agriculture

MDPI

Article

Peanut (*Arachis hypogea*) Response to Low Rates of Dicamba at Reproductive Growth Stages

John W. Seale *, Taghi Bararpour, Jason A. Bond, Jeffrey Gore and Bobby R. Golden

Delta Research and Extension Center, Mississippi State University, Stoneville, MS 38776, USA; mtb436@msstate.edu (T.B.); jbond@drec.msstate.edu (J.A.B.); jgore@drec.msstate.edu (J.G.); bgolden@drec.msstate.edu (B.R.G.)

* Correspondence: jws764@msstate.edu

Received: 3 August 2020; Accepted: 9 September 2020; Published: 16 September 2020

Abstract: Tank contamination and off-target movement of dicamba is a probable issue facing peanut producers in Mississippi. In 2017 and 2018, a field study was conducted at Mississippi State University's Delta Research and Extension Center in Stoneville, Mississippi, to evaluate the response of peanut to low rates of dicamba at three growth stages. Dicamba at 35 and 17.5 g ae ha^{-1} with and without non-ionic surfactant (NIS) was applied to peanut at R1 (beginning bloom), R2 (beginning peg), and R3 (beginning pod). In each site year, peanut injury was visible following exposure to dicamba. Peanut lateral growth was also reduced regardless of treatment or growth stage following exposure to dicamba. Peanut injury was most prominent 14 days following exposure to dicamba, regardless of timing in both site years. Peanut yield was not different following dicamba treatments in 2018 due to late-season environmental conditions. In 2017, dicamba at 1/32 X plus NIS, 1/16 X and 1/16 X plus NIS reduced peanut yield 16%, 16%, and 30% when averaged over growth stage, respectively. Based on this study, visible peanut injury, lateral growth reduction, and yield decreases were observed following exposure to dicamba.

Keywords: peanut; dicamba; drift; tank contamination; sublethal rate; peanut growth; canopy closure; lateral growth

1. Introduction

Dicamba is a plant growth regulator (PGR) commonly used as a herbicide [1]. Dicamba, a benzoic acid derivative, can be formulated as various salts that are prone to volatilization [2,3]. Dicamba formulations vary in volatility potential, but have the same effect on targeted weed species [3]. Dimethylamine (DMA) salts are known to be the most volatile, while diglycolamine (DGA) salts are less volatile [4]. The newest additions to the benzoic acid family consist of a DGA salt of dicamba with the trade name XtendiMax® (Bayer CropScience LP, 800 Lindbergh Blvd., Saint Louis, MO, USA) and an (*N*,*N*-bis-(3-aminopropyl) methylamine salt) (BAPMA) salt of dicamba with the trade name Engenia® (BASF Corporation, 26 Davis Drive, Research Triangle Park, NC, USA) [5]. While DGA and BAPMA salts are less volatile than their DMA predecessor, they can still volatilize [6].

Evolution and pressure from herbicide-resistant weeds led to the advancement of herbicide-resistant soybean [*Glycine max* (L.) Merr.] cultivars [7]. In 2016, commercialization of 2,4-D-and dicamba-tolerant soybean provided new systems to control herbicide-resistant weeds [8,9]. Roundup Ready® Xtend (Bayer CropScience LP, 800 Lindbergh Blvd.) is a dicamba-resistant (DT) cropping system widely adopted across the U.S. that allows producers to apply registered formulations of dicamba herbicides at preplant, planting, and POST timings [10–12]. The adoption of DT soybean and in-crop use of dicamba formulations has created great concern due to non-DT soybean expressing synthetic auxin symptoms in recent years [11,13].

In 2017 and 2018, >1.4 million and ~1 million ha of soybean were damaged from off-target movement of dicamba in the U.S., respectively [11,13]. Applications of dicamba made during the growing season are prone to injure adjacent crops sensitive to dicamba from off-target movement [14–16]. Off-target movement of herbicides is defined as the unintended airborne movement of particles to a non-targeted area after an application has been made to a specific area [17]. Off-target movement of dicamba can occur from volatility and primary drift [18,19]. Movement of herbicide particles to off-target sites are common when environmental conditions, such as temperature and wind, favor volatilization and/or primary drift [17,20]. Volatility of dicamba will increase when temperature increases and damage to off-target sites can occur from spray droplets in windy conditions [21].

In addition to volatilization and primary drift, dicamba residue in spray equipment can damage sensitive crops [1,22]. Typically, applicators use the same spray equipment for all crops and rely on proper cleanout to reduce injury to susceptible crops [23,24]. Plant growth regulators, specifically dicamba, will bind to materials in the spray tank due to their lack of water solubility [1,25]. Dicamba can bond to nozzles, plastic, rubber hoses, and the spray tank itself [26]. A cleaning agent must be used to displace and solubilize dicamba particles from a spray tank [27]. Proper tank cleanout can reduce dicamba residue in spray equipment and mitigate potential for dicamba exposure to sensitive crops [1].

Leaf cupping, leaf strapping, and epinastic twisting of stems can be expressed when an application of dicamba has been made in proximity to non-DT soybean cultivars [16,27]. Dicamba concentrations of 0.056 g ae ha^{-1} applied to soybean can produce injury symptoms [28]. Soybean and peanut are both commercially grown legume crops [29]; therefore, peanut exhibits similar injury symptoms to that of soybean following exposure to dicamba [30]. Soybean and peanut sensitivity to dicamba has been documented in recent years [14,28,31,32].

