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Dicamba effects on fruiting in sensitive cotton

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Abstract

Since the release of dicamba-tolerant cotton in 2016, preplant and POST applications of dicamba to control glyphosate-resistant Palmer amaranth have increased. With the increase in area treated with dicamba, the risk of off-target movement to nontarget crops has increased. A field study was conducted at the Texas Tech University New Deal Research Farm equipped with subsurface drip irrigation in 2017 and 2018 to evaluate non-dicamba tolerant cotton response to dicamba when applied at four crop growth stages [first square (FS) + 2 wk, first bloom (FB), FB + 2 wk, and FB + 5 wk]. Dicamba at 0.56 (1×), 0.056 (1/10×), 0.0112 (1/50×), 0.0056 (1/100×), and 0.00112 (1/500×) kg ae ha^{-1} was applied to ‘FM 1830GLT’ cotton. When applications were made at FS + 2 wk, a shift in boll nodal position was apparent following dicamba at the 1/50× rate in 2017 and at 1/10× in 2018 compared to the nontreated control (NTC). A shift in boll distribution from the 1/50× rate of dicamba was apparent at FB in 2017, but not in 2018. Dicamba applied at the 1× rate at FB + 2 wk resulted in reduced boll numbers. No change in boll number or boll position was apparent following any dicamba rate when applied at FB + 5 wk in both years. Dicamba applied at 1/500×, 1/100×, and 1/50× rates at all timings did not affect yield relative to the NTC. When dicamba was applied at the 1/10× rate, the greatest yield loss was observed at FS + 2 wk followed by FB and FB + 2 wk. Micronaire increased following dicamba applied at 1/10× at FS + 2 wk, FB, and FB + 2 wk in 2017. In 2018, micronaire decreased following dicamba applied at 1/10× at FB + 5 wk.

Introduction

Upland cotton is grown on 5.7 million hectares in the United States with approximately 40% grown in Texas (USDA-NASS 2018). Prior to 1997, weed management in cotton was accomplished primarily by a combination of tillage plus preplant-, PRE-, and/or POST-directed applications of contact and soil residual herbicides (Keeling and Abernathy 1989; Keeling et al. 1989). In 1997, cotton production began a radical transformation in weed management due to the introduction of glyphosate-resistant cotton (Dill et al. 2008). With glyphosate-resistant cotton, producers gained additional options to control troublesome weeds but often relied solely on a single herbicide mode of action applied POST (Norsworthy et al. 2007).

Due to the rapid adoption of this technology and the success following over-the-top POST applications, high selection pressure for glyphosate-resistance weeds led to the emergence of glyphosate-resistant Palmer amaranth (Culpepper et al. 2006; Heap 2019). Glyphosate-resistant Palmer amaranth has become widespread across the United States and was first identified in the Texas High Plains in 2011 (Heap 2019). Older herbicide modes of action are being reevaluated in order to gain control of the growing problems caused by glyphosate-resistant Palmer amaranth.

Dicamba, a synthetic auxin herbicide, was first discovered in 1958 and registered for use in monocot crops in 1962 (Timmons 2005). Both the dimethylamine (DMA) and diglycolamine (DGA) salt of dicamba have been used in grain crops to control troublesome broadleaf weeds (Keeling and Abernathy 1988; Keeling et al. 1989; Kruger et al. 2010; Spandl et al. 1997; Wiese and Lavake 1986). The DGA and DMA salts of dicamba more readily lead to dicamba acid, which is one of several concerns for off-target movement to susceptible broadleaf crops such as cotton and soybean (*Glycine max* L.; Mueller et al. 2013; Strachan et al. 2010). Other pathways of off-target movement of herbicides include particle drift and tank contamination.

Cotton cultivars tolerant to dicamba and 2,4-D were commercially available in 2016 followed by new formulations of dicamba and 2,4-D. Although the new auxin-tolerant cotton technology is a useful tool for weed control, an increase in crop injury due to off-target movement has occurred in areas that produce cotton and soybean (Bennett 2018).

