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ORIGINAL ARTICLE

Effect of nozzle type selection on prickly sida (*Sida spinosa* L.) and barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) control in Mississippi cotton (*Gossypium hirsutum*)

J. Connor Ferguson[1,2]*, Justin S. Calhoun[3,2], Kayla L. Broster[2], Luke H. Merritt[4,2],
Zachary R. Treadway[5,2], Michael T Wesley Jr.[6,2], Nicholas Fleitz[7]

[1] Weed Science and Technical Agronomy, Sesaco Corporation, Yukon, Oklahoma, United States
[2] Plant and Soil Sciences, Mississippi State University, Mississippi State, Mississippi, United States
[3] Plant Science and Technology, University of Missouri, Portageville, Missouri, United States
[4] Orr Agricultural Research & Demonstration Center, University of Illinois, Baylis, Illions, United States
[5] Plant and Soil Sciences, Oklahoma State University, Ardmore, Oklahoma, United States
[6] Agronomy, Bayer Crop Science, Jerseyville, Illions, United States
[7] Application Agronomist, Pentair-Hypro, New Brighton, Minnesota, United States

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*Corresponding address:
cferguson@sesaco.com

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Abstract

Nozzle type and herbicide application timing can affect herbicide efficacy. Prickly sida (*Sida spinosa*) and barnyardgrass (*Echinochloa crus-galli*) are problematic weeds in eastern Mississippi cotton production and have reduced yield in recent years. Field studies were conducted at two locations – Brooksville, MS (2018, 2019) and Starkville, MS (2019) to understand the nozzle type and herbicide application timing effects on prickly sida and barnyardgrass control in cotton. Studies also compared applications made by an eight-nozzle tractor-mounted sprayer with a four-nozzle backpack sprayer. Herbicide applications were made at four timings: preemergence (PRE), early-postemergence (EPOST), mid-postemergence (MPOST), and late-postemergence (LPOST) corresponding to the preemergence (immediately after planting), two-to-three leaf, four-to-six leaf, and early-bloom stages, respectively. Treatments were made at 140 $l \cdot ha^{-1}$ applied at each growth stage, with nozzle type and sprayer as variables by each timing. Results showed no differences in treatments applied with backpack and tractor-mounted sprayers. Control of barnyardgrass was significantly affected by nozzle type, but control of prickly sida was not significantly influenced by nozzle type. In all three site-years, plots receiving a MPOST only herbicide application resulted in less weed control than areas receiving a two-pass POST herbicide program. Cotton yield was significantly affected by the herbicide program at one site-year, but was not significantly affected by the herbicide program except where cotton injury exceeded 15%. A two- or three-pass herbicide program was most effective in controlling prickly sida and barnyardgrass in Mississippi cotton.

Keywords: acetochlor, clethodim, cotton (*Gossypium hirsutum*), glufosinate, pyrithiobac sodium, spray droplet size, sprayer type, weed control

Introduction

With the release of auxin-herbicide-resistant cotton varieties, additional over-the-top herbicide options were made available to cotton growers. However, due to the sensitivity of some non-target species, these herbicides have been highly regulated with strict application guidelines, including restrictions on the nozzle type. These restrictions have led to many labeled applications requiring Extremely-Coarse or Ultra-Coarse sprays. With a growing concern for off-target movement and adherence to new label standards, growers are adopting drift reducing nozzle type technologies to increase their droplet size and reduce their likelihood of off-target movement (Ferguson *et al.* 2015). The US Environmental Protection Agency (EPA) definition for off-target movement is "the physical movement of a pesticide through the air at the time of application or soon thereafter, to any site other than the one intended for application" (EPA 1999).

Drift reduction nozzle types are designed to increase droplet size, thus reducing the likelihood for off-target movement. Some nozzle types use the Venturi process, which restricts the liquid flow, and results in lower velocity of existing droplets. The drop in pressure in the nozzle due to the Venturi process causes air to be drawn in, which mixes into the spray solution in the nozzle, creating larger, air-entrained droplets (Dorr *et al.* 2013). These drift reducing nozzle types often have a pre-orifice insert or chamber which produces the Venturi effect, leading to larger droplets.

Previous research investigated nozzle type effects on herbicide activity of six different modes of action herbicides: clodinafop (Weed Science Society of America – WSSA group 1), imazamox (WSSA group 2) plus imazapyr (WSSA group 2), metribuzin (WSSA group 5), glyphosate (WSSA group 9), amitrole (WSSA group 11 – carotenoid biosynthesis inhibitors), and paraquat (WSSA group 22) on winter grasses (Ferguson *et al.* 2018). Nozzle type effects were not seen for systemic herbicides (glyphosate, imazamox plus imazapyr and clodinafop) across grass species, but the TTI nozzle type reduced efficacy of paraquat and amitrole.