Research reported that peanut emergence was reduced 15% for every 100 g ha^{-1} of dicamba applied PRE with a maximum emergence reduction of 81% at 560 g ha^{-1} [31]. Peanut yield loss from applications of dicamba ranged from 0 to 86% at PRE timing, 24% to 82% at V2 growth stage, 30 to 95% at V3 growth stage, and 45% to 88% at V5 growth stage [31]. Other research observed peanut yield loss was most severe when dicamba was applied at 30, 60, and 90 days after planting (DAP) [30]. Results indicated 60 DAP was the most sensitive timing [30]. Dicamba applied at 40 g ha^{-1} resulted in 2% to 29% yield loss in peanut [30]. These results reiterate the need for producers and applicators to be mindful of sensitivity and damage that can occur if dicamba applications are made in proximity to peanut [15].

In recent years, various formulations of dicamba have been approved for use in DR soybean cultivars [5]. Applications of dicamba made in proximity to peanut can cause injury and reduce yield [5,30,31]. Therefore, a field study was conducted in 2017 and 2018 to evaluate peanut response to low rates of dicamba at three reproductive growth stages.

2. Materials and Methods

A field study was conducted at the Delta Research and Extension Center in Stoneville, MS, in 2017 (33°26′34.7″ N, 90°54′36.4″ W) and 2018 (33°26′37.3″ N, 90°54′45.0″ W) to characterize peanut growth and yield response following exposure to low rates of dicamba at reproductive growth stages. Soil type in 2017 was a Commerce silty clay loam (fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts) with a pH of 6.3 and an organic matter content of approximately 1.3%. Soil type in 2018 was a Beulah sandy loam (coarse-loamy, mixed, active, thermic Typic Dystrudepts) containing 0.7% organic matter with a pH of 5.3.

In each site year, 'Georgia-06G' peanut (University of Georgia-Coastal Plain Experiment Station, Tifton, GA, USA) were planted to a depth of 5 cm at a seeding rate of 258,300 seeds ha^{-1}, using a small-plot planter (John Deere MaxEmerge Plus 1700, Moline, IL, USA). Planting was undertaken on 23 May and 5 May in 2017 and 2018, respectively. Plot size was 4 m × 6 m and consisted of four rows spaced 101.6 cm apart. Rows two and three received dicamba treatments, while rows one and four remained as a nontreated buffer between adjacent plots.

Paraquat (Gramoxone SL 2.0, herbicide, 841 g ai ha^{-1}, Syngenta Crop Protection, P.O. Box 18300 Greensboro, NC, USA) at 420 g ai ha^{-1} was applied before planting to eliminate existing weeds. In each site year, flumioxazin (Valor SX, herbicide, Valent, Walnut Creek, CA, USA) at 53.6 g ai ha^{-1} was applied PRE immediately following planting. Clethodim (Select Max, herbicide, Valent) at 59.5 g ai ha^{-1} was applied three weeks after peanut emergence to control grass weeds in each site year. Plots were maintained weed-free by mechanical or hand weeding throughout the growing season.

Treatments were arranged as three by four factorial arrangement in a randomized complete block with three replications. Factor A was peanut reproductive growth stage where treatments were applied at R1 (beginning bloom), R2 (beginning peg), and R3 (beginning pod). Factor B was dicamba treatment and consisted of dicamba (Clarity, herbicide, BASF Corporation, Durham, NC, USA) at 35 and 17.5 g ae ha^{-1} with and without non-ionic surfactant (NIS) (Induce, adjuvant, Helena Chemical Company, Collierville, TN, USA) at 0.25% *v*/*v*. A nontreated control was included. Dicamba applied at 35 and 17.5 g ae ha^{-1} represent 1/16 and 1/32 X (X = recommended dicamba rate of 560 g ae ha^{-1}) of the labeled use rate, respectively. Treatments were applied using a CO_2-pressurized backpack sprayer equipped with turbo induction nozzles (Turbo TeeJet Induction 110015 nozzle, Springfield, IL, USA) set to deliver 140 L ha^{-1} at 206 kPa.

Visible estimates of aboveground peanut injury were recorded 7 days after (DA)-R1, 7 and 14 DA-R2, and 14 and 28 DA-R3 applications in 2017. Visual estimates of aboveground peanut injury in 2018 were recorded 7 and 14 DA-R1, 7 DA-R2, and 7, 21, 35, and 49 DA-R3. Injury estimations were based on a scale of 0 to 100% where 0 indicated no visual effect and 100 indicated complete plant death. Peanut lateral growth measurements were taken 14 and 28 DA-R3 applications in 2017. In 2018, peanut lateral growth was measured 7 DA-R1, 7 DA-R2, and 7, 21, and 35 DA-R3 applications. Visual estimates of peanut canopy closure were recorded 35 DA-R3 and were based on percent ground coverage as compared to the nontreated control. Peanut was harvested with a small-plot combine on 20 October 2017, and 11 October 2018. Since year was significantly different, data was presented separately. Percent peanut yield loss following dicamba treatments as compared to the nontreated control were calculated by the following equation:

Percent yield reduced = 1 − (Weight of peanut yield following dicamba/Weight of peanut yield in nontreated control) [31].