Upland cotton is extremely sensitivity to synthetic auxin herbicides, especially 2,4-D (Buol et al. 2018, 2019; Byrd et al. 2015; Everitt and Keeling 2009). Byrd et al. (2015) evaluated cotton

Table 1. Rates of dicamba used for simulated drift applications.

Dicamba rate	Relative rate to standard POST application of dicamba in the Texas High Plains
kg ae ha^{-1}	
0.56	1× rate
0.056	1/10× rate
0.0112	1/50× rate
0.0056	1/100× rate
0.00112	1/500× rate

Table 2. Cotton growth stages and timings of applications.

Cotton growth stage[a,b]	2017	2018
FS + 2 wk	July 7 (52)[c]	July 10 (56)
FB	July 18 (63)	July 16 (62)
FB + 2 wk	July 28 (73)	July 31 (77)
FB + 5 wk	August 21 (97)	August 24 (101)

[a]Cotton growth stages were in agreement with "Cotton growth and development" (Ritchie et al. 2004).
[b]Abbreviations: FB, first bloom; FS, first square.
[c]Days after planting indicated in parentheses.

sensitivity to 2,4-D and determined that more mature cotton was more tolerant to 2,4-D than immature cotton. Everitt and Keeling (2009) focused on the impact of simulated dicamba and 2,4-D drift on lint yield and fiber quality at different growth stages ranging from two-leaf cotton to first bloom (FB). Cotton exposed to the same rate of dicamba or 2,4-D expressed less visual injury after FB application than at the two-leaf stage.

Little information exists on the effects dicamba has on cotton physiology; namely, boll production and reduction following applications of labeled and sub-labeled rates of dicamba at different growth stages. Fiber quality as affected by dicamba were not reported in the previous trials following the different rates of synthetic auxin herbicides at different growth stages. The objectives of this study were to determine the effect of dicamba rate and timing on boll production and retention, the effects of dicamba rate and timing on cotton yield, and the rate of dicamba that reduces yield and fiber quality following exposure at different growth stages.

Materials and Methods

Experimental Design and Management Practices

A field experiment was conducted at the Texas Tech University New Deal Research Farm (33.44°N, 101.43°W) equipped with subsurface drip irrigation in 2017 and 2018. 'FM 1830GLT' (BASF, Florham Park, NJ) cotton was planted at 101,300 seeds ha^{-1} on May 16, 2017, and May 15, 2018. Fertilizer was applied through the irrigation system in the form of 32-0-0 at a rate of 70 kg ha^{-1} in a split application of 35 kg ha^{-1} at 2 and 4 wk after planting. Plot size was four rows spaced 102 cm apart by 9.1 m, but only the center two rows were sprayed. The trial was arranged as a randomized complete block design with three replications.

Dicamba (Clarity®, BASF) at 0.56 (1×), 0.056 (1/10×), 0.0112 (1/50×), 0.0056 (1/100×), and 0.00112 (1/500×) kg ae ha^{-1} (Table 1) was applied at the following four cotton growth stages: first square (FS) + 2 wk, FB, FB + 2 wk, and FB + 5 wk (Table 2). Herbicide treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver a carrier volume of 140 L ha^{-1} equipped with TTI 11004 nozzles (Teejet® Technologies, Glendale Heights, IL) were used to produce ultra-coarse droplets to minimize off-target movement. Accumulated growing degree days ($GDD_{15.6}$), computed as the average of the daily maximum and minimum air temperatures minus a base temperature of 15.6 C (Hake et al. 1990; Peng et al. 1989), were calculated from data collected from a weather station 200 m from the study (Model GRWS100, Campbell Scientific, Logan, UT). A broadcast defoliation application was made once the nontreated control (NTC) plots reached 60% open boll.

