4 + 10% wt wt^{-1}	5.5 + 5.3	Corteva Agriscience
Glyphosate potassium salt	Roundup PowerMAX	540 g ae L^{-1}	1,260	Monsanto Co.
Glufosinate-ammonium	Liberty	280 g ai L^{-1}	655	BASF
Paraquat dichloride	Parazone	360 g ai L^{-1}	840	Adama

[a] Specimen labels for each product and mailing addresses and web site addresses of each manufacture can be found at www.cdms.net.

Stoneville cotton cultivars 'ST 4946GLB2' or 'ST 5020GLT' (Bayer CropScience, Research Triangle Park, NC), resistant to glufosinate and glyphosate, were planted on dates listed in Table 1. Cultivars without 2,4-D or dicamba tolerance were selected to avoid the possibility of either trait conferring tolerance to halauxifen. Cotton at both Virginia locations and the Eure location was planted using a strip-tillage system; however, strip-tillage occurred prior to any herbicide applications so as not to disturb herbicides. At the Clayton, Lewiston, and Rocky Mount 2017 and 2018 locations, cotton was planted no-till. At the Belvidere location, cotton was planted using conventional tillage, with tillage occurring prior to application of herbicides. Trials in Clayton, Eure, Lewiston, Painter, and Suffolk received glyphosate at 1,260 g ae ha^{-1} plus glufosinate at 655 g ai ha^{-1} applied immediately prior to planting, whereas Rocky Mount received paraquat applied at 840 g ai ha^{-1} (Table 2). Plots were maintained weed-free at all locations using glyphosate plus glufosinate applied in-season as needed at the rates listed above. Experiments in Clayton and Rocky Mount 2017 received aldicarb [2-methyl-2-(methylthio)propionaldehyde *O*-(methylcarbamoyl)oxime] insecticide (Temik®; Bayer CropScience, Research Triangle Park, NC) applied in-furrow at 5,600 g ai ha^{-1}. Experiments in Eure and Belvidere received imidacloprid [1-(6-chloro-3-pyridinylmethyl)-*N*-nitroimidazolidin-2-ylideneamine] (Admire Pro™; Bayer CropScience, Research Triangle Park, NC) applied in-furrow at 370 g ai ha^{-1}. All other locations received acephate (O,S-Dimethyl acetylphosphoramidothioate) (Orthene® 97; AMVAC, Newport Beach, CA) applied POST at 204 g ai ha^{-1}. All other agronomic practices varied among locations but were consistent with recommendations for the region (Edmisten et al. 2018).

Interest is increasing in halauxifen plus florasulam applied preplant burndown for control of herbicide-resistant horseweed and other winter annual weeds. However, the current label for halauxifen plus florasulam premix products prohibits planting cotton within 90 d of the application (Anonymous 2018b). To determine when halauxifen plus florasulam can be safely applied preplant prior to planting cotton, halauxifen plus florasulam premix applied 2 and 4 WBP was added to experiments during 2018. Halauxifen plus florasulam premix was applied at 5.3 g ae ha^{-1} halauxifen plus 5.3 g ai ha^{-1} florasulam. Herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TTI 11001 Turbo TeeJet® Induction Flat Spray Tip; TeeJet Technologies, Wheaton, IL). Applications were made at 140 L ha^{-1} of solution delivered at 206 kPa.

Weekly rainfall totals prior to cotton planting, for the first 10 d after planting and accumulated rainfall between each application and cotton emergence can be found in Table 3. Cotton growth reduction and total injury, recorded separately, were estimated visually 1, 2, and 4 wk after emergence (WAE) using a 0 to 100% scale, where 0 = no injury and 100 = complete crop death. Cotton stand and percentage of plants with distorted leaves were recorded 2 and 4 WAE. Cotton stand was determined by counting all cotton plants in the middle two rows of each plot. Leaf distortion was determined by counting the number of plants with visibly distorted leaves in the middle two rows of each plot and dividing that by the total number of plants (York et al. 2004). Thrips were managed early in the season according to North Carolina Extension recommendations to ensure that insect injury did not mask cotton response to herbicide treatments (Edmisten et al. 2018). Cotton plant height was recorded from 10 plants in each of the middle two rows of a plot at 4 and 8 WAE. Plots were harvested on dates listed in Table 1 using a spindle-type picker modified for small-plot research and weighed to determine seed cotton yield.