Nontreated data were excluded from analysis of peanut injury. However, nontreated data were included in analysis for peanut lateral growth and yield. Nontransformed data were subjected to ANOVA using the GLIMMIX procedure in SAS 9.4 (SAS Institute, Inc., Cary, NC, USA) with year set as a random effect parameters. Injury data was constricted to 7 DA-R2 and 28 DA-R3 and peanut lateral growth data was constricted to 14 DA-R3 and 28 DA-R3 in 2017. Therefore, data was analyzed separately by year due to evaluation recordings. All outlying observations were deleted from the data to reduce variability among peanut yield response to dicamba treatments. Least square means were calculated and mean separation ($p \leq 0.05$) was produced to determine significance of the treatments. The analysis determined the main effect of peanut response to dicamba treatments.

3. Results and Discussion

3.1. Peanut Injury—2017

In 2017, peanut injury was not significant at 7 DA-R1 ($p = 0.0701$), 14 DA-R2 ($p = 0.4381$), and 14 DA-R3 ($p = 0.0534$). At 7 DA-R2 ($p = 0.0105$), dicamba at 1/16 X and 1/32 X at R1 caused greater injury than 1/32 X with and without NIS at R2 (Table 1). Dicamba at 1/16 X plus NIS at R1, dicamba with and without NIS at R2, and dicamba at 1/32 X plus NIS at R1 produced similar injury, which ranged from 11 to 13%. Peanut injury was least at 9% following dicamba applied at 1/32 X with and without NIS at R2. At 28 DA-R3 ($p < 0.0001$), injury was greatest following dicamba at 1/16 X with and without NIS at R3. All R3 applications resulted in greater injury ranging from 5 to 10% at 28 DA-R3 than R1 or R2 applications. All R1 and R2 applications were ≤2% injury at 28 DA-R3.

Table 1. Peanut injury, width, canopy closure, and yield following exposure to dicamba 7 DA-R2 [1] and 28 DA-R3 at Stoneville, MS in 2017.

Dicamba Rate (g ae ha^{-1})	Timing	Injury (%)		Width (cm)		Canopy Closure [2] (% of nontreated)	Peanut Yield (kg ha^{-1})
		7 DA-R2	28 DA-R3	14 DA-R3	28 DA-R3	35 DA-R3	
0	N/A	-	-	84 a	99 a	-	5232 ab
35 (1/16 X)	R1	15 a	0 d	72 d	93 bcd	94 bcd	4317 abc
	R2	11 bc	0 d	75 bcd	94 bcd	95 bcd	3952 bc
	R3	-	9 a	76 bc	91 cd	92 cd	5106 ab
35 plus NIS [3]	R1	13 ab	0 d	73 cd	90 cd	91 cd	4091 bc
	R2	11 bc	0 d	73 cd	89 d	90 d	3574 bc
	R3	-	10 a	77 b	94 bcd	95 bcd	2777 c
17.5 (1/32 X)	R1	15 a	0 d	77 b	90 cd	91 cd	4028 bc
	R2	9 c	2 c	75 bcd	95 ab	97 ab	4942 ab
	R3	-	5 b	78 b	93 bcd	94 bcd	5879 a
17.5 plus NIS	R1	12 abc	0 d	72 d	91 cd	92 cd	4274 bc
	R2	9 c	1 cd	75 bcd	94 bc	95 bc	4389 ab
	R3	-	6 b	78 b	90 cd	91 cd	4786 ab

Means followed by the same letter for each parameter are not different at $p < 0.05$. [1] DA = days after, [2] Data for canopy closure are expressed as a percentage of nontreated control, [3] Non-ionic surfactant = NIS. R1 = beginning bloom, R2 = beginning peg, R3 = beginning pod.

3.2. Peanut Lateral Growth and Canopy Closure—2017

Peanut lateral growth 14 and 28 DA-R3 was reduced ($p < 0.0001$) following exposure to dicamba (Table 1). At 14 DA-R3, the nontreated control measured 84 cm wide, which was different from plots following exposure to dicamba treatments. At 14 DA-R3, dicamba at 1/32 X with and without NIS at R3 and dicamba at 1/16 X with and without NIS at R3 resulted in peanut lateral growth of 76 cm to 78 cm. All dicamba treatments at R2 resulted in 73 cm to 75 cm peanut lateral growth 14 DA-R3. All dicamba treatments at R1 resulted in 72 cm to 77 cm peanut lateral growth 14 DA-R3. The greatest difference among treatments 14 DA-R3 were observed following dicamba at 1/32 with and without NIS at R3, which resulted in peanut lateral growth of 78 cm, as compared to dicamba at 1/16 X plus NIS at R2 and R3 that resulted in peanut lateral growth of 73 cm.

Peanut lateral growth 28 DA-R3 was different among treatments ($p = 0.0145$). The nontreated control was 99 cm wide (Table 1). At 28 DA-R3, dicamba at 1/32 X at R2 measured 95 cm and was the only treatment with comparable peanut lateral growth to the nontreated control. All dicamba treatments resulted in peanut lateral growth ranging from 89 cm to 95 cm. Dicamba at 1/16 X plus NIS at R2 resulted in peanut lateral growth of 89 cm, which was the only treatment different from dicamba at 1/32 X with and without NIS at R2.