Further research found that using coarser sprays results in equal to or greater herbicide activity than finer sprays (Wolf 2000; Ramsdale and Messersmith 2001; Etheridge *et al.* 2001); however, other research has shown the converse (Wolf 2000; Sikkema *et al.* 2008). Nozzle type effects on herbicide activity are herbicide mode of action dependent. Ferguson *et al.* (2019) concluded that drift reduction nozzle types that produce coarser sprays can maintain control of summer annual grass species. However, Ferguson *et al.* (2018) and Butts *et al.* (2018) determined that even with systemic herbicides, there is a critical point in which creating droplets too large will result in decreased activity – given fewer total droplets produced.

Though extensive literature is available on the effects of droplet size on herbicide activity, most research evaluated a single herbicide application. Limited literature is available on nozzle type and droplet size effects on multiple herbicide applications in a season for weed control. Carter *et al.* (2017) investigated the activity of multiple herbicide applications in a season and observed no differences in weed control when comparing drift reduction nozzle types to non-drift reducing (conventional) nozzle types. While these findings are significant, there is no straightforward evidence to suggest that the same would be true in cotton weed control programs. Weed control programs in peanut have fewer available modes of action (Faircloth and Prostko 2010) necessitating the use of more contact active herbicides, which favor smaller droplets produced by conventional nozzle types (Etheridge *et al.* 2001; Carter *et al.* 2017).

Prickly sida (*Sida spinosa* (L.)) is an annual summer broadleaf weed, that is commonly found in the mid-southern United States. Prickly sida was found to be one of the most prevalent weeds in eastern Mississippi row-crop production (Rankins *et al.* 2005). Barynardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) is a summer annual grass that is found across the mid-southern United States and has been found to be a troublesome weed in row-crop production in Mississippi (Norsworthy *et al.* 2013). Given their distribution across eastern Mississippi, effectively controlling them with the right nozzle and herbicide program is a priority in cotton production. The objectives of this research were to determine if nozzle type affects prickly sida and barnyardgrass control in Mississippi cotton production systems. Secondly, the relatability of the use of small-plot backpack sprayers is often in question because smaller nozzle flow rates are typically used when making applications utilizing backpack sprayers. Therefore, this research sought to determine if nozzle flow rate 04 ($1.5\,l \cdot min^{-1}$) and 02 ($0.76\,l \cdot min^{-1}$), influences herbicide activity. Finally, this research sought to investigate the nozzle type and flow rate effects when used in single, double, and triple pass herbicide programs common in cotton production.

Materials and Methods

Herbicide application and study parameters

Studies were initiated May 14, 2018 (site-year 1), and May 21, 2019 (site-year 2), at the Black Belt Experiment Station (Black Belt) in Brooksville, MS, USA and May 1, 2019 (site-year 3) at the R.R. Foil Plant Science Research Center (R.R. Foil) in Starkville, MS, USA to investigate nozzle type effects on season-long weed control in cotton. Cotton planted at Black Belt was 'Deltapine® 1646 B2XF' (Bayer Crop Science, St. Louis, MO, USA) and cotton planted at R.R. Foil was 'PhytoGen® 430 W3FE'(Corteva Agriscience, Indianapolis, IN, USA). Cotton at both locations was planted at 108,680 plants per ha^{-1} on beds with a row spacing of 96.5 cm in plot sizes of 4 m by 15 m. Studies conducted at the Black Belt station were conducted on a Brooksville Silty Clay (fine, smectitic, thermic Aquic Hapluderts), while soil types at R.R. Foil were Leeper Silty Clay Loam (fine, smectitic, nonacid, thermic Vertic Epiaquepts). Rainfall amounts for the duration of studies are listed for each site/year in Table 1.

The studies were conducted in a 4 by 3 by 2 augmented factorial design with a non-sprayed control treatment (NTC) arranged in a randomized complete block design with four replicates within each site-year. The non-sprayed control treatment plot per rep was used for weed control evaluation comparisons. The factors were: Factor 1 consisted of four nozzle types, Factor 2 consisted of three herbicide programs (Table 2), and Factor 3 was the two nozzle flow rates. Herbicide programs were developed to include single-, double-, and triple-pass herbicide applications. The single-pass program consisted of a mid-post (MPOST)-only treatment applied at the four-to-six leaf stage. The double-pass program received applications at the two-to-three leaf stage – early-post (EPOST) and at the early-bloom stage – late-post (LPOST) application timings. The triple-pass program received treatments at preemergence (PRE), EPOST, and LPOST application timings. Herbicides and rates used for all treatments were acetochlor (Warrant®, Bayer Crop Science, St. Louis, MO, USA) at 1,260 g a.i. · ha^{-1} applied PRE, pyrithiobac sodium (Staple® LX, Corteva Agriscience, Indianapolis, IN, USA) at 76 g a.i. · ha^{-1}, plus glufosinate (Liberty®, BASF, Research Triangle Park, NC, USA) at 594 g a.i. · ha^{-1} plus clethodim (Select Max®, Valent, Walnut Creek, CA, USA) plus NIS at 0.25% v/v were applied EPOST and MPOST, and glufosinate plus clethodim plus NIS used LPOST at the same rates as the EPOST and MPOST applications. No plot received both the EPOST and MPOST timing, therefore, the season-long use rate for glufosinate in cotton was not exceeded. Nozzle types used were the Ultra Lo-Drift 120-02/04 (ULD), Guardian-Air 110-02/04 (GA), Guardian-Air Twin 110-02/04 (GAT), and 3D 100-02/04 (3D) (Pentair-Hypro, New Brighton, MN, USA). The backpack-sprayer treatments used 02 flow rate nozzle types and the tractor-mounted sprayers used 04 flow rate nozzle types. The 3D nozzle types were oriented in an alternating direction across the boom for both sprayer types. Due to limited field space, only 04 flow rate nozzle types were tested at the R.R. Foil location in 2019.