Data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS software (version 9.4, SAS Institute Inc., Cary, NC). Application timing and herbicide treatment were considered fixed factors, whereas location and replications were treated as random. Because the halauxifen plus florasulam premix was only evaluated during 2018, a separate analysis, using the aforementioned statistical procedure, was used to analyze 2018 data including halauxifen plus florasulam applied 2 and 4 WBP. The three-way interaction of application timing, herbicide treatment, and location was significant for cotton growth reduction, total injury, leaf distortion, and cotton stand 2 an 4 WAE. However, the *F* values associated with the main effects of application timing and herbicide treatment were at least 10 times greater than the *F* values associated with the interaction; hence, data were pooled across locations. Furthermore, the main effect of application timing and herbicide treatment as well as the two-way interaction of application timing by herbicide treatment were significant for cotton growth reduction, total injury, leaf distortion, and cotton stand 2 and 4 WAE. However, little injury was observed from herbicides applied 1, 2, 3, and 4 WBP, whereas herbicides applied 0 WBP were more injurious. Exclusion of data for the 0 WBP timing allowed pooling of growth reduction, total injury, and stand data for 1, 2, 3, and 4 WBP. Data from the 0 WBP applications are presented separately. The two-way interaction of application timing by herbicide treatment was not significant for cotton height and seed cotton yield. Data for these parameters are presented pooled over all application timings. Means were separated using Fisher's protected LSD at $P = 0.05$ when appropriate.

Results and Discussion

Cotton response to herbicides applied at planting

Cotton treated with dicamba and 2,4-D at 0 WBP was slower to emerge than cotton treated with halauxifen at the same timing and slower also than nontreated cotton. Cotton stand totaled 87 plants 10 m row^{-1} in nontreated 2 WAE and was similar to cotton stand in plots treated with halauxifen 0 WBP (83 plants 10 m row^{-1})

Table 3. Rainfall 1 to 28 d before planting (DBP) and for the first 10 d after planting (DAP), and accumulated rainfall between each application and cotton emergence.

		Rainfall					Accumulated rainfall[a]				
Location	Year	22 to 28 DBP	15 to 21 DBP	8 to 14 DBP	1 to 7 DBP	0 to 10 DAP	4 WBP[a]	3 WBP	2 WBP	1 WBP	0 WBP
		cm									
Painter, VA	2017	0	2.4	1.4	6.0	6.4	16.2	16.2	13.8	12.4	6.4
Suffolk, VA	2017	2.7	0.9	1.7	1.8	6.2	13.3	10.6	9.7	8	6.2
Clayton, NC	2017	5.1	7.6	0	2.2	2.6	17.5	12.4	4.8	4.8	2.6
Rocky Mount, NC	2017	1.8	9.1	4.8	4.1	1.8	21.6	19.8	10.7	5.9	1.8
Belvidere, NC	2018	0	1.9	1.9	0.8	6.7	11.3	11.3	9.4	7.5	6.7
Eure, NC	2018	0.1	0	1.5	1.8	1.7	5.1	5	5	3.5	1.7
Lewiston, NC	2018	3.2	4.7	0	2.8	5.6	16.3	13.1	8.4	8.4	5.6
Rocky Mount, NC	2018	1.8	9.1	4.8	4.1	1.8	21.6	19.8	10.7	5.9	1.8

[a] WBP, weeks before planting. Cotton emergence occurred at least 10 DAP.