Peanut canopy closure was significant ($p = 0.0116$) among treatments. Dicamba at 1/32 X at R2 resulted in 97% canopy closure and was the only treatment that was not different from the nontreated control (Table 1). All remaining treatments resulted in 90 to 95% canopy closure. Dicamba at 1/16 X plus NIS at R2 resulting in 90% canopy closure was the only treatment different from dicamba at 1/32X with and without NIS at R2.

3.3. Peanut Yield—2017

A main effect ($p = 0.0457$) of dicamba treatments was observed for peanut yield (Table 1). All treatments had comparable peanut yield to the nontreated control, except dicamba at 1/16 X plus NIS at R3. Dicamba at 1/16 X at R3 and 1/32 X with and without NIS at R2 and R3 were the only treatments different from dicamba at 1/16 X plus NIS at R3.

3.4. Summary of Results—2017

Based on 2017 study, peanut injury was significant 7 DA-R2 and 28 DA-R3 treatments. Dicamba at 1/16 X with and without NIS at R1 resulted in greater injury than 1/32 X with and without NIS at R2. At 28 DA-R3, dicamba at 1/16 X and 1/32 X with and without NIS at R3 resulted in greater injury than dicamba treatments at R1 and R2. Peanut lateral growth for the nontreated control was different from all dicamba treatments at 14 DA-R3. At 28 DA-R3, peanut lateral growth following dicamba at 1/32 X at R2 was the only treatment that was not different from the nontreated control. Peanut canopy closure was not different between dicamba at 1/32 X at R2 and the nontreated control. However, dicamba at 1/16 X plus NIS at R2 was different from dicamba at 1/32 X at R2 and the nontreated control. Peanut yield was not different following dicamba treatments, except for dicamba at 1/16 X plus NIS at R3.

3.5. Peanut Injury—2018

In 2018, all treatments were significant for peanut injury at each evaluation, except 21 DA-R3 ($p = 0.1070$) and 35 DA-R3 ($p = 0.1761$). At 7 DA-R1 ($p = 0.0147$), dicamba at 1/16 X plus NIS at R1 was different from 1/16 X at R1 and 1/32 X with and without NIS at R1 (Table 2). At 7 DA-R1, dicamba at 1/16 X at R1 was not different from dicamba at 1/32 X with and without NIS at R1. However, at 7 DA-R1, dicamba at 1/32 X at R1 was different from dicamba at 1/32 X plus NIS at R1. At 7 DA-R1, peanut injury following exposure to dicamba at 1/32 X, 1/16 X, 1/32 X plus NIS, and 1/16 X plus NIS was 20, 23, 25, and 30%, respectively. At 14 DA-R1 ($p = 0.0348$), dicamba at 1/16 X and 1/32 X plus NIS were different from 1/16 X and 1/32 X plus NIS at R1. However, dicamba at 1/16 X plus NIS at R1 and 1/32 X plus NIS at R1 were not different. At 14 DA-R1, dicamba at 1/32 X, 1/16 X, 1/32 X plus NIS, and 1/16 X plus NIS resulted in 18, 20, 25, and 25% peanut injury, respectively.

Table 2. Peanut injury following exposure to dicamba 7 and 14 DA-R1 [1], 7 DA-R2, and 7 and 49 DA-R3 at Stoneville, MS in 2018 [2].

Dicamba Rate (g ae ha^{-1})	Timing	Injury (%)				
		7 DA-R1	14 DA-R1	7 DA-R2	7 DA-R3	49 DA-R3
0	N/A	-	-	-	-	-
35 (1/16 X)	R1	23 bc	20 b	22 ab	17 ef	7 abc
	R2	-	-	12 cd	32 a	5 cd
	R3	-	-	-	23 bcd	9 abc
35 plus NIS [3]	R1	30 a	25 a	25 a	23 bcd	11 a
	R2	-	-	17 bc	28 ab	10 ab
	R3	-	-	-	20 de	9 abc
17.5 (1/32 X)	R1	20 c	18 b	20 ab	13 f	3 d
	R2	-	-	10 d	28 ab	6 bcd
	R3	-	-	-	18 def	5 cd
17.5 plus NIS	R1	25 b	25 a	22 ab	17 ef	6 bcd
	R2	-	-	12 cd	27 abc	5 cd
	R3	-	-	-	22 cde	7 abc

[1] DA = days after, [2] Data are pooled across a single experiment in 2018, R1 = beginning bloom, R2 = beginning peg, R3 = beginning pod. [3] Non-ionic surfactant = NIS. Means followed by the same letter for each parameter are not different at $p < 0.05$.

Peanut injury at 7 DA-R2 ($p = 0.0002$) was greatest following exposure to dicamba at R1 (Table 2). Dicamba at 1/16 X plus NIS at R1 resulted in the greatest peanut injury, but was not different from 1/16 X at R1 and 1/32 X with and without NIS at R1. At 7 DA-R2, there were no differences in peanut injury between dicamba treatments at R1. However, dicamba at 1/16 X at R2 and 1/32 X with and without NIS at R2 were different from dicamba at 1/16 X and 1/32 X with and without NIS at R1. At 7 DA-R2, peanut injury following dicamba exposure at R2 ranged from 10% to 17%, while injury ranged from 20 to 25% following exposure to dicamba at R1.

