Weed Technology

www.cambridge.org/wet

Research Article

Cite this article: Meyeres T, Lancaster S, Kumar V, Roozeboom K, Peterson D (2021) Response of non-dicamba-resistant soybean (*Glycine max*) varieties to dicamba. Weed Technol. **35**: 718–724. doi: 10.1017/wet.2021.4

Received: 25 August 2020
Revised: 16 December 2020
Accepted: 8 January 2021
First published online: 22 January 2021

Associate Editor:
Aaron Hager, University of Illinois

Nomenclature:
dicamba; soybean, *Glycine max* L. Merr.

Keywords:
Off-target movement; injury; soybean varieties; yield components; offspring

Author for correspondence:
Tyler Meyeres, Graduate Research Assistant, Kansas State University, Throckmorton Plant Sciences Center, 1712 Claflin Road, Manhattan, KS 66506 Email: tpmeyeres@ksu.edu

Response of non-dicamba-resistant soybean (*Glycine max*) varieties to dicamba

Tyler Meyeres[1], Sarah Lancaster[2], Vipan Kumar[3], Kraig Roozeboom[4] and Dallas Peterson[5]

[1]Graduate Research Assistant, Department of Agronomy, Kansas State University, Manhattan, KS; [2]Assistant Professor, Department of Agronomy, Kansas State University, Manhattan, KS, USA; [3]Assistant Professor, Department of Agronomy, Kansas State University, Agricultural Research Center, Hays, KS, USA; [4]Professor, Department of Agronomy, Kansas State University, Manhattan, KS, USA and [5]Professor Emeritus, Department of Agronomy, Kansas State University, Manhattan, KS, USA

Abstract

Introduction and rapid adoption of dicamba-resistant (DR) soybean led to an increase of post-emergent applications of dicamba. This resulted in a widespread increase in nontarget dicamba injury to non-DR soybean in 2017. Field studies were conducted in Manhattan, KS, in 2018 and 2019 and in Ottawa, KS, in 2019 to investigate the injury and yield response of soybean varieties with varying herbicide-resistance traits and maturity groups when exposed to dicamba. Four varieties were tested: 'Credenz 3841LL' (glufosinate resistant), 'Credenz 4748LL' (glufosinate resistant), 'Asgrow AG4135RR2Y' (glyphosate resistant), and 'Stine 40BA02' (glyphosate and isoxaflutole resistant), abbreviated as CR3841, CR4748, AG4135, and ST40B, respectively. Soybeans were treated with 5.6 g ae ha^{-1} of dicamba at V3 and R1 stages. Percent soybean injury, soybean height, soybean yield and yield components, and injury to offspring were evaluated. Four weeks after treatment (WAT) at V3, the greatest injury was observed in AG4135 and ST40B. Dicamba application at R1 resulted in the greatest injury to ST40B both 4 WAT and at senescence. Minimal injury was observed in all varieties treated at V3 at senescence and yield loss was 5% or less. Dicamba application at R1 resulted in 19 to 34% yield loss, with the least yield loss in CR4748, and the greatest in ST40B. Varieties with greater injury at senescence generally yielded less than other varieties.

Introduction

Dicamba is a synthetic auxin herbicide that has been extensively used to control broadleaf weeds in corn, small grains, and pasture crops since the 1960s (Al-Khatib and Peterson 1999). Widespread use of dicamba often resulted in off-target movement and injury to susceptible plants, including soybean and cotton (Auch and Arnold 1978; Wax et al. 1969). Introduction of dicamba-resistant (DR) soybean and cotton technology in 2017 increased the application of dicamba in the vicinity of actively growing, susceptible soybean. Various injury symptoms, including epinasty of petioles and shoots, leaf malformation, terminal bud chlorosis, malformed pods, and delayed maturity are associated with off-target dicamba movement to non-DR soybean (Solomon and Bradley 2014; Wax et al. 1969). Less injury is often observed in soybean exposed to dicamba during vegetative stages compared with early reproductive stages (Auch and Arnold 1978; Wax et al. 1969). In addition, soybean during vegetative stages exposed to dicamba doses high enough to cause 30% injury were not likely to cause yield reductions greater than 5%; however, exposure during reproductive stages to doses high enough to cause 12% injury were likely to cause greater than 5% yield loss (Kniss 2018).