Table 4. Cotton growth reduction, total injury, distorted leaf, and stand 2 and 4 wk after emergence (WAE) in response to halauxifen, dicamba, and 2,4-D applied at planting at all locations.[a,b]

	Growth reduction		Total injury		Distorted leaf		Cotton stand	
Herbicide[c]	2 WAE	4 WAE	2 WAE	4 WAE	2 WAE	4 WAE	2 WAE	4 WAE
	%						plants 10 m row^{-1}	
Halauxifen	3 c	0 c	9 c	0 b	6 b	0 c	83 a	84 a
Dicamba	20 a	10 a	26 a	12 a	22 a	5 a	74 b	77 a
2,4-D	17 b	8 b	21 b	11 a	9 b	2 b	72 b	76 a
Nontreated	–	–	–	–	–	–	87 a	88 a

[a] Herbicides applied immediately prior to planting were allowed to dry for 1 h prior to planting.
[b] Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05.
[c] Halauxifen, dicamba, and 2,4-D were applied at 5, 280, and 1,060 g ae ha^{-1}, respectively. Herbicide sources can be found in Table 2.

(Table 4). Relative to nontreated cotton, dicamba and 2,4-D applied 0 WBP reduced cotton stand 15% to 17% 2 WAE. At 4 WAE, cotton stand totaled 76, 77, 84, and 88 plants 10 m row^{-1} in response to 2,4-D, dicamba, halauxifen, and no herbicide, respectively. York et al. (2004) reported that dicamba (280 g ha^{-1}) and 2,4-D (1,060 g ha^{-1}) reduced cotton stand when applied 1 WBP in a strip-till system. These researchers did not investigate cotton response to these herbicides applied at planting.

Cotton response was greatest when synthetic auxin herbicides were applied at planting. Dicamba applied at planting caused 20% and 10% growth reduction 2 and 4 WAE, respectively, which was the greatest growth reduction among herbicides evaluated (Table 4). Growth reduction in response to 2,4-D applied 0 WBP was 2% to 3% less than response to dicamba. Halauxifen was the safest of all auxin herbicides evaluated, reducing cotton growth 3% and 0% 2 and 4 WAE, respectively. Total cotton injury followed a trend similar to that of growth reduction. Dicamba applied at-planting caused 26% total injury 2 WAE and was more injurious than 2,4-D (21%) and halauxifen (9%). Overall, injury decreased as the season progressed. At 4 WAE, dicamba and 2,4-D caused similar injury (11% to 12%). Early cotton injury caused by halauxifen was transient, with no injury observed 4 WAE.

Typical injury from low doses of synthetic auxin herbicides or preplant applications of these herbicides includes malformed leaves, twisting and bending of stems, and cracked or swollen stems (Al-Khatib and Peterson 1999; Andersen et al. 2004; Auch and Arnold 1978; Guy and Ashcraft 1996; Kelley et al. 2005; Sciumbato et al. 2004; Solomon and Bradley 2014; Wax et al. 1969; York et al. 2004). To capture this injury in these experiments, percentage of plants with visible leaf distortion was determined similar to methods outlined by York et al. (2004). Dicamba caused the greatest percentage of cotton plants with distorted leaves 2 WAE (22%), whereas fewer plants exhibited visible leaf distortion when treated with 2,4-D or halauxifen (6% to 9%). Cotton leaf distortion symptomology caused by halauxifen differed from dicamba and 2,4-D. Whereas 2,4-D and dicamba produced leaf strapping and leaf cupping, respectively, halauxifen caused cotton leaves to curl or roll upward much like early cotton symptomology resulting from aminopyralid exposure (Rhodes et al. 2015). At 4 WAE, dicamba continued to cause some leaf distortion; leaf distortion in response to dicamba at this time was 5%, whereas 2% leaf distortion was noted with 2,4-D, and no leaf distortion was observed in plots treated with halauxifen.