Box Mapping

Cotton plants were box mapped prior to harvest to determine boll distribution, as described by Bednarz and Nichols (2005) and Ritchie et al. (2011). A one-square-meter plant sample was removed from a center row of each plot, and the harvestable bolls from each plant within the sample were removed and placed in a grid box based on node and sympodial fruiting position. Each boll was recorded by fruiting site, and bolls were weighed in cohorts corresponding with first position bolls between nodes 4 and 8, 9 and 11, and from node 12 and above. Second position bolls were grouped with first position bolls two nodes higher based on a similarity of flowering dates on the plant as suggested by Schaefer et al. (2017). Vegetative (monopodial) bolls were grouped. Mass per boll for each cohort was calculated as the total mass divided by the total number of bolls within each cohort. Green or immature bolls that were not open at the time of harvest were not counted.

Cotton Seed Yield

Plots were harvested immediately after box mapping samples were taken using a two-row John Deere 7445 harvester equipped with load cells (Rusty's Weigh, Lubbock, TX) from the residual plot to determine plot yield. Samples were ginned to separate lint from the seeds, and lint samples were submitted for high volume instrument testing to the Texas Tech University Fiber and Biopolymer Institute in Lubbock, TX.

Statistical Analysis

Statistical analysis was performed using the Generalized Linear Mixed Model procedure in SAS 9.4 (SAS Institute, Cary, NC). Based on recommendations by Littell et al. (2006), rate and timing treatments were treated as a fixed effect, and the blocking factor (replicate) was treated as a random effect. Year was treated as a random effect and the interaction of year with treatment was tested. As a result, treatment analysis was conducted separately within years. Only treatment differences that were significant using a Type III test of fixed effects were tested for differences in mean using Fisher's protected least significant difference at $\alpha = 0.05$.

Results and Discusion

Boll Production and Reduction

First Square + 2 Wk

At the FS + 2 wk application timing, the 1× rate of dicamba resulted in complete boll loss in 2017 and 2018 (Figure 1). The 1/10× rate resulted in a substantial boll reduction between nodes 5 and 14 relative to the NTC. Additional boll production was