Peanut injury was significant ($p < 0.0001$) at 7 DA-R3. Dicamba at 1/16 X plus NIS and 1/32 X at R2 were not different from dicamba at 1/32 X plus NIS at R2 or 1/16 X + NIS at R1 (Table 2). No differences were detected for peanut injury 7 DA-R3 following dicamba at 1/16 at R3, 1/16 X plus NIS at R1 and R3, 1/32 X at R3, and 1/32 X plus NIS at R3. Peanut injury was not different 7 DA-R3 following dicamba at 1/32 X plus NIS at R3, 1/16 X plus NIS at R3, and 1/32 X at R3, 1/16 X at R1, and 1/32 X plus NIS at R1. Peanut injury 7 DA-R3 was not different following exposure to dicamba at 1/32 X at R3, 1/16 X at R1, 1/32 X plus NIS at R1, and 1/32 X at R1. At 7 DA-R3, dicamba treatments at R2 resulted in 27 to 32% visible injury. Greatest difference among treatments 7 DA-R3 was observed between 1/16 X at R3 and 1/16 X plus NIS at R1 when compared to dicamba at 1/16 X at R2, which resulted in 23, 23, and 32% visible peanut injury, respectively.

Peanut injury at 49 DA-R3 was significant ($p = 0.0272$) among treatments. Differences in peanut injury were not observed 49 DA-R3 following exposure to dicamba at 1/16 X plus NIS at R1, R2, and R3, 1/16 X at R1 and R3, and 1/32 X plus NIS at R3 (Table 2). Peanut injury 49 DA-R3 was not different following exposure to dicamba at 1/32 X plus NIS at R1 and R2, 1/32 X at R1, R2, and R3, and 1/16 X at R2 (Table 3). At 49 DA-R3, visible peanut injury was ≤11% across all treatments. The greatest difference in peanut injury 49 DA-R3 was dicamba at 1/32 X at R2 compared to 1/16 X plus NIS at R1, which resulted in 6 and 11% injury, respectively.

Table 3. Peanut lateral growth and canopy closure following exposure to dicamba 7 DA-R1 [1], 7 DA-R2, and 7 and 21 DA-R3 at Stoneville, MS in 2018 [2].

Dicamba Rate (g ae ha^{-1})	Timing	Width (cm)				Canopy Closure (% of nontreated) [3]
		7 DA-R1	7 DA-R2	7 DA-R3	21 DA-R3	35 DA-R3
0	N/A	55 a	74 a	85 a	91 a	-
35	R1	44 b	52 bc	67 fg	80 de	94 abc
	R2	-	57 b	68 efg	83 bcde	94 abc
	R3	-	-	76 bcd	83 bcd	94 abc
35 plus NIS [4]	R1	41 b	47 c	61 g	77 e	91 c
	R2	-	61 b	67 fg	81 cde	92 bc
	R3	-	-	75 bcdef	88 ab	94 abc
17.5	R1	41 b	58 b	75 bcde	86 abc	97 a
	R2	-	57 b	69 def	87 abc	96 ab
	R3	-	-	77 abc	86 abcd	95 ab
17.5 plus NIS	R1	41 b	54 bc	71 bcdef	84 bcd	94 abc
	R2	-	61 b	70 cdef	85 abcd	94 abc
	R3	-	-	79 ab	87 abc	95 ab

[1] DA = days after, [2] Data are pooled across a single experiment in 2017. Means followed by the same letter for each parameter are not different at $p \leq 0.05$. [3] Data for canopy closure are expressed as a percentage of nontreated control. [4] Non-ionic surfactant = NIS. R1 = beginning bloom, R2 = beginning peg, R3 = beginning pod.

3.6. Peanut Lateral Growth and Canopy Closure—2018

Peanut lateral growth was different at 7 DA-R1, 7 DA-R2, and 7 and 21 DA-R3. At 7 DA-R1, dicamba treatments were different ($p = 0.0019$) when compared to the nontreated control (Table 3). However, there were no differences in peanut lateral growth following among dicamba treatments. The nontreated control measured 55 cm, making it different from dicamba at 1/16 X plus NIS, 1/32 X, 1/32 X plus NIS, and 1/16 X which resulted in lateral growth of 41 cm, 41 cm, 41 cm, and 44 cm, respectively.

Peanut lateral growth 7 DA-R2 was significant ($p = 0.0009$). A difference in the nontreated control was observed from peanut exposed to dicamba. At 7 DA-R2, dicamba at 1/32 X with and without NIS at R1 and R2, 1/16 X at R1 and R2, and dicamba at 1/16 X plus NIS at R2 were not different from each other (Table 3). Dicamba at 1/16 X plus NIS at R1 was different from dicamba at 1/32 X at R1 and R2, 1/32 X plus NIS at R2, 1/16 X at R2, and 1/16 X plus NIS at R2. The greatest difference among dicamba treatments was dicamba at 1/16 X plus NIS at R1 compared to 1/32 X plus NIS at R2 and 1/16 X plus NIS at R2 which resulted in peanut lateral growth of 52 cm and 61 cm, respectively.