Cotton response to herbicides applied prior to planting

Cotton response was minimal from herbicides applied 1, 2, 3, and 4 WBP; therefore, data were pooled across these timings. Cotton growth reduction and total injury was 2% or less at 2 WAE, and early-season cotton injury dissipated quickly (Table 5). No cotton growth reduction or injury was observed 4 WAE when synthetic auxin herbicides had been applied 1 WBP or earlier. In contrast to the percentage of cotton plants with distorted leaves observed when herbicides were applied at planting, herbicides applied 1 WBP or earlier produced ≤3% cotton leaf distortion (data not shown). Similarly to synthetic auxin herbicide injury, thrips can cause distorted cotton leaves (Reisig 2019). However, in this study, thrips were managed early in the season to ensure that insect injury did not mask cotton response to herbicide treatments. Like injury, cotton stand was not influenced by 2,4-D, dicamba, or halauxifen

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Table 5. Cotton growth reduction, total injury, and stand 2 and 4 wk after emergence (WAE) in response to halauxifen, dicamba, and 2,4-D applied 1, 2, 3, and 4 wk prior to planting.[a,b]

	Growth reduction		Total injury		Cotton stand	
Herbicide[c]	2 WAE	4 WAE	2 WAE	4 WAE	2 WAE	4 WAE
	%				plants 10 m row^{-1}	
Halauxifen	1 b	0 a	1 a	0 a	85 a	88 a
Dicamba	2 a	0 a	2 a	0 a	83 a	87 a
2,4-D	1 b	0 a	1 a	0 a	84 a	87 a
Nontreated	–	–	–	–	84 a	86 a

[a] Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05.
[b] Data were pooled over timings 1, 2, 3, and 4 wk before cotton planting.
[c] Halauxifen, dicamba, and 2,4-D were applied at 5, 280, and 1,060 g ae ha^{-1}, respectively.

Table 6. Cotton height 4 and 8 wk after emergence (WAE) and seed cotton yield in response to halauxifen, dicamba, and 2,4-D applied 0, 1, 2, 3, and 4 wk prior to planting at all locations.[a,b]

	Cotton height		
Herbicide[c]	4 WAE	8 WAE	Seed cotton yield
	cm		kg ha^{-1}
Halauxifen	25 b	63 a	3,210 a
Dicamba	25 b	63 a	3,020 a
2,4-D	25 b	66 a	3,450 a
Nontreated	26 a	64 a	3,200 a

[a] Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05.
[b] Data were pooled over applications 0, 1, 2, 3, and 4 wk before cotton planting.
[c] Halauxifen, dicamba, and 2,4-D were applied at 5, 280, and 1,060 g ae ha^{-1}, respectively. Herbicide sources can be found in Table 2.

applied 1 to 4 WBP. Cotton stand in response to all herbicide treatments applied 1 to 4 WBP ranged 83 to 85 plants 10 m row^{-1} at 2 WAE and 86 to 88 plants 10 m row^{-1} at 4 WAE and were similar to the nontreated cotton. York et al. (2004) noted ≤10% cotton plants with distorted leaves at five of seven locations when dicamba (280 g ae ha^{-1}) and 2,4-D (1,060 g ae ha^{-1}) were applied 1 to 6 WBP. At the remaining locations in this study, dicamba at 280 g ae ha^{-1} produced 12% to 40% and 0 to 30% plants with distorted leaves when applied 1 and 2 WBP, respectively. The percentage of cotton plants with distorted leaves in response to 2,4-D at 1,060 g ae ha^{-1} applied 1 to 2 WBP ranged from 0 to 29%. Differences in cotton injury across locations observed by York et al. (2004) were probably influenced by rainfall. The risk of cotton injury from synthetic auxin herbicides applied preplant burndown is reduced when moderate rainfall accumulates between herbicide application and cotton planting (Anonymous 2018c, 2018d, 2018j; York et al. 2004). At locations where York et al. (2004) observed <2.5 cm accumulated rainfall for the 3 wk preceding cotton planting, percentage of cotton plants with distorted leaves was at most 74%. In contrast, ≤2% cotton plants exhibited distorted leaves at locations with ≥2.5 cm rainfall. Other researchers have noted a similar relationship between accumulated rainfall and cotton response to synthetic auxin herbicides applied prior to planting (Ferguson 1996; Guy and Ashcraft 1996). North Carolina and Virginia both experienced abnormally wet springs during 2017 and 2018, which explains limited injury observed by synthetic auxin herbicides applied prior to cotton planting. In these experiments, accumulated rainfall following herbicides applied 1, 2, 3, and 4 WBP and cotton planting ranged from 3.5 to 21.6 cm (Table 3). Following synthetic auxin herbicides applied at planting, rainfall the first 10 d after planting totaled at least 1.7 cm but was less than rainfall prior to cotton planting. Cotton response to synthetic auxin herbicides applied at planting may be more exaggerated under drier conditions than experienced in this study.