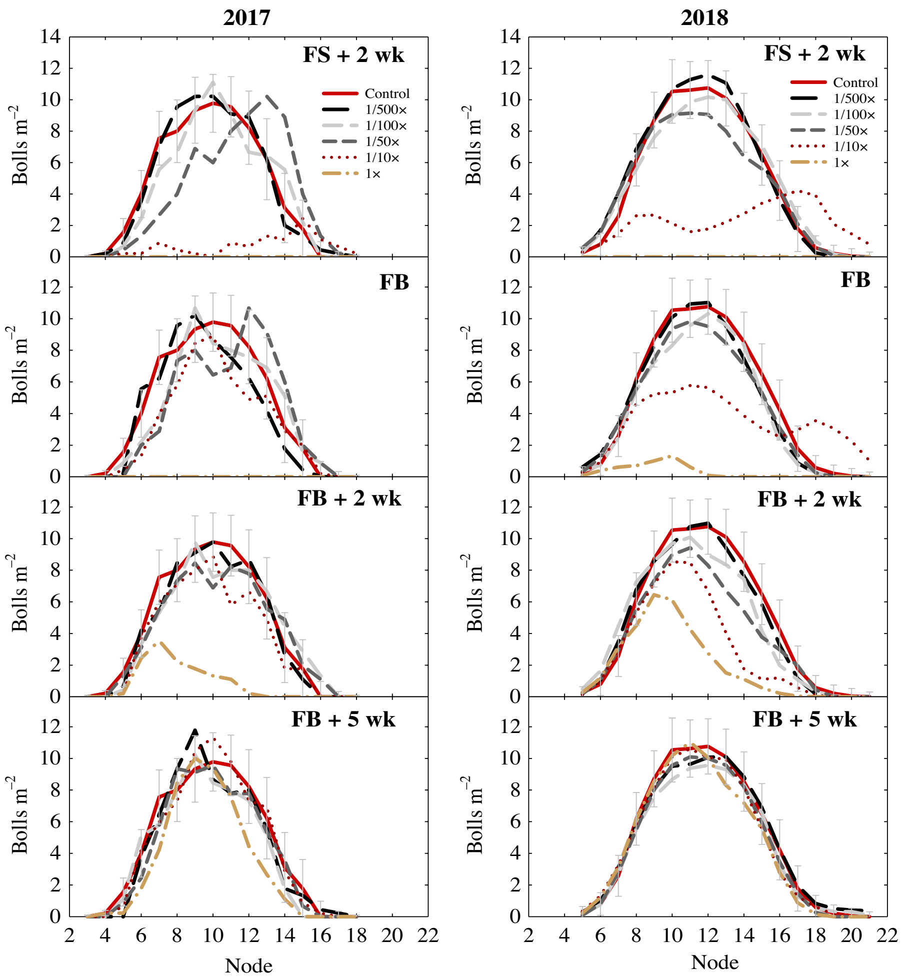

Figure 1. Harvested boll distribution by rate and timing of applications of dicamba in 2017 and 2018. Error bars represent standard errors of the means across rate treatments per node in 2017 and 2018. Green or immature bolls present at the time of box mapping were not accounted for. FB, first bloom; FS, first square.

observed on nodes above node 16 in 2018 when conditions were favorable for late-season growth and development (Table 3). Dicamba applied at 1/50× rate in 2017 resulted in a decrease in boll production from nodes 8 through 11 and an increase in production from nodes 13 to 16. In 2018, no reduction in boll number was observed. No reduction in boll number was observed from the 1/100× or 1/500× rate of dicamba in either 2017 or 2018.

First Bloom

At FB, the 1× rate of dicamba resulted in complete boll loss in 2017. In 2018, boll reductions were observed from nodes 6 through 11, and complete boll loss from nodes 12 and above. Following application of dicamba at the 1/10× rate, boll loss was observed from nodes 11 through 13 in 2017 and from nodes 9 through 15 in 2018. An increase in boll production was observed in 2018 from nodes 17 and above, compensating for what was lost earlier in the growing season. A decrease in boll production was observed at nodes 9 through 11 in 2017 from the 1/50× rate of dicamba; however, no yield loss was observed. No boll production changes or reductions were observed from the 1/50× rate in 2018, or the 1/100× rate or the 1/500× rate in both 2017 and 2018.

First Bloom + 2 Wk

At FB + 2 wk, the 1× rate of dicamba resulted in boll reductions from nodes 7 and above in 2017, and from nodes 10 and above in 2018. No reduction in the number of bolls were observed from nodes below node 7 in either year resulting in the first harvestable yield in 2017 from the 1× rate of dicamba. Reductions in boll production were observed following the 1/10× treatment in 2017 from nodes 11 and 12. In 2018, boll reductions were observed from nodes 10 through 16. No compensation was observed in the upper section of the plant from reductions in the middle of the plant. Boll reductions in both 2017 and 2018 resulted in yield reductions from the 1/10× rate of dicamba.

First Bloom + 5 Wk

At FB + 5 wk, a boll reduction was observed between nodes 11 and 15 in 2017 from the 1× rate of dicamba. No other boll reduction was observed in 2017 from any other rate of dicamba. In 2018, no boll reductions were observed from any rate of dicamba. These results indicate that as cotton matures, it becomes more tolerant to dicamba. Similar results were observed by Buol et al. (2018) where no yield losses were observed following dicamba applied at 35 g ae ha^{-1} when a flower was on node 10 and higher.

Table 3. Heat units, rainfall, and irrigation by month in 2017 and 2018 at the Texas Tech University Research Farm, New Deal, TX.

Year	Month	Accumulated heat units[a]	Rainfall	Irrigation
			mm	
2017	May	85	45	25
	June	380	21	79
	July	706	23	177
	August	956	66	41
	September	1,138	76	0
	October	1,210	3	0
	November	1,226	0	0
2018	May	159	8	76
	June	510	37	107
	July	864	22	101
	August	1,180	41	113
	September	1,370	56	7
	October	1,424	101	0
	November	1,424	10	0

[a]Computed as the average of the daily maximum and minimum air temperatures minus a base temperature of 15.6 C for each month (Hake et al. 1990; Peng et al. 1989).