Soybean injury and yield loss are influenced by the dicamba dose and exposure timing, but there is also speculation that soybean cultivars may respond differently to dicamba exposure (Auch and Arnold 1978). However, minimal peer reviewed literature exists comparing varieties. Auch and Arnold (1978) observed no differences in yield among non-DR soybean varieties exposed to various rates of dicamba. Most available literature has explored the differences among indeterminate and determinate soybean (McCown et al. 2018; Wax et al. 1969; Weidenhamer et al. 1989). It is understood that whether a soybean is indeterminate or determinate may affect the way the plant respond to dicamba at different times (Wax et al. 1969). Weidenhamer et al. (1989) reported more severe yield loss for indeterminate varieties at more mature growth stages compared to determinate varieties, but McCown et al. (2018) reported that indeterminate and determinate varieties responded similarly.

Quantifying soybean yield components provides greater understanding of the impacts of dicamba exposure on soybean yield (Robinson et al. 2013). McCown et al. (2018) and Solomon and Bradley (2014) observed greater reductions in pods per plant following dicamba application during early reproductive stages compared to vegetative stages. Similarly, Solomon and Bradley (2014) reported dicamba exposure at R2 reduced seeds per pod and nodes per square meter more than exposure at vegetative stages.

The effects of off-target dicamba movement on soybean offspring are not well understood; however, understanding the impacts is crucial for soybean seed production (Jones et al. 2018). Off-target dicamba movement has been shown to reduce germination, emergence, and vigor, and injure offspring of soybean treated with dicamba during reproductive stages (Auch and Arnold 1978; Jones et al. 2018; Thompson and Egli 1973; Wax et al. 1969. In addition, offspring that emerge may have reduced vigor or foliar injury symptoms following dicamba application to the parent plant during reproductive growth (Jones et al. 2018, 2019). Few peer-reviewed articles have described the relative responses of different soybean varieties. Therefore, the main objective of this research was to determine the response of non-DR soybean varieties with various herbicide-resistant traits when exposed to a reduced rate of dicamba at V3 and R1.

Materials and Methods

Field Experiments

Field studies were conducted at the Kansas State University Ashland Bottoms Research Farm in Manhattan, Kansas (39.12N, 96.63W) in 2018 (MHK18) and 2019 (MHK19) and in 2019 at the Kansas State University East Central Experiment Field in Ottawa, Kansas (OTT19; 38.54N, 95.25W). Seed beds were prepared using a field cultivator on the day of planting at MHK18 and MHK19, and before the early preplant herbicide application at OTT19. Soil series at MHK18, MHK19, and OTT19 are as follows: Wymore silty clay loam, Reading silt loam, and Woodson silt loam. Information regarding planting dates, in-season precipitation, and PRE herbicide treatments for early-season weed control for each site-year is summarized in Table 1. Plots were hand-weeded as needed to keep weed free throughout the growing season across all site-years.

The same soybean varieties were planted across all site-years. Soybean varieties included Asgrow AG4135RR2Y® (glyphosate-resistant), Credenz 3841LL® (glufosinate-resistant), Credenz 4748LL® (glufosinate-resistant), and Stine 40BA02® (glyphosate and isoxaflutole-resistant). Details regarding maturity group, herbicide traits, and company are presented in Table 2. Soybean were planted at approximately 308,880 seeds ha^{-1}, 3.8 cm deep, and in 76.2-cm rows using a 4-row row crop planter across all site-years.

The *N,N*-Bis-(3-aminopropyl) methylamine (BAPMA) salt of dicamba (Engenia®, BASF Corp., Research Triangle Park, NC) was applied to all varieties at V3 or R1 (Fehr and Caviness 1977). Dates of dicamba application and environmental conditions during application for each site-year are presented in Table 3. Dicamba was applied at 5.6 g ae ha^{-1} (1/100th the field-use rate). A split-plot design with four replications was used. Soybean variety was the main plot, and the application timing was randomly assigned to subplots. Each main plot included a nontreated check. Individual plots were 3 m by 9 m in size.