Cotton height and seed cotton yield

The two-way interactions of application timing by herbicide treatment for cotton height and seed cotton yield were not significant; therefore, data for these parameters are presented by herbicide treatment pooled over all application timings. Despite early-season growth reduction, synthetic auxin herbicides had little effect on cotton height 4 WAE (Table 6). Cotton in nontreated plots averaged 26 cm in height, whereas cotton treated with 2,4-D, dicamba, and halauxifen averaged 25 cm. At 8 WAE, cotton height ranged from 63 to 66 cm with no differences between herbicide treatments and the nontreated check. York et al. (2004) reported that cotton height and number of main-stem nodes in mid-July were not affected by 2,4-D or dicamba applied prior to cotton planting. Similar to cotton height, seed cotton yield was not influenced by early-season cotton injury or stand reduction. Seed cotton yield totaled 3,020 to 3,450 kg ha^{-1}, and plots treated with 2,4-D, dicamba, and halauxifen yielded similarly to nontreated plots. State average cotton lint yields during 2017 were 1,090 kg ha^{-1} and 1,250 kg ha^{-1} for North Carolina and Virginia, respectively (USDA-NASS 2017a, 2017b); average yields for both states in 2018 are estimated to be >930 kg lint ha^{-1} (USDA-NASS 2018). Cotton is an indeterminate plant capable of simultaneous vegetative and reproductive growth, giving the plant the ability to recover well from early-season stressors, including drought, insects, diseases, weed competition, and herbicide injury (Edmisten and Collins 2018). Cotton lint yields during 2017 and 2018 are evidence of plentiful rainfall during these years and may explain why seed cotton yields in these experiments were not affected by minimal to moderate cotton injury observed early in the season.

Cotton tolerance to halauxifen plus florasulam premix

Halauxifen plus florasulam premix was applied 2 and 4 WBP during 2018 only. Halauxifen plus florasulam did not affect cotton stand compared to the nontreated (data not shown). Likewise, cotton response to halauxifen plus florasulam was minimal, with ≤3% cotton growth reduction and ≤2% total injury (data not shown). Similar to cotton response to 2,4-D, dicamba, and halauxifen applied at the same application timings, halauxifen plus florasulam did not affect cotton height or seed cotton yield compared to the nontreated (data not shown).

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In general, results from these experiments and from other research from North Carolina and Georgia (York et al. 2004) confirm that cotton can be safely planted following 2,4-D and dicamba applied preplant burndown if label requirements for plant-back interval and rainfall or soil moisture are met. Current labels for halauxifen and halauxifen plus florasulam require at least 30 and 90 d between application of these herbicides and cotton planting, respectively. Much shorter plant-back intervals were investigated in this research. Cotton tolerance to halauxifen applied preplant burndown was greater than tolerance to 2,4-D or dicamba. Early-season cotton injury caused by halauxifen was transient, with no injury observed in response to the herbicide 4 WAE. Furthermore, regardless of timing, halauxifen did not affect cotton stand or seed cotton yield. Likewise, halauxifen plus florasulam applied 2 and 4 WBP during 2018 caused little injury and did not affect cotton stand or seed cotton yield.