Table 1. Rainfall amounts for the duration of field trials at Black Belt (2018 and 2019) and R.R. Foil sites (2019)

Month	Black Belt 2018	Black Belt 2019	R.R. Foil 2019
		[cm]	
May	3.1	13.7	19.2
June	1.9	6.7	21.2
July	5.7	3.6	27.1
August	3.2	7.9	14
September	15.6	0	0.1
October	4.4	15.2	30.5
Total	33.9	47.1	112.2

Table 2. Herbicide treatments used at Black Belt in 2018–2019 and R.R. Foil in 2019 for season long weed control in cotton

Program[1]	Herbicide	Rate
	[g a.i. · ha^{-1}]	
PRE	acetochlor	1,260
EPOST (2–3 leaf cotton) & MPOST (4–6 leaf cotton)	pyrithiobac + glufosinate + clethodim[2]	76 594 136
Late POST	glufosinate + clethodim[2]	594 136

[1] each program was applied using each nozzle type and size tested
[2] NIS (0.25% v/v) was included in each clethodim mixture

All applications were made at 276 kPa, with an application volume of 140 l · ha^{-1}. For the tractor-mounted sprayer treatments, a compressed-air, tractor-mounted eight-nozzle research sprayer was utilized at 13.4 km · h^{-1}. Backpack treatments were applied using a CO_2-pressurized backpack-sprayer with a four-nozzle boom at an application speed of 6.7 km · h^{-1}. All applications for tractor-mounted and backpack treatments were made simultaneously. Speeds differed between the backpack and tractor-mounted sprayers due to the difference in nozzle flow rate (02 & 04) to maintain the constant application volume of 140 l · ha^{-1}.

Weed species heights and data collection

Prickly sida and barnyardgrass populations were uniformly present across all plots in all three site-year locations, Black Belt (site-years 1 & 2) and R.R. Foil (site-year 3). Application timings were related to cotton growth stage, but all prickly sida plants were no greater than 12 cm tall and barnyardgrass plants were at or below 15 cm tall at the time of application for the EPOST applications. Prickly sida plants averaged 22 cm and barnyardgrass plants averaged 30 cm at the MPOST application timing.

Visual control evaluations on a 1 to 100 scale (0 = no control, 100 = complete control) were recorded weekly following each application timing. In addition to weed control, visual injury ratings were also taken weekly following each application on a 1 to 100 scale (0 = no injury, 100 = complete termination of plant). At complete harvest maturity, the center two rows of each plot were harvested and weighed to calculate the yield of each experimental unit.

Weed control and cotton harvest evaluation statistical methods

Visual weed control, cotton injury, and cotton seed yield were subjected to Shapiro-Wilks, Barlett, and Fligner-Killeen testing using RStudio (Version 1.2.1335) to test for normality and homogeneity. Data were determined to be non-significant in normality and homogeneity testing, therefore data transformations were not utilized. The data were then subjected to ANOVA using the "agricolae" package in RStudio, where the main effects of site-year, nozzle type, nozzle flow rate, and herbicide program, as well as interaction between any (or all) factors were tested for significance with replication within each location being treated as random. The main effect of site-year was determined to be significant in all response categories, therefore the data were a subset into individual site-years and analyzed for the main effect and interaction of the three study factors. Because only 04 flow rate nozzles were tested at the R.R. Foil 2019 site, only the main effect and interaction of nozzle type and herbicide program were tested there. If significance was observed, means were separated using Fisher's protected LSD ($\alpha = 0.05$). Evaluations from 7 days after LPOST (final application) are presented to portray weed control response from a season long perspective, as any control escapes would still be visible, and weed emergence after this period would be unlikely due to cotton canopy closure.