There was a significant difference in peanut lateral growth at 7 DA-R3 ($p = 0.0003$). The greatest difference among dicamba treatments was dicamba at 1/16 X plus NIS at R1 and 1/32 X plus NIS at R3, which resulted in peanut lateral growth of 61 cm and 79 cm, respectively (Table 3). Dicamba at 1/16 X with and without NIS at R1 and R2 produced similar peanut lateral growth ranging from 61 to 68 cm. Treatments with comparable peanut lateral growth 7 DA-R3 were dicamba at 1/16 X at R2, 1/32 X at R2, 1/32 X plus NIS at R2, 1/32 X plus NIS at R1, 1/16 X plus NIS at R3, and 1/32 X at R1, which resulted in lateral growth ranging from 68 cm to 75 cm. At 7 DA-R3, dicamba at 1/32 X at R3, 1/32 X plus NIS at R3, and the nontreated control were comparable in terms of peanut lateral growth, which resulted in 77 cm, 79 cm, and 84 cm, respectively.

Differences in peanut lateral growth following dicamba treatments were significant at 21 DA-R3 ($p = 0.0100$). Peanut lateral growth was similar among all dicamba treatments, except dicamba at 1/16 X with and without NIS at R1 and Dicamba at 1/16 X plus NIS at R2 (Table 3). At 21 DA-R3, peanut lateral growth in the nontreated control was 91 cm. All comparable dicamba treatments resulted in 83 cm to 88 cm peanut lateral growth. Greatest difference in peanut lateral growth among dicamba treatments was observed between dicamba at 1/16 X plus NIS at R1 and dicamba at 1/16 X plus NIS at R3, which resulted in 77 cm and 88 cm, respectively.

There was a difference among treatments for canopy closure 35 DA-R3 ($p = 0.0073$). Regardless of dicamba treatment, peanut did not reach 100% canopy coverage following exposure to dicamba (Table 3). All dicamba treatments resulted in comparable canopy coverage (94% to 97%), except dicamba at 1/16 X plus NIS at R2 and R1, which resulted in 92% and 91% canopy coverage, respectively. Greatest difference in peanut canopy coverage was observed following dicamba at 1/16 X plus NIS at R2 and dicamba at 1/32 X at R1, which resulted in 92% and 97% canopy coverage.

3.7. Summary of Results—2018

Based on a 2018 study, peanut injury 7 DA-R1 was greater following dicamba at 1/16 X plus NIS at R1 than 1/16 X at R1 and 1/32 X with and without NIS at R1 (Table 2). However, at 14 DA-R1, dicamba at 1/16 X and 1/32 X plus NIS at R1 resulted in greater peanut injury than dicamba at 1/16 X and 1/32 X at R1. At 7 DA-R2, peanut injury was greater following dicamba at 1/16 X and 1/32 X with and without NIS at R1 than dicamba at 1/16 X at R2 and 1/32 X with and without NIS at R2. At 7 DA-R3, dicamba at 1/16 X and 1/32 X with and without NIS at R2 resulted in greater peanut injury than dicamba at 1/16 X at R1, 1/16 X plus NIS at R3, 1/32 X at R1 and R3, and dicamba at 1/32 X plus NIS at R1. Peanut injury 49 DA-R3 ranged from 3% to 11% across all dicamba treatments.

Peanut lateral growth 7 DA-R1 was not different among dicamba treatments at R1 (Table 3). At 14 DA-R1, dicamba at 1/32 X at R1 resulted in the least reduction of peanut lateral growth, while dicamba at 1/16 X plus NIS at R1 resulted in the greatest reduction of lateral growth. At 7 DA-R2, greatest difference among dicamba treatments was observed between 1/16 X plus NIS at R1 and 1/16 X and 1/32 X plus NIS at R2 resulting in 47 and 61 cm, respectively. At 7 DA-R3, 1/16 X plus NIS at R1 resulted in the least peanut lateral growth at 61 cm as compared to 1/32 X plus NIS at R3, which resulted in the greatest lateral growth at 79 cm. At 21 DA-R3, dicamba at 1/16 X plus NIS at R3 reduced peanut lateral growth the most, resulting in 77 cm as compared to dicamba at 1/16 X plus NIS at R3, which reduced lateral growth the least at 88 cm. At 35 DA-R3, peanut canopy closure across all dicamba treatments resulted in 90 to 97% closure. Greatest difference among treatments were dicamba at 1/16 X plus NIS at R1 and 1/32 X at R1, which resulted in 91% and 97% closure, respectively.

Yield was not different ($p = 0.0532$) among treatments in 2018. Adverse weather conditions prolonged harvest, which influenced peanut yield variability.

3.8. Discussion of 2017 and 2018 Results

As per this two-year study, peanut is very sensitive following exposure to dicamba. In most instances, peanut injury was greater following higher rates of dicamba than lower rates of dicamba, which compliments the results from previous research [31]. However, peanut injury was not directly related to yield in this study. Therefore, peanut injury should not be used to estimate yield loss potential. Peanut canopy never reached 100% closure following exposure to dicamba, regardless of rate, addition of adjuvant, or growth stage. Open canopy may lead to new flushes of weeds based on weed soil seedbank and environmental conditions [33]. New flushes of weeds may create harvest difficulty and further reduce peanut yield [34,35].