Table 4. ANOVA P-value results for treatment interactions in cotton fiber quality parameters.[a,b]

Year	Effects	Yield	Micronaire	Length	Uniformity	Strength	Elongation
	Yr*Timing	0.007	0.09	0.013	0.010	0.09	0.0035
	Yr*Rate	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
2017	Rate	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
2017	Timing	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
2017	Rate*Timing	0.012	<0.001	<0.001	<0.001	<0.001	<0.001
2018	Rate	<0.001	0.018	0.032	0.009	0.012	0.30
2018	Timing	<0.001	0.14	0.88	0.41	0.34	0.079
2018	Rate*Timing	<0.001	0.39	0.16	0.68	0.67	0.32

[a]Type III tests (yield, fiber quality) year*treatment (test 1); rate timing rate*timing (test 2).
[b]Significance was determined between all interactions at $\alpha < 0.05$.

Lint Yield and Fiber Quality

The 2017 and 2018 growing seasons represented contrasting weather, with 2017 being cooler and receiving more precipitation than 2018 (Table 3). There was a significant year-by-treatment interaction for yield and all fiber quality parameters except for micronaire and strength (Table 4). According to a report by Lokhande and Reddy (2014), many fiber quality parameters decrease under water stressed conditions, which could be an explanation for the variance in measurements. Due to a dicamba rate by timing interaction, treatments were analyzed within year.

In 2017 and 2018, dicamba at 1/500×, 1/100×, and 1/50× rates did not result in a yield decrease regardless of application timing (Tables 5 and 6). The 1/10× rate of dicamba resulted in decreased yield when applied at FS + 2 wk, FB, and FB + 2 wk compared with the NTC, but did not cause a yield response when applied at FB + 5 wk in either year. Following the 1× rate of dicamba, reductions in lint yield were observed at every application timing in 2017, with the application at FB + 2 wk resulting in no harvestable lint. The cotton stage least affected by dicamba at 1× was FB + 5 wk, where a 30% yield loss was observed in 2017 and no yield loss was observed in 2018. In 2017, fiber quality was affected by dicamba rate, timing, and a combination of rate and timing (Table 4).

In general, greater dicamba rates resulted in substandard micronaire values. Applications made at FS + 2 wk and FB had the greatest effects on fiber quality relative to applications made at FB + 2 wk and FB + 5 wk. For FS + 2 wk and FB applications, bolls distributions were shifted, which led to the underdevelopment of bolls. Applications made at FB + 2 wk and FB + 5 wk when fiber quality was decreased, the fiber development was inhibited due to extreme stress from dicamba. Environmental conditions influence cotton growth and development following plant stress. Byrd et al. (2015) reported that water deficit coupled with 2,4-D injury would likely influence crop growth, recovery, and yield. Rainfall and irrigation varied from 556 mm in 2017 to 679 mm in 2018. Accumulated heat units (1,226) were low during the 2017 growing season relative to 2018 (1,424), which was likely a contributing factor to these measurements (Table 3).

The 1× dicamba rate consistently affected micronaire, length, uniformity, and strength in cases when sufficient cotton was harvested for fiber quality determination. These differences were most noticeable in cotton treated at FB, largely because the cotton treated prior to FB did not produce harvestable bolls and cotton treated later in the season already had mature bolls below node 9. Applications made after FB also affected micronaire, length, uniformity, and strength, although the numeric effects were smaller than those at FB. Elongation was affected by the 1× rate at FB timing, but not at the other timings.

The 1/10× and 1/50× dicamba rates had similar effects as the 1× rate in 2017, although the effects were less dramatic. Both the 1/50× and 1/10× application rates resulted in reductions to length, uniformity, and strength at the FB application (Table 5). The 1/100× and 1/500× rates resulted in slight changes in uniformity and length that were different from the NTC at the FB + 2 wk timing.