Spray solution was applied directly to plots with 140 L ha^{-1} spray volume using a CO_2 powered backpack sprayer and a 4-tip, 1.9-m hand-held boom equipped with TTI110015 nozzles (TeeJet Technologies, 1801 Business Park Dr, Springfield, IL 62703) at 220 kPa. The center two rows of each plot received the full rate, whereas the two outer rows acted as a buffer between treatments. Evaluations were conducted from 2 wk after treatment (WAT) through progeny seed analysis.

Soybean injury was visually assessed 2 and 4 WAT and at the onset of senescence (R7). Soybean plants were evaluated on a 0% to 100% crop injury scale with 0% indicating no injury and 100% indicating plant death. Symptomology at lower injury levels included leaf cupping, leaf crinkling, and chlorosis of terminal buds. Symptomology at greater injury levels included the aforementioned symptomology and necrosis of terminal buds, pod malformation, and stunting (Behrens and Lueschen 1979; Sciumbato et al. 2004; Wax et al. 1969). To further evaluate soybean response to dicamba, the heights of five randomly selected plants from the center two rows of each plot were recorded at the onset of senescence. Soybean yield component data were collected at harvest from 1 m row^{-1} from one of the two center rows of each plot. Yield components measured included seed weight, pods per plant, seeds per pod, and main stem nodes per plant. Soybeans were harvested for grain yield from the center two rows of each plot with a small plot combine and grain moisture was adjusted to 13%.

Soybean Offspring Fitness

To test seed germination, 50-g soybean seed samples were taken from samples harvested by the small-plot combine and sent to the Seed Laboratory at the Kansas Crop Improvement for analysis. One-hundred soybean seeds were counted and placed on Kimpack (Anchor Paper Co., St. Paul, MN), which was placed on a food tray and moistened with 500 ml of tap water. Soybean seeds were then covered with 0.6 to 1.3 cm of mason sand. Trays were placed in a germination chamber at 30 C for 8 h and 20 C for 16 h with lights on during the warm cycle. After 8 d of incubation, seedlings were evaluated to determine normal, abnormal, dead, or hard seed (AOSA 2019).

To quantify response of offspring, 10 seeds from each plot sample were planted into 14-cm pots containing Miracle-Gro Moisture Control® potting mix (The Scotts Company LLC, Marysville, OH) and grown in the Kansas State University Weed Science greenhouse until V3. Pots were arranged by plot within site-year. The daytime temperature was 30 C and the nighttime temperature was 22 C. The 15-h photoperiod was supplemented with a metal-halide lighting system. Soybean were subirrigated with municipal water as need to maintain adequate moisture levels. The number of injured offspring and percent soybean injury of emerged offspring were recorded on a 0% to 100% crop injury scale with 0% indicating no injury and 100% indicating plant death when soybean reached V3. No injury was observed in soybean offspring.

Statistical Analyses

Soybean height, yield components, and yield were converted to a relative percent of the nontreated check before statistical analysis to account for differences that may naturally exist among varieties. The relative percent of the nontreated check was calculated by subtracting the plot value from the nontreated check value for the corresponding replication and dividing the difference by the nontreated check value. Raw data were visually assessed for normality and did not violate ANOVA assumptions. Soybean injury ratings, relative soybean height, relative soybean yield components, relative soybean yield, germination, offspring emergence, offspring height, number offspring injured, and soybean injury of offspring were subjected to ANOVA using the GLIMMIX procedure in SAS (SAS v.9.4, SAS Institute Inc., Cary, NC). Replication was considered a random effect and site-year, dicamba application timing, and soybean variety were considered fixed effects. Means were

Table 1. Planting date, total in season rainfall, and maintenance herbicide application timing, date, product, and rate used prior to crop emergence in experiments evaluating dicamba drift injury in Manhattan, KS in 2018 and 2019, and in Ottawa, KS in 2019.[a]