Droplet size analysis

Each nozzle type was analyzed for droplet size distribution at the Mississippi State University, R.R. Foil Plant Sciences Center in Starkville, MS, on November 22, 2019. Nozzles were sprayed using a research track sprayer (Series III Research Track Sprayer, DeVries Manufacturing, Hollandale, MN, USA) modified to spray perpendicular to the measurement system at a constant 0.8 $\text{km} \cdot \text{h}^{-1}$ travel speed. Each nozzle type was analyzed using a particle/droplet image analysis (PDIA) system (VisiSize P15, Oxford Lasers, Didcot, UK) to measure the volumetric droplet size spectrum. The volumetric droplet size spectrum parameters selected for data collection were the volumetric droplet diameters which represent the 0.1 ($D_{v0.1}$), 0.5 ($D_{v0.5}$), and the 0.9 ($D_{v0.9}$) fractions of the spray (Ferguson *et al.* 2016b), the relative span, and the volume of spray contained in droplets with diameters below 150 μm (% < 150 μm). The % < 150 μm is included to help provide a clearer picture of the relative drift potential of each treatment (Ferguson *et al.* 2016b). The % < 150 μm is defined in this study as a relative measurement for 'driftable fines' but is not intended to represent actual values of driftable droplets, as any droplet can drift under the right conditions. Droplet size measurements were replicated to supply three measurements within ±3% of the mean of the $D_{v0.1}$, a standard operating procedure used in the lab. The VisiSize P15 was positioned 50 cm below the nozzle, to allow for the complete sheet breakup. Nozzles were traversed where the entire spray plume passed through the measurement area – 7 seconds per measurement. Temperature and relative humidity (RH) were constant throughout the duration of droplet spectrum measurements (20°C and 55% RH). All nozzles were sprayed and classified using water only which is consistent with the classification of droplet sizing using the ASABE/ANSI references nozzles operated according to the pressures consistent with ASABE/ANSI S572.2 (ASABE 2018). Nozzle types were classified in each category by their $D_{v0.1}$, the volumetric part of the spectrum at which off-target movement would be most concerned. This way of classification also follows a previously published method, consistent with ASABE/ANSI S572.2 (Ferguson *et al.* 2016a, b; 2018, 2019).

Results and Discussion

Prickly sida control

Results indicate that control of prickly sida 7 days after the LPOST was not significantly influenced by nozzle type (Table 3). This finding is complemented by substantial literature suggesting that nozzle type has little to no effect with respect to weed control response when comparing systemic herbicide chemistries (Carter *et al.* 2017; Ferguson *et al.* 2018). Although nozzle type had no significant effect, lower flow rate nozzles (02) resulted in less control of prickly sida (81%) at the Black Belt site in 2019 than 04 flow rate nozzles (88% control) (Table 4). No differences between the nozzle flow rate existed at the Black Belt site in 2018. Ferguson *et al.* (2016a) suggest that decreasing nozzle flow rates proves effective in maintaining coverage while balancing application factors such as pressure and speed. However, in this case, less weed control was noted in plots treated with 02 flow rate nozzles, suggesting that factors other than spray coverage must influence control of this weed species. Control of prickly sida was significantly affected by the herbicide program at both Black Belt and R.R. Foil sites in 2019. At both sites plots receiving a MPOST only herbicide application resulted in less weed control than areas receiving double and triple pass programs (Table 5). The reduced weed control of the MPOST application was influenced by the larger prickly sida and barnyardgrass plants at the time of spraying. Supporting literature suggests that the utilization of multiple herbicide

Table 3. Weed control, injury and seed cotton yield response to the nozzle type[1,2]

Nozzle	Weed control 7 days after LPOST		Injury 7 days after EPOST	Yield [kg · ha^{-1}]
	prickly sida	barnyardgrass		
	[%]			
	Black Belt 2018			
GAT	99 a	96 ab	7	2,663
GA	98 a	93 b	7	2,775
3D	98 a	94 ab	7	2,674
ULD	98 a	98 a	6	2,806
NTC	0 b	0 c	0	–
	Black Belt 2019			
GAT	86 a	88 ab	13 a	2,055
GA	87 a	89 ab	11 ab	2,029
3D	85 a	90 a	11 ab	2,041
ULD	81 a	81 b	10 b	1,824
NTC	0 b	0 c	0 c	—
	R.R. Foil 2019			
GAT	92 a	87 a	0	3,148
GA	94 a	91 a	0	3,652
3D	95 a	90 a	0	3,442
ULD	89 a	85 a	0	2,921
NTC	0 b	0 b	0	—

[1] means in the same column and location followed by the same lowercase letter are not statistically different based upon Fisher's protected LSD ($\alpha = 0.05$)

[2] response averaged across two nozzle sizes (11004 and 11002) and three herbicide programs (PRE fb EPOST fb LPOST, EPOST fb LPOST, and MPOST only)