Table 5. Least-square means of yield and fiber quality parameters of 21 treatments (rate × timing) applied in 2017.[a,b]

Rate	Timing	Yield[c]	Micronaire	Length	Uniformity	Strength	Elongation
		kg ha^{-1}		mm	%	g tex^{-1}	%
NTC	–	1,590 ab	3.2 cdef	30.1 a	81.4 a	28.7 ab	8.5 abcde
1/500×	FS + 2 wk	1,500 ab	3.2 def	30.1 a	80.8 ab	28.4 ab	8.0 e
	FB	1,460 abc	3.2 cdef	29.9 ab	80.3 abc	28.8 ab	8.4 abcde
	FB + 2 wk	1,530 ab	3.0 fg	29.0 bcdef	79.4 bcd	28.3 ab	8.8 ab
	FB + 5 wk	1,590 ab	3.3 cde	29.7 abc	81.0 ab	28.5 ab	8.3 bcde
1/100×	FS + 2 wk	1,660 a	3.4 cde	29.7 abc	79.8 abc	28.9 ab	8.3 abcde
	FB	1,420 abcd	3.2 cdef	29.3 abcd	79.8 abc	28.2 ab	8.1 cde
	FB + 2 wk	1,680 a	3.1 ef	29.2 abcd	79.2 bcd	27.8 ab	8.6 abcd
	FB + 5 wk	1,500 abc	3.4 cde	29.4 abcd	80.7 ab	27.9 ab	8.9 a
1/50×	FS + 2 wk	1,290 abcd	3.4 bc	29.2 abcd	79.7 abcd	28.5 ab	8.1 cde
	FB	1,560 ab	3.2 cdef	28.5 def	78.8 cd	26.9 bc	8.3 bcde
	FB + 2 wk	1,290 abcd	3.4 cd	29.2 abcd	79.5 bcd	27.2 b	8.1 cde
	FB + 5 wk	1,540 ab	3.1 ef	29.2 abcd	80.3 abc	28.1 ab	8.4 abcde
1/10×	FS + 2 wk	770 ef	3.7 ab	28.0 f	80.1 abc	29.4 a	8.6 abc
	FB	1,190 bcde	3.9 a	28.1 ef	77.9 d	24.9 c	8.1 cde
	FB + 2 wk	1,040 de	3.7 a	29.7 abc	79.4 bcd	27.8 ab	8.1 de
	FB + 5 wk	1,650 a	3.3 cde	29.1 abcde	80.6 ab	28.3 ab	8.4 abcde
1×	FS + 2 wk[d]	0	—	—	—	—	—
	FB	240 gh	2.8 g	25.3 g	74.2 e	21.9 d	7.3 f
	FB + 2 wk	600 fg	3.1 ef	28.9 bcdef	79.7 abcd	28.4 ab	8.6 abcd
	FB + 5 wk	1,100 cde	3.0 fg	28.7 cdef	79.4 bcd	27.0 bc	8.4 abcde

[a]Means within the same column and followed by a common letter are not significantly different at the 0.05 level of significance.
[b]Abbreviations: FB, first bloom; FS, first square; NTC, nontreated control.
[c]Yield was determined through mechanical harvest from residual plot following box mapping.
[d]Treatment not included in analysis of variance.

Table 6. Least-square means of yield and fiber quality parameters of 21 treatments (rate × timing) applied in 2018.[a,b]