This research confirms that halauxifen and halauxifen plus florasulam can be safely applied prior to planting cotton at currently required plant-back intervals and indicates that plant-back intervals could be shortened with a minimum rainfall or irrigation requirement between herbicide application and cotton planting. These herbicides applied at least 2 WBP with ≥4.8 cm rainfall between application and cotton planting injured cotton ≤2%. Because cotton tolerance to halauxifen plus florasulam was only investigated during 2018, more research is needed on cotton tolerance to this premix applied prior to planting. As a result of wet conditions during April and May of each year, cotton tolerance to halauxifen applied preplant when conditions are dry between application and cotton planting should also be investigated.

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References

Al-Khatib K, Peterson D (1999) Soybean (*Glycine max*) response to simulated drift from selected sulfonylurea herbicides, dicamba, glyphosate, and glufosinate. Weed Technol 13:264–270

Andersen SM, Clay SA, Wrage LJ, Matthees D (2004) Soybean foliage residues of dicamba and 2,4-D and correlation to application rates and yield. Agron J 96:750–760

Anonymous (2018a) Elevore™ herbicide product label. Dow AgroSciences, Indianapolis, IN. http://www.cdms.net/ldat/ldE1J001.pdf. Accessed: February 14, 2018

Anonymous (2018b) Quelex™ herbicide product label. Dow AgroSciences, Indianapolis, IN. http://www.cdms.net/ldat/ldDBL000.pdf. Accessed: February 15, 2018

Anonymous (2018c) Barrage® HF herbicide product label. Helena Chemical Company, Collierville, TN. https://s3-us-west-1.amazonaws.com/www.agrian.com/pdfs/Barrage_HF_Label1h.pdf. Accessed: February 15, 2018

Anonymous (2018d) Salvo® herbicide product label. Loveland Products, Inc., Loveland, CO. https://s3-us-west-1.amazonaws.com/www.agrian.com/pdfs/Salvo_Label5.pdf. Accessed: February 15, 2018

Anonymous (2018e) Savage® herbicide product label. Loveland Products, Inc., Loveland, CO. https://s3-us-west-1.amazonaws.com/www.agrian.com/pdfs/Savage_Label7.pdf. Accessed: February 15, 2018

Anonymous (2018f) Weedar® 64 herbicide product label. Nufarm, Inc., Alsip, IL. http://www.cdms.net/ldat/ld08K001.pdf. Accessed: February 15, 2018

Anonymous (2018g) Weedone® LV4 EC herbicide product label. Nufarm, Inc., Aslip, IL. http://www.cdms.net/ldat/ld5PB000.pdf. Accessed: February 15, 2018

Anonymous (2018h) Enlist Duo™ herbicide product label. Dow AgroSciences, Indianapolis, IN. http://www.cdms.net/ldat/ldAEA005.pdf. Accessed: February 15, 2018

Anonymous (2018i) Enlist One™ herbicide product label. Dow AgroSciences, Indianapolis, IN. http://www.cdms.net/ldat/ldE27000.pdf. Accessed: February 15, 2018

Anonymous (2018j) Clarity® herbicide product label. BASF, Research Triangle Park, NC. http://www.cdms.net/ldat/ld797012.pdf. Accessed: February 15, 2018

Anonymous (2018k) Engenia® herbicide product label. BASF, Research Triangle Park, NC. http://www.cdms.net/ldat/ldDG8028.pdf. Accessed: February 15, 2018

Anonymous (2018l) Xtendimax™ herbicide product label. Monsanto Company, St. Louis, MO. http://www.cdms.net/ldat/ldDF9006.pdf. Accessed: February 15, 2018

Anonymous (2018m) FeXapan™ herbicide product label. DuPont, Wilmington, DE. http://www.cdms.net/ldat/ldDJ1002.pdf. Accessed: February 15, 2018

Askew MC (2018) Rapeseed (*Brassica napus* L.) termination and integration of halauxifen-methyl into Virginia cotton (*Gossypium hirsutum* L.) production. M.S. thesis. Blacksburg, VA: Virginia Tech. 90 p