Peanut yield was not different among treatments, except for dicamba at 1/16 X plus NIS at R3. Previous research has reported peanut yield losses following dicamba at 1/14 X ranged from 2% to 29% [30]. In 2017, our study reported peanut yield loss of 10% and 24% following exposure to dicamba at 1/32 X with and without NIS and 1/16 X with and without NIS, respectively. Therefore, this two-year study falls within peanut yield loss range of previously conducted research [30].

The addition of NIS did not influence peanut yield or injury in most instances. However, in 2018, peanut injury at 14 DA-R1 was the only evaluation where the addition of NIS to dicamba at 1/16 X and 1/32 X was different from treatments without NIS in this two-year study. Peanut yield was not different among treatments when NIS was included, except in one instance. Dicamba at 1/16 X plus NIS at R3 resulted in the greatest yield loss and was the only treatment different from the nontreated control. Therefore, our research suggests that the addition of NIS with dicamba may not influence peanut injury, lateral growth, canopy closure, or yield as compared to dicamba alone.

4. Conclusions

Based on results from this two-year study, if peanut is exposed to dicamba, auxin symptoms will be visible in the form of epinastic twisting of stems and leaf cupping. A reduction in peanut lateral growth will occur following exposure to dicamba. Wider rows, such as 101.6 cm spacing used in this study, may reduce the ability of peanut to achieve canopy closure following exposure to dicamba. Yield loss may occur if peanut is exposed to dicamba at reproductive growth stages. Peanut may have greater yield loss potential at R3 than R1 or R2 growth stages. Peanut injury was not different from applications made with dicamba alone when compared with dicamba plus NIS in most instances. Therefore, producers and applicators should be mindful of peanut sensitivity to dicamba if applications are made in proximity to peanut [15,21,30,31]. Applicators that use the same spray equipment for different crops must reduce the possibility for peanut exposure to dicamba by properly cleaning out equipment [1,26]. Further research should be conducted to evaluate peanut response to dicamba at rates <17.5 g ae ha^{-1} with and without NIS at reproductive growth stages.

Author Contributions: Conceptualization, T.B.; methodology, T.B.; validation, T.B.; investigation, J.W.S. and T.B.; data curation, J.W.S. and T.B.; formal analysis, J.W.S., J.A.B., B.R.G., and J.G.; writing—original draft preparation, J.W.S.; writing—review and editing, J.W.S., J.A.B., T.B., J.G., B.R.G.; supervision, T.B. All authors have read and agreed to the published version of the manuscript.

Funding: This publication is a contribution of the Delta Research and Extension Center and Mississippi Agricultural and Forestry Experiment Station. This material is based upon work that is supported by the Mississippi Peanut Promotion Board and the National Institute of Food and Agriculture, U.S. Department of Agriculture, Hatch project under accession number 230080.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Steckel, L.; Craig, C. *Cleaning Plant Growth Regulator (PGR) Herbicides Out of Field Sprayers*; University of Tennessee Agricultural Extension Service: Boston, MA, USA, 2005.
2. Behrens, R.; Lueschen, W.E. Dicamba volatility. *Weed Sci.* **1979**, *27*, 486–493. [CrossRef]
3. Rathmann, D. Management of New Technologies Discussion Outline. Available online: http://docplayer.net/91635731-Management-of-new-technologies-duane-rathmann-basf-technical-service-waseca-mn.html (accessed on 22 April 2018).
4. Egan, J.F.; Mortensen, D.A. Quantifying vapor drift of dicamba herbicides applied to soybean. *Environ. Toxicol. Chem.* **2012**. [CrossRef]
5. Osipitan, O.A.; Scott, J.E.; Knezevic, S.Z. Glyphosate-resistant soybean response to micro-rates of three dicamba-based herbicides. *Agrosyst. Geosci. Environ.* **2019**. [CrossRef]
6. Schmitz, G. Best Management Practices for Dicamba Use in Illinois. Available online: http://ifca.com/files/IFCA_2017-Schmitz_Herbicide_BMPs.pdf (accessed on 16 April 2018).
7. McCown, S.; Barber, T.; Norsworthy, J.K. Response of non-dicamba-resistant soybean to dicamba as influenced by growth stage and herbicide rate. *Weed Technol.* **2018**. [CrossRef]
8. Egan, J.F.; Barlow, K.M.; Mortensen, D.A. A Meta-analysis on the effects of 2,4-D and dicamba drift on soybean and cotton. *Weed Sci.* **2014**, *62*, 193–206. [CrossRef]
9. Registration of Dicamba for Use on Genetically Engineered Crops. Available online: https://19january2017snapshot.epa.gov/ingredients-used-pesticide-products/registration-dicamba-use-genetically-engineered-crops_.html (accessed on 5 March 2019).
10. Weed Control in Dicamba-Resistant Soybeans. Available online: https://dl.sciencesocieties.org/publications/cm/pdfs/9/1/2010-0920-01-RS (accessed on 28 February 2019).
11. Kniss, A.R. Soybean response to dicamba: A meta-analysis. *Weed Technol.* **2018**, *32*, 507–512. [CrossRef]
12. Seifert-Higgins, S.; Arnevik, C.L. Development of weed management recommendations for dicamba tolerant soybeans. *Weed Sci.* **2012**, *65*, 266.