Table 4. Weed control, injury, and seed cotton yield response to nozzle size[1,2]

Nozzle size	Weed control 7 days after LPOST		Injury 7 days after EPOST	Yield [kg · ha^{-1}]
	prickly sida	barnyardgrass		
	[%]			
	Black Belt 2018			
11004	99 a	99 a	7 a	2,745
11002	98 a	92 b	6 a	2,714
NTC	0 b	0 c	0 b	–
	Black Belt 2019			
11004	88 a	87 a	11 a	2,011
11002	81 b	87 a	10 a	1,965
NTC	0 c	0 b	0 b	–

[1] means in the same column and location followed by the same lowercase letter are not statistically different based upon Fisher's protected LSD ($\alpha = 0.05$)

[2] response averaged across three herbicide programs (PRE fb EPOST fb LPOST, EPOST fb LPOST, and MPOST only) and four nozzle types (Guardian-Air Twin, Guardian-Air, 3D, ULD)

applications throughout a production season results in increased control of prickly sida (Ivy and Baker 1972; Scott *et al.* 2002). However, this weed species remains an issue in many production systems across the Midsouth (Rankins *et al.* 2005) indicating that control issues may be a response to improper weed management practices.

Table 5. Weed control, injury, and seed cotton yield response to herbicide program[1,2]

Herbicide program	Weed control 7 days after LPOST		Injury 7 days after EPOST	Yield [kg · ha^{-1}]
	prickly sida	barnyardgrass		
	[%]			
Black Belt 2018				
PRE fb EPOST fb LPOST	100 a	98 a	9 a	2,625 b
EPOST fb LPOST	100 a	98 a	11 a	2,960 a
MPOST	97 a	91 b	0 b	2,603 b
NTC	0 c	0 c	0 b	–
Belt Black 2019				
PRE fb EPOST fb LPOST	89 a	96 a	19 a	1,798 b
EPOST fb LPOST	91 a	95 a	13 b	2,092 a
MPOST	74 b	68 b	0 c	2,070 a
NTC	0 c	0 c	0 c	–
R.R. Foil 2019				
PRE fb EPOST fb LPOST	96 a	89 ab	0	3,156
EPOST fb LPOST	95 a	92 a	0	3,500
MPOST	87 b	83 b	0	3,216
NTC	0 c	0 c	0	–

[1]means in the same column and location followed by the same lowercase letter are not statistically different based upon Fisher's protected LSD (α = 0.05)
[2]response averaged across two nozzle sizes (11004 and 11002) and four nozzle types (Guardian-Air Twin, Guardian-Air, 3D, ULD)

Barnyardgrass control

Control of barnyardgrass 7 days after the LPOST application was significantly affected by nozzle type at the Black Belt site in both 2018 and 2019 (Table 3). In 2018, treatments applied utilizing ULD nozzles resulted in greater weed control than GA nozzles (98 and 93%, respectively). According to droplet sizing results, ULD nozzles produce greater $D_{v0.5}$ values than GA nozzles which may result in greater canopy penetration and coverage sprays (Wolf 2000; Ramsdale and Messersmith 2001; Etheridge *et al.* 2001). In a converse manner, however, at the Black Belt site in 2019, the ULD nozzle resulted in less weed control than the 3D nozzle (81 and 90% control, respectively) (Table 3), a nozzle that produces a smaller $D_{v0.5}$ than the ULD (Table 6). This also is complemented by previous research (Wolf 2000; Sikkema *et al.* 2008) and suggests that control response to nozzle type is highly variable. Baryardgrass control was not affected by the nozzle flow rate at the Black Belt 2019 site but was affected in 2018. In 2018, plots receiving treatments applied with 04 nozzle flow rates resulted in greater control than applications with 02 flow rates (99 and 92%, respectively). Again, larger droplet sizes associated with higher nozzle flow rates can result in greater penetration and deposition in the lower regions of dense canopies (Zhu *et al.* 2002; Creech *et al.* 2015), thus increasing control. The main effect of the herbicide program significantly affected barnyardgrass control at all three site-years. Barnyardgrass control at the Black Belt 2018 site was reduced when plots received a MPOST application only (91% control) compared to the double- and triple-pass programs (both resulting in 98% control) (Table 5). Similarly, plots treated with the double- and triple-pass herbicide programs at the Black Belt 2019 resulted in 96 and 95% barnyard grass control, respectively, while plots receiving a MPOST only resulted in much less control (68%) (Table 5). Plots receiving a MPOST only treatment at the R.R. Foil 2019 site resulted in less control than areas treated with an EPOST and LPOST application, 83 and 92%, respectively. These findings are similar to those of Talbert and Burgos (2007), where sequential post-emergent applications were determined to be essential in control of barnyardgrass.