Site-year	Planting date	Total in-season precipitation, mm[b]	Application timing	Application date	Product	Rate
MHK18	5/22/2018	584	PRE	5/22/2018	Sulfentrazone + *S*-metolachlor[c]	59 + 529 g ai ha^{-1}
MHK19	6/2/2019	541	PRE	6/2/2019	Sulfentrazone + *S*-metolachlor[c]	59 + 529 g ai ha^{-1}
OTT19	6/13/2019	833	EPP; PRE	5/16/2019, 6/13/2019	Sulfentrazone + chlorimuron[d] & *S*-metolachlor[e]; *S*-metolachlor[e]	304 + 20 g ai ha^{-1} & 1,649 g ai ha^{-1}; 1,099 g ai ha^{-1}

[a]Abbreviations: EPP, early preplant; MHK18, Manhattan, KS in 2018; MHK19, Manhattan, KS in 2019; OTT19, Ottawa, KS in 2019; PRE, pre-emergent.
[b]Sourced from Kansas State University (2019).
[c]Authority Elite (FMC Corporation, Philadelphia, PA) at 0.7 L ha^{-1}.
[d]Authority Maxx (FMC Corporation, Philadelphia, PA) at 0.49 kg ae ha^{-1}.
[e]Cinch (Corteva Agriscience, Wilmington, DE) at 1.8 and 1.2 L ha^{-1}.

Table 2. Soybean varieties planted in Manhattan, KS in 2018 and 2019, and in Ottawa, KS in 2019 with corresponding herbicide traits, maturity groups, abbreviations, and companies.

Variety	Herbicide traits	Maturity group	Abbreviation	Company
Asgrow AG4135RR2Y	Glyphosate resistant	4.1	AG4135	Bayer Crop Science[a]
Credenz 3841LL	Glufosinate resistant	3.8	C3841	BASF Agriculture[b]
Credenz 4748LL	Glufosinate resisant	4.7	C4748	BASF Agriculture[b]
Stine 40BA02	Glyphosate and isoxaflutole resistant	4.0	ST40B	Stine Seed Company[c]

[a]Bayer Crop Science, St. Louis, Missouri.
[b]BASF Agriculture, Florham Park, New Jersey.
[c]Stine Seed Company, Adel, Iowa.

Table 3. Application date and meteorological conditions during all application timings in experiments evaluating dicamba injury in 2018 and 2019.

Site-year[a]	Date of application	Air Temperature (start, stop)	Soil temperature	Relative humidity (start, stop)	Wind speed, direction (start; stop)
		V3			
		——— C ———		%	kph
MHK18	6/12/2018	30	34	63	6, N
MHK19	6/26/2019	21, 21	22	78, 76	6, NNW; 8 NW
OTT19	7/3/2019	21, 22	25	86, 77	8, S; 10, S
		R1			
		——— C ———		%	kph
MHK18	7/2/2018	24	31	70	5, E
MHK19	7/16/2019	22, 27	26	88, 80	2, W; 5, W
OTT19	7/23/2019	15,18	22	89	5, N; 6, N

[a]Abbreviations: MHK18, Manhattan, KS in 2018; MHK19, Manhattan, KS in 2019; OTT19, Ottawa, KS in 2019.

separated using Fisher's protected LSD ($\alpha = 0.05$). Soybean injury ratings, soybean height, soybean yield components, soybean yield, germination, offspring emergence, offspring height, number of offspring injured, and soybean injury of offspring were subjected to the CORR procedure in SAS. Pearson coefficients were considered weak if less than 0.3, moderate if greater than 0.3 but less than 0.5, and strong if greater than 0.5 (Mukaka 2012). Yield and height data were subjected to the REG procedure in SAS using a linear model, which was selected as the best fit based on R^2 and P-values.