13. A Final Report on Dicamba-Injured Soybean Acres. Available online: https://ipm.missouri.edu/IPCM/2017/10/final_report_dicamba_injured_soybean/ (accessed on 2 March 2019).
14. Griffin, J.L.; Bauerle, M.J.; Stephenson, D.O.; Miller, D.K.; Boudreaux, J.M. Soybean response to dicamba applied at vegetative and reproductive growth stages. *Weed Technol.* **2013**, *27*, 696–703. [CrossRef]
15. Leon, R.G.; Ferrell, J.A.; Brecke, B.J. Impact of exposure to 2,4-D and dicamba on peanut injury and yield. *Weed Sci.* **2014**, *28*, 465–470. [CrossRef]
16. Wax, L.; Knuth, L.; Slife, F. Response of soybeans to 2,4-D, dicamba, and picloram. *Weed Sci.* **1969**, *17*, 388–393. [CrossRef]
17. Henry, W.B.; Shaw, D.R.; Reddy, K.R.; Bruce, K.M.; Tamhankar, H.D. Remote sensing to detect herbicide drift of crops. *Weed Technol.* **2004**, *18*, 358–368. [CrossRef]
18. Jones, G.T.; Norsworthy, J.K.; Barber, T. Off-target movement of diglycolamine dicamba to non-dicamba soybean using practices to minimize primary drift. *Weed Technol.* **2019**, *33*, 24–40. [CrossRef]
19. Solomon, C.B.; Bradley, K.W. Influence of application timings and sublethal rates of synthetic auxin herbicides on soybean. *Weed Technol.* **2014**, *28*, 454–464. [CrossRef]
20. Al-Khatib, K.; Claassen, M.M.; Stahlman, P.W.; Geier, P.W.; Regehr, D.L.; Duncan, S.R.; Heer, W.F. Grain sorghum response to simulated drift from glufosinate, glyphosate, imazethapyr, and sethoxydim. *Weed Sci.* **2003**, *17*, 261–265.
21. Strachan, S.; Ferry, N.; Cooper, T. Vapor movement of aminocyclopyrachlor, aminopyralid, and dicamba in the field. *Weed Technol.* **2013**, *27*, 143–155. [CrossRef]
22. Boerboom, C. Field Case Studies of Dicamba Movement to Soybeans. Available online: https://extension.soils.wisc.edu/wcmc/field-case-studies-of-dicamba-movement-to-soybeans/ (accessed on 28 February 2019).
23. Cleaning Field Sprayers to Avoid Crop Injury. Available online: http://extension.missouri.edu/explorepdf/agguides/crops/g04852.pdf (accessed on 28 February 2019).
24. Thompson, M.A.; Steckel, L.E.; Ellis, A.T.; Mueller, T.C. Soybean tolerance to early preplant applications of 2,4-D ester, 2,4-D amine, and dicamba. *Weed Technol.* **2007**, *21*, 882–885. [CrossRef]
25. Proper Spray Tank Cleanout. Available online: http://www.croplife.com/equipment/sprayers/proper-spray-tank-cleanout/ (accessed on 28 February 2019).
26. Cleaning Spray Tanks In and Out. Available online: http://www.ipmnet.org/Tim/Pesticide_Ed/Pesticide_Courses_-_2009/Cent_OR/Peachy.pdf (accessed on 28 February 2019).
27. Weidenhamer, J., Jr.; Triplett, G.; Sobotka, F. Dicamba injury to soybean. *Agron. J.* **1988**, *81*, 637–643. [CrossRef]
28. Kelley, K.B.; Wax, L.M.; Hager, A.G.; Riechers, D.E. Soybean response to plant growth regulator herbicides is affected by other postemergence herbicides. *Weed Sci.* **2005**, *53*, 101–112. [CrossRef]
29. Pandey, R.K.; Herrera, W.A.T.; Villegas, A.N.; Pendleton, J.W. Drought response of grain legumes under irrigation gradient: III. Plant growth. *Agron. J.* **1984**, *76*, 557–569. [CrossRef]
30. Prostko, E.; Grey, T.; Marshall, M.; Ferrell, J.; Dotray, P.; Jordan, D.; Grichar, W.; Brecke, B.; Davis, J. Peanut yield response to dicamba. *Peanut Sci.* **2011**, *38*, 61–65. [CrossRef]
31. Blanchett, B.H.; Grey, T.L.; Prostko, E.P.; Webster, T.M. The effect of dicamba on peanut when applied during vegetative growth stages. *Peanut Sci.* **2015**, *42*, 109–120. [CrossRef]
32. McCown, M.; Barber, L.; Norsworthy, J. Soybean response to low rates of dicamba applied at vegetative and reproductive growth stages. *Ark. AES RES SER* **2017**, *637*, 137–140.
33. Smith, C.W.; Betran, J.; Runge, E. *Corn: Origin, History, Technology, and Production*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2004; pp. 719–721.
34. Hill, L.V.; Santelmann, P.W. Competitive effects of annual weeds on Spanish peanuts. *Weed Sci.* **1969**, *17*, 1–2. [CrossRef]
35. Zimdahl, R.L. *Weed-Crop Competition: A Review*; International Plant Protection Center: Corvallis, OR, USA, 1980; 195p.