Cotton crop injury response

Weekly injury evaluations determined that a visible injury only occurred in the weeks following the EPOST applications. Injury 7 days after the EPOST application was only affected by the main effect of nozzle type at the Black Belt 2019 site where the GAT nozzle resulted in greater cotton injury than the ULD, 13 and 10%, respectively (Table 3). Wolf *et al.* (1990) also noted increased crop injury when treatments of imazethapyr were applied to soybean using nozzles producing smaller droplet sizes. The nozzle flow rate was determined to have no effect on cotton injury at both Black Belt site years (Table 4). Cotton injury response to the herbicide program varied by site-year. At the Black Belt 2018 site, cotton injury in plots receiving a PRE application of acetochlor did not result in greater injury than those in the double pass system that did not receive a PRE application (Table 5). Injury in both double- and triple-pass programs was greater than cotton that had gone untreated at the time of evaluation (Table 5). At the Black Belt 2019 site, cotton injury was greater in plots receiving a PRE application of acetochlor than treatments that, at the time of evaluation, had only received an EPOST application (Table 5). No cotton injury was observed at R.R. Foil 2019 site. Differences in cotton injury response could be attributed to wetter conditions in 2019 than 2018. The combination of wet field conditions during the first month of growth and heavier soil types at the Black Belt site could have resulted in cotton injury following a PRE application of acetochlor (Eure *et al.* 2013; Cahoon *et al.* 2015a, b).

Cotton seed yield

The cotton seed yield response was only significantly affected by the herbicide program; however, the response was variable depending on site-year. No yield differences were observed in response to the herbicide program at the R.R. Foil 2019 site. At the Black Belt 2019 site, no yield differences were observed between the single- and double-pass herbicide programs, but areas treated with triple-pass programs resulted in yield reductions (Table 5). The cause of this yield reduction could be attributed to the aforementioned crop injury associated with the PRE application of acetochlor under unfavorable cotton growing conditions. Yield at the Black Belt 2018 site also resulted in decreased yields for plots treated with triple-pass herbicide programs compared to double-pass programs (2,625 and 2,960 kg · ha^{-1}, respectively) (Table 5). However, no differences between those programs existed in injury or weed control. The source of this yield reduction is unknown and may be due to field variability.

Droplet size results

$D_{v0.5}$

Nozzles used in the study were classified across five droplet size categories (Fine to Extremely-Coarse) (Table 6). The 3D 10002 was classified as Fine with a $D_{v0.5}$ of 192 µm, whereas the ULD 12004 was classified as Extremely-Coarse with a $D_{v0.5}$ of 642 µm. The variation of the droplet size spectrum across the nozzle type with respect to nozzle flow rate was minimal for the GA where a $D_{v0.5}$ of 323 was measured for the GA 11002 and the GA 11004 had a $D_{v0.5}$ of 351 µm and both were classified as Coarse (Table 6). All nozzle types had $D_{v0.5}$s within 80 µm for both flow rates, except for the ULD. The ULD 12002 had a $D_{v0.5}$ of 374 µm where the ULD 12004 had a $D_{v0.5}$ of 642 µm.

Table 6. Droplet size results with water only for each nozzle type used in the season long cotton weed control study across all desired droplet spectrum measurements and the ASABE/ANSI classification of each treatment

Nozzle type	Pressure [kPa]	$D_{v0.1}$ [µm]	$D_{v0.5}$ [µm]	$D_{v0.9}$ [µm]	RS[1]	% < 150 [µm]	ASABE/ANSI Classification[2]
11001	450	81	134	202	0.90	63.26	Very-Fine/Fine
3D 10002	276	128	192	312	0.96	23.45	Fine
11003	**300**	**115**	**207**	**367**	**1.22**	**26.99**	**Fine/Medium**
3D 10004	276	132	240	346	0.90	17.64	Medium
GAT 11002	276	162	292	492	1.12	4.92	Medium
11006	**200**	**135**	**318**	**573**	**1.38**	**11.99**	**Medium/Coarse**
GA 11002	276	152	323	534	1.18	9.60	Coarse
GA 11004	276	133	351	624	1.41	13.46	Coarse
8008	**250**	**142**	**354**	**584**	**1.25**	**11.77**	**Coarse/Very-Coarse**
GAT 11004	276	178	367	586	1.11	4.68	Very-Coarse
ULD 12002	276	178	374	558	1.01	0.93	Very-Coarse
6510	**200**	**204**	**460**	**762**	**1.21**	**4.68**	**Very-Coarse/Extremely-Coarse**
ULD 12004	276	268	642	931	1.03	0.44	Extremely-Coarse
6515	**150**	**259**	**713**	**924**	**0.92**	**2.00**	**Extremely-Coarse/Ultra-Coarse**

[1] the Rs – the relative span, calculated by taking the difference of the $D_{v0.9}$ and $D_{v0.1}$ and dividing by the $D_{v0.5}$. This is a measurement of the evenness of the spray dropelt spectrum