Rate	Timing	Yield[c]	Micronaire	Length	Uniformity	Strength	Elongation
		kg ha^{-1}		mm	%	g tex^{-1}	%
NTC	–	1,600 a	4.1 abcd	31.0 a	81.3 ab	31.3 abcd	6.2 ab
1/500×	FS + 2 wk	1,630 a	3.9 bcde	31.1 a	82.1 ab	33.5 a	6.2 ab
	FB	1,500 ab	4.0 abcde	29.8 ab	81.8 ab	31.5 abc	6.1 bc
	FB + 2 wk	1,590 ab	4.0 bcde	29.7 abc	81.9 ab	32.3 abc	6.1 bc
	FB + 5 wk	1,430 abc	3.9 bcde	28.9 bc	81.4 ab	33.1 ab	6.5 a
1/100×	FS + 2 wk	1,510 ab	4.2 abc	29.9 ab	80.6 ab	29.7 cd	6.2 ab
	FB	1,610 a	4.0 abcd	30.1 ab	81.8 ab	31.6 abc	6.1 ab
	FB + 2 wk	1,540 ab	4.2 ab	30.0 ab	81.3 ab	31.7 abc	6.2 ab
	FB + 5 wk	1,630 a	4.1 abcd	29.6 abc	82.2 a	32.5 abc	6.3 ab
1/50×	FS + 2 wk	1,590 ab	4.4 a	29.5 abc	81.4 ab	30.1 bcd	6.0 bc
	FB	1,650 a	4.0 bcde	30.8 a	81.9 ab	32.2 abc	6.2 ab
	FB + 2 wk	1,490 ab	4.1 abcd	30.6 ab	81.4 ab	32.2 abc	6.1 bc
	FB + 5 wk	1,600 a	4.2 ab	30.5 ab	82.5 a	31.1 abcd	6.1 bc
1/10×	FS + 2 wk	1,130 d	3.9 bcde	29.3 abc	82.2 ab	31.7 abc	6.3 ab
	FB	1,180 cd	3.8 cde	30.5 ab	81.3 ab	31.8 abc	5.7 c
	FB + 2 wk	1,320 bcd	4.2 ab	30.8 a	82.6 a	32.6 abc	6.0 bc
	FB + 5 wk	1,490 ab	3.6 e	30.8 a	81.9 ab	32.0 abc	6.3 ab
1×	FS + 2 wk	20 f	—	—	—	—	—
	FB	150 f	3.9 bcde	27.7 c	77.7 c	27.9 d	6.0 bc
	FB + 2 wk	600 e	4.0 abcde	28.8 bc	79.7 bc	29.7 cd	6.0 bc
	FB + 5 wk	1,590 ab	3.7 de	29.9 ab	81.1 ab	30.9 abcd	6.1 bc

[a]Means within the same column and followed by a common letter are not significantly different at the 0.05 level of significance.
[b]Abbreviations: FB, first bloom; FS, first square; NTC, nontreated control.
[c]Yield was determined through mechanical harvest from residual plot following box mapping.

In 2018, application rate had an effect on fiber quality, but timing and the interaction of timing and rate did not have significant effects. Differences were observed at the 1/10× and 1× rates of dicamba (Table 6). In all cases, greater dicamba rates resulted in lower fiber quality, regardless of application timing.

Cotton cultivars susceptible to off-target movement of dicamba show differing levels of injury depending on rate and cotton growth stage at the time of the application, which is consistent with previous research evaluating different rates of synthetic auxin herbicides on susceptible cotton cultivars at different growth stages (Buol et al. 2018, 2019; Byrd et al. 2015; Everitt and Keeling 2009; Marple et al. 2008). Differences in boll distributions could vary if cultivars with different maturity groups were compared. Although rates of dicamba and growth stages that were treated remained the same, lint production and fiber quality measurements varied between years. Cotton is able to compensate for in-season injury; however, changing the normal boll distribution can negatively influence fiber quality (Bednarz and Roberts 2001). This is consistent with results observed in 2018 when the 1/10× and 1× rates of dicamba decreased yield and fiber quality. In contrast, micronaire increased following a 1/10× rate of dicamba at the FS + 2 wk, FB, and FB + 2 wk in 2017. This is likely due to reduced boll production above node 9, resulting in the majority of bolls coming from nodes 9 and below, which have more time to mature relative to nodes located above node 9.

Cotton boll positioning, lint yield, and fiber quality are all influenced by off-target movement of dicamba. Shifts in boll production, which has the potential to delay maturity and decrease lint production, and boll reductions occurred at early reproductive growth stages following dicamba applications. Although boll production is shifted from lower portions to higher portions of the plant following dicamba applications, lint yield and fiber quality measurements were only impacted at 1/10× and 1× rates of dicamba. Results from these trials indicate that timing and rate of dicamba are important factors when evaluating boll production and reduction, lint yield, and fiber quality following off-target movement of dicamba.

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