Auch DE, Arnold WE (1978) Dicamba use and injury on soybeans (*Glycine max*) in South Dakota. Weed Sci 26:471–475

Bruce JA, Kells JJ (1990) Horseweed (*Conyza canadensis*) control in no-tillage soybeans (*Glycine max*) with preplant and preemergence herbicides. Weed Technol 4:642–647

Byker HP, Soltani N, Robinson DE, Tardif FJ, Lawton MB, Sikkema PH (2013) Control of glyphosate resistant horseweed (*Conyza canadensis*) with dicamba applied preplant and postemergence in dicamba-resistant soybean. Weed Technol 27:492–496

Cahoon CW, York AC, Jordan DL, Everman WJ, Seagroves RW (2014) An alternative to multiple protoporphyrinogen oxidase inhibitor applications in no-till cotton. Weed Technol 28:58–71

[CTIC] Conservation Technology Information Center (2008) National crop residue management survey: conservation tillage data. https://www.ctic.org/crm/. Accessed: April 26, 2019

Edmisten K, Collins G (2018) The cotton plant. Pages 5–15 *in* 2018 Cotton Information. Publication AG-417. Raleigh, NC: North Carolina Cooperative Extension Service

Edmisten K, Collins G, Crozier C, Meijer A, York A, Hardy D, Reisig D, Bullen G, Thiessen L, Vann R (2018) 2018 Cotton Information. Publication AG-417. Raleigh, NC: North Carolina Cooperative Extension Service

Ellis JM, Walton LC, Richburg JS, Haygood BA, Huckaba RM, Lovelace ML, Perry DH, Peterson MA (2017) Utility of Elevore™ herbicide with Arylex™ active for preplant burndown applications. Page 150 *in* Proceedings of the Southern Weed Science Society 70th Annual Meeting. Birmingham, AL. Las Cruces, NM: Southern Weed Science Society

Epp JB, Alexander AL, Balko TW, Buysse AM, Brewster WK, Bryan K, Daeuble JF, Fields SC, Gast RE, Green RA, Irvine NM, Lo WC, Lowe CR, Renga JM, Richburg JS, Ruiz JM, Satchivi NM, Schmitzer PR, Siddall TL, Webster JD, Wimer MR, Whiteker GT, Yerkes CN (2016) The discovery of Arylex™ active and Rinskor™ active: two novel auxin herbicides. Bioorgan Med Chem 24:362–371

Eubank TW, Poston DH, Nandula VK, Koger CH, Shaw DR, Reynolds DB (2008) Glyphosate-resistant horseweed (*Conyza canadensis*) control using glyphosate-, paraquat-, and glufosinate-based herbicide programs. Weed Technol 22:16–21

Ferguson G (1996) Banvel SGF for preplant weed control in cotton. Pages 48–49 *in* Proceedings of the Beltwide Cotton Conference, Nashville, TN. Memphis, TN: National Cotton Council

Flessner ML, McElroy JS, McCurdy JD, Toombs JM, Wehthe GR, Burmester CH, Price AJ, Ducar JT (2015) Glyphosate-resistant horseweed (*Conyza canadensis*) control with dicamba in Alabama. Weed Technol 29:633–640

Gillespie JM, Hatch LU, Duffy PA (1990) Effect of the 1985 farm bill provisions on farmers' soil conservation decisions. South J Ag Econ 22:179–189

Guy CB, Ashcraft RW (1996) Horseweed and cutleaf eveningprimrose control in no-till cotton. Page 1557 *in* Proceedings of the Beltwide Cotton Conference, Nashville, TN. Memphis, TN: National Cotton Council

Heap I (2018) The International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/Summary/Species.aspx?WeedID=61. Accessed: February 28, 2018

Keeling JW, Henniger CG, Abernathy JR (1989) Horseweed (*Conyza canadensis*) control in conservation tillage cotton (*Gossypium hirsutum*). Weed Technol 3:399–401