[2] nozzle types classified using ASABE/ANSI S572.2 by their $D_{v0.5}$ with values shown as an average of three replicates

% < 150 µm

Though the ULD 12002 had a much lower $D_{v0.5}$ than the ULD 12004, the % < 150 µm for both nozzle types was below 1%, which has significant implications in reducing off-target movement of the sprays. The % < 150 µm values ranged from 23.45% for the 3D10002 to 0.44% for the ULD 12004. The % < 150 µm followed the $D_{v0.5}$ trend where the larger the $D_{v0.5}$ was, the lower the percent of 'driftable fines'. The exceptions were for the GAT nozzle type, where the GAT 11002 was classified as a Medium spray, but had a lower % < 150 µm than the GA 11002 and 11004, both classified as Coarse sprays (4.92, 9.60, 13.46%, respectively).

RS

The RS is used as a determination of the "evenness" of the spray pattern (Ferguson *et al.* 2015), which ranged from 0.9 to 1.41. The GA 11004 had the largest RS which can be explained by the wide range between the $D_{v0.1}$ and the $D_{v0.9}$. This helps to explain why the coarser spray produced a greater percentage of droplets < 150 µm than the GAT 11002, classified as a Medium spray. The most even spray pattern RS is 1.00, which means that volumetrically, the largest and smallest droplets are closest to the $D_{v0.5}$ when calculated. The ULD 12002 had an RS of 1.01 and the ULD 12004 had an RS of 1.03, both of which are ideal given the Extremely-Coarse classification for the ULD 12004.

Conclusions

Given the variation across nozzle type, where sprays ranged from Fine to Extremely-Coarse, differences with respect to weed control should be expected. The idea that one droplet size spray is more effective than another for weed control is something that cannot be generalized. As noted above, the coarser sprays from the 04 flow-rate nozzle types effectively penetrated the cotton canopy to provide better barnyardgrass control than 02 flow-rate nozzle types. Even with differences noted for weed control based on nozzle type, the overall effect on cotton yield was not significant with respect to nozzle type. Prickly sida and barnyardgrass both continue to pose challenges for cotton growers, but it was clear that a two-pass POST program was most effective in controlling these weeds, and with a less injurious PRE than acetochlor, a three-pass program (at a minimum) would be needed to provide ample weed control in Mississippi cotton production. With increasing nozzle technologies entering the market, discerning which nozzle type performs the best in a given situation, is not a one-size-fits-all answer.

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References

Butts T.R., Samples C.A., Franca L.X., Dodds D.M., Reynolds D.B., Adams J.W., Zollinger R.K., Howatt K.A., Fritz B.K., Hoffmann W.C., Kruger G.R. 2018. Spray droplet size and carrier volume effect on dicamba and glufosinate efficacy. Pest Management Science 74: 2020–2029. DOI: https://doi.org/10.1002/ps.4913

Cahoon C.W., York A.C., Jordan D.L., Everman W.J., Seagroves R.W., Braswell L.R., Jennings K.M. 2015a. Weed control in cotton by combinations of microencapsulated acetochlor and various residual herbicides applied preemergence. Weed Technology 29: 740–750. DOI: https://doi.org/10.1614/WT-D-15-00061.1

Cahoon C.W., York A.C., Jordan D.L., Everman W.J., Seagroves R.W., Culpepper A.S., Eure P.M. 2015b. Palmer amaranth (*Amaranthus palmeri*) management in dicamba-resistant cotton. Weed Technology 29: 758–770. DOI: https://doi.org/10.1614/WT-D-15-00041.1

Carter O.W., Prostko E.P., Davis J.W. 2017. The influence of nozzle type on peanut weed control programs. Peanut Science 44 (2): 93–99. DOI: https://doi.org/10.3146/PS17-4.1

Creech C.F., Henry R.S., Fritz B.K., Kruger G.R. 2015. Influence of herbicide active ingredient, nozzle type, orifice size, spray pressure, and carrier volume rate on spray droplet size characteristics. Weed Technology 29 (2): 298–310. DOI: https://doi.org/10.1614/WT-D-14-00049.1

Dorr G.J., Hewitt A.J., Adkins S.W., Hanan J., Zhang H., Noller B.A. 2013. A comparison of initial spray characteristics produced by agricultural nozzles. Crop Protection 53: 109–117. DOI: https://doi.org/10.1016/j.cropro.2013.06.017

Etheridge R.E., Hart W.E., Hayes R.M., Mueller T.C. 2001. Effect of Venturi-type nozzles and application volume on postemergence herbicide efficacy. Weed Technology 15 (1): 75–80. DOI: https://doi.org/10.1614/0890-037-X(2001)015[0075:EOVTNA]2.0.CO;2

Eure P.M., Culpepper A.S., Merchant R.M. 2013. An assessment of cotton tolerance to pyroxasulfone, acetochlor, and S-metolachlor. p. 740–750. In: Proceedings of "The 2013 Beltwide Cotton Conferences". San Antonio, TX: National Cotton Council of America, January 7–10, 2013.