Results and Discussion

Soybean Injury

Soybean injury 2 WAT had a significant interaction among site-year, application timing, and variety (Table 4). At MHK18, injury was greater in soybean treated at V3 rather than at R1, regardless of variety. (Table 5). At MHK19, soybean similar injury was similar regardless of timing or variety, except for ST40B treated at R1, which resulted in 40% injury (Table 5). Soybean treated at R1 had greater injury than soybean treated at V3 regardless of the variety at OTT19 (Table 5). At 4 WAT, there was also a significant interaction among site-years, application timing, and variety for soybean injury (Table 4). Soybean injury was greater for soybean treated at R1 than V3 at all locations (Table 5). Reduced injury observed in CR4748 could be attributed to the longer maturity group. Greater injury observed in ST40B may be linked to the presence of two herbicide-resistant events; however, no research has investigated this hypothesis.

Soybean injury 2 WAT at all site-years was similar to injury previously reported for similar dicamba application rates and timings (Andersen et al. 2004; McCown et al. 2018; Solomon and Bradley 2014). In general, soybean treated at R1 had greater injury 4 WAT than those treated at V3. Soybean injury observed following dicamba application at V3 was similar to what Osipitan et al. (2019) observed at lower doses of dicamba, but was greater than

https://doi.org/10.1017/wet.2021.4 Published online by Cambridge University Press

Table 4. Analysis of variance of fixed effects and all interactions for soybean injury as a response of different soybean varieties exposed to a reduced rate[a] of dicamba at varying application timings at Manhattan, KS in 2018 and 2019, and in Ottawa, KS in 2019.

Fixed effects	2WAT[b]	4WAT[b]	At senescence
		P-value	
Site-year	<.0001	<.0001	<.0001
Variety	0.0401	<.0001	<.0001
Timing	<.0001	<.0001	0.0687
Site-year by variety	<.0001	<.0001	<.0001
Site-year by timing	<.0001	<.0001	0.1127
Timing by variety	<.0001	<.0001	0.0090
Site-year by variety by timing	0.0428	0.0001	0.2787

[a]Rate = 5.6 g ae ha^{-1} dicamba.
[b]Abbreviation: WAT, weeks after treatment.

Table 5. Soybean injury at 2WAT and 4WAT as a result of varying soybean varieties exposed to dicamba[a] at varying application timings at Manhattan, KS in 2018 and 2019 and in Ottawa, KS in 2019.[b,c]

Site-years	Timing	Variety	2WAT	4WAT
			%	
MHK18	V3	AG4135	24 ab	33 c
		CR3841	23 ab	31 c
		CR4748	25 a	26 c
		ST40B	26 a	32 c
	R1	AG4135	18 c	53.8 b
		CR3841	16 c	50 b
		CR4748	18 c	55 b
		ST40B	20 bc	64 a
MHK19	V3	AG4135	28 b	35 c
		CR3841	27 b	33 c
		CR4748	27.8 b	34 c
		ST40B	27.6 b	37 c
	R1	AG4135	32.3 b	59 ab
		CR3841	32.5 b	55 b
		CR4748	31.3 b	59 ab
		ST40B	40 a	63 a
OTT19	V3	AG4135	30 b	39 c
		CR3841	26 b	34 d
		CR4748	28 b	34 d
		ST40B	28 b	37 cd
	R1	AG4135	45 a	66 ab
		CR3841	44 a	65 b
		CR4748	47 a	65 b
		ST40B	43 a	69 a

[a]5.6 g ae ha^{-1} dicamba.
[b]Abbreviations: AG4135, Asgrow AG4135; CR3841, Credenz 3841LL; CR4748, Credenz 4748LL; MHK18, Manhattan, KS in 2018; MHK19, Manhattan, KS in 2019; OTT19, Ottawa, KS in 2019; ST40B, Stine 40BA02; WAT, weeks after treatment.
[c]Means separated within site-year and means followed by the same letter within a column are not statistically different according to Fisher's protected LSD (α = 0.05).

injury observed by McCown et al. (2018) when soybeans were treated at V4 with 2.2 and 8.8 g ae ha^{-1} dicamba. Similarly, injury following dicamba application at R1 was greater than injury observed by McCown et al. (2018) and Jones et al. (2018) when soybeans were treated at R1 with 2.2 and 8.8 g ae ha^{-1} dicamba. Injury observed in this trial was similar to injury observed by Soltani et al. (2016) when soybeans were treated at R1 with 30 g ae ha^{-1} dicamba.