Kelley KB, Wax LM, Hager AG, Riechers DE (2005) Soybean response to plant growth regulator herbicides is affected by other postemergence herbicides. Weed Sci 53:101–112

Kruger GR, Davis VM, Weller SC, Johnson WG (2010) Control of horseweed (*Conyza canadensis*) with growth regulator herbicides. Weed Technol 24:425–429

McCauley CL, Young B (2016) Control of glyphosate-resistant horseweed (Conyza canadensis) with halauxifen-methyl versus dicamba and 2,4-D. Page 37 in Proceedings of the 71st Annual North Central Weed Science Society, Des Moines, IA. Las Cruces, NM: North Central Weed Science Society

Mehlich A (1984) Photometric determination of humic matter in soils, a proposed method. Commun Soil Sci Plan 15:1417–1422

Reisig D (2019) Managing insects on cotton. Pages 134–152 *in* 2019 Cotton Information. Publication AG-417. Raleigh, NC: North Carolina Cooperative Extension Service

Rhodes GN, Israel TD, Steckel L (2015) Diagnosing suspected off-target herbicide damage to cotton. https://cotton.ces.ncsu.edu/wp-content/uploads/2015/07/UT-Diagnosing-Suspected-Off-target-Herbicide-Damage-to-Cotton.pdf?fwd=no. Accessed: November 21, 2018

Sciumbato AS, Chandler JM, Senseman SA, Bovey RW, Smith KL (2004) Determining exposure to auxin-like herbicides. I. Quantifying injury to cotton and soybean. Weed Technol 18:1125–1134

Scott R, Shaw DR, Barrentine WL (1998) Glyphosate tank mixtures with SAN 582 for burndown or postemergence applications in glyphosate-tolerant soybean (*Glycine max*). Weed Technol 12:23–26

Solomon CB, Bradley KW (2014) Influence of application timings and sublethal rates of synthetic auxin herbicides on soybean. Weed Technol 28:454–464

[USDA-NASS] United States Department of Agriculture––National Agricultural Statistics Service (2017a) 2017 State Agriculture Overview North Carolina. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NORTH%20CAROLINA. Accessed: December 15, 2018

[USDA-NASS] United States Department of Agriculture––National Agricultural Statistics Service (2017b) 2017 State Agriculture Overview Virginia. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=VIRGINIA. Accessed: December 15, 2018

[USDA-NASS] United States Department of Agriculture––National Agricultural Statistics Service (2018) Quick Stats Cotton Yield Projection. https://quickstats.nass.usda.gov/results/012A7167-43D4-306F-8766-B0EF88E302D1. Accessed: December 15, 2018

Wax LM, Knuth LA, Slife FW (1969) Response of soybeans to 2,4-D, dicamba, and picloram. Weed Sci 17:388–393

[WSSA] Weed Science Society of America (2018) Summary of herbicide mechanism of action according to WSSA. http://wssa.net/wp-content/uploads/WSSA-Mechanism-of-Action.pdf. Accessed: February 13, 2018

Wilson JS, Worsham AD (1988) Combinations of nonselective herbicides for difficult to control weeds in no-till corn, *Zea mays*, and soybeans, *Glycine max*. Weed Sci 36:648–652

York AC, Cahoon CW (2018) Weed management in cotton. Pages 83–132 *in* 2018 Cotton Information. Publication AG-417. Raleigh, NC: North Carolina Cooperative Extension Service.

York AC, Culpepper AS, Stewart AM (2004) Response of strip-tilled cotton to preplant applications of dicamba and 2,4-D. J Cotton Sci 8:213–222

Zimmer M, Young BG, Johnson WG (2018a) Herbicide programs utilizing halauxifen-methyl for glyphosate-resistant horseweed (*Conyza canadensis*) control in soybean. Weed Technol 32:659–654

Zimmer M, Young BG, Johnson WG (2018b) Weed control with halauxifen-methyl applied alone and in mixtures with 2,4-D, dicamba, and glyphosate. Weed Technol 32:597–602

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