EPA. 1999. Spray drift on pesticides. EPA Publication No. 735 F99024, Washington, D.C.: United States Environmental Protection Agency.

Faircloth W.H., Prostko E.P. 2010. Effect of imazapic and 2,4-DB on peanut yield, grade, and seed germination. Peanut Science 37: 78–82. DOI: https://doi.org/10.3146/PS09-011.1

Ferguson J.C., Chauhan B.S., Chechetto R.G., Hewitt A.J., Adkins S.W., Kruger G.R., O'Donnell C.C. 2019. Droplet-size effects on control of *Chloris* spp. With six POST herbicides. Weed Technology 33 (1): 153–158. DOI: https://doi.org/10.1017/wet.2018.99

Ferguson J.C., Chechetto R.G., Adkins S.W., Hewitt A.J., Chauhan B.S., Kruger G.R., O'Donnell C.C. 2018. Effect of spray droplet size on herbicide efficacy on four winter annual grasses. Crop Protection 112: 118–124. DOI: https://doi.org/10.1016/j.cropro.2018.05.020

Ferguson J.C., Chechetto R.G., Hewitt A.J., Chauhan B.S., Adkins S.W., Kruger G.R., O'Donnell C.C. 2016a. Assessing the deposition and canopy penetration of nozzles with different spray qualities in an oat (*Avena sativa* L.) canopy. Crop Protection 81: 14–19. DOI: https://doi.org/10.1016/j.cropro.2015.11.013

Ferguson J.C., Chechetto R.G., O'Donnell C.C., Dorr G.J., Moore J.H., Baker G.J., Powis K.J., Hewitt A.J. 2016b. Determining the drift potential of Venturi nozzles compared with standard nozzles across three insecticide spray solutions in a wind tunnel. Pest Management Science 72 (8): 1460–1466. DOI: 10.1002/ps.4214

Ferguson J.C., O'Donnell C.C., Chauhan B.S., Adkins S.W., Kruger G.R., Wang R., Urach Ferreira P., Hewitt A.J. 2015. Determining the uniformity and consistency of droplet size across spray drift reducing nozzles in a wind tunnel. Crop Protection 76: 1–6. DOI: 10.1016/j.cropro.2015.06.008

Ivy H.W., Baker R.S. 1972. Prickly sida control and competition in cotton. Weed Science 20 (2): 137–139. DOI: https://doi.org/10.1017/S0043174500035189

Norsworthy J.K., Bond J., Scott R.C. 2013. Weed management practices and needs in Arkansas and Mississippi rice. Weed Technology 27: 623–630. DOI: https://doi.org/10.1614/WT-D-12-00172.1

Ramsdale B.K., Messersmith C.G. 2001. Drift-reducing nozzle effects on herbicide performance. Weed Technology 15 (3): 453–460. DOI: https://doi.org/10.1614/0890-037-X(2001)015[0453:DRNEOH]2.0.CO;2

Rankins A., Byrd J.D., Mask D.B., Barnett J.W., Patrick G.D. 2005. Survey of soybean weeds in Mississippi. Weed Technology 19 (2): 492–498.

Scott G.H., Askew S.D., Wilcut J.W. 2002. Glyphosate systems for weed control in glyphosate-tolerant cotton (*Gossypium hirsutum*). Weed Technology 16 (1): 191–198. DOI: https://doi.org/10.1614/0890-037X(2002)016[0191:GSFWCI]2.0.CO;2

Sikkema P.H., Brown L., Shropshire C., Spieser H., Soltani N. 2008. Flat fan and air induction nozzles affect soybean herbicide efficacy. Weed Biology Management 8 (1): 31–38. DOI: 10.1111/j.1445-6664.2007.00271.x

Talbert R.E., Burgos N.R. 2007. History and management of herbicide-resistant barnyardgrass (*Echinocloa crus-galli*) in Arkansas rice. Weed Technology 21 (2): 324–331. DOI: https://doi.org/10.1614/WT-06-084.1

Wolf R., Bode L., Wax L. 1990. Effect of volume, pressure, and nozzle type on coverage and weed control from postemergence herbicides. FAPC Illinois:101.

Wolf T.M. 2000. Low-drift nozzle efficacy with respect to herbicide mode of action. Aspects of Applied Biology 57: 29–34.

Zhu H., Rowland D.L., Dorner J.W., Derksen R.C., Sorensen R.B. 2002. Influence of plant structure, orifice size, and nozzle inclination on spray penetration into peanut canopy. American Society of Agricultural Engineers 45 (5): 1295–1301. DOI: 10.13031/2013.11058