Soybean injury at the onset of senescence had significant interactions for site-year by variety and timing by variety (Table 4). When pooled over application timings, soybean injury ranged from 26% to 42% across all site-years (Table 6). At MHK18 and OTT19, CR4748 had the least injury at senescence, whereas

Table 6. Soybean injury at the onset of senescence of varying soybean varieties exposed to dicamba[a] at varying application times at Manhattan, KS in 2018 and 2019, and in Ottawa, KS in 2019.[b,c]

	Site-year[d]			Application timing	
Variety	MHK18	MHK19	OTT19	V3	R1
			%		
AG4135	36 a	33 a	36 b	5 a	64 b
CR3841	38 a	30 ab	34 c	6 a	62 b
CR4748	28 b	26 b	28 d	5 a	50 c
ST40B	42 a	34 a	38 a	7 a	69 a

[a]5.6 g ae ha^{-1} dicamba.
[b]Abbreviations: AG4135, Asgrow AG4135; CR3841, Credenz 3841LL; CR4748, Credenz 4748LL; MHK18, Manhattan, KS in 2018; MHK19, Manhattan, KS in 2019; OTT19, Ottawa, KS in 2019; ST40B, Stine 40BA02.
[c]Means followed by the same letter within a column are not statistically different according to Fisher's protected LSD (α = 0.05).
[d]Means within site year pooled across application timings and means within application timing pooled across locations.

ST40B was among the varieties with the greatest injury at all locations. When pooled over site-years, soybean injury was similar across all varieties as a result of dicamba application at V3 and injury was 7% or less. However, dicamba application at R1 was associated with soybean injury ranging from 50% in CR4748 to 69% in ST40B (Table 6).

Limited injury at senescence following dicamba application at V3 is consistent with reports by Al-Khatib and Peterson (1999), Osipitan et al. (2019), and Soltani et al. (2016) who observed end-of-the-season recovery in soybean treated at V3 with low rates of dicamba. The varieties in this study responded differently to dicamba at R1, with injury similar to that reported by France et al. (2019) after soybeans were treated with similar dicamba rates at R1.

Height

There was a significant effect of dicamba application timing on soybean height across varieties (Table 7). Dicamba application at V3 resulted in 5% height reduction, whereas application at R1 resulted in 36% height reduction when pooled over site-years and varieties (data not shown). Height reductions were similar to those previously reported in the literature as a result of application at both V3 (Foster and Griffin 2018) and R1 (Kelley et al. 2005).

Yield Components and Yield

There were significant interactions between site-year and variety, site-year and application timing, and application timing and variety for relative main stem nodes per plant (Table 7). Main stem nodes per plant ranged from 59% to 98% of that of the nontreated checks when pooled across varieties (Table 8). Dicamba application at R1 resulted in a greater reduction of main stem nodes per plant than application at V3 at OTT19, but the main stem nodes per plant were similar for both application timings at MHK18 and MHK19. When pooled across site-years, main stem nodes per plant ranged from 57% to 98% of that of the nontreated checks. Dicamba applications at V3 had less impact on main stem nodes per plant compared to applications at R1 for all varieties except CR3841. Reductions in main stem nodes per plant were similar for all varieties when pooled across site-years (data not shown). These observations are in agreement with those of Robinson et al. (2013) who observed 5% to 20% reduction of

Table 7. Analysis of significance of fixed effects and all interactions for soybean trait response to a reduced rate[a] of dicamba at multiple timings.

Fixed effects	Height reduction	Nodes per plant reduction	Seeds pod per reduction	Pods per plant reduction	Seed weight reduction	Relative yield
	P-value					
Site-year	0.1948	0.2641	0.4454	0.5494	0.5939	0.42
Variety	0.4513	0.1118	0.4775	0.1368	0.3525	0.4504
Timing	<0.0001	<0.0001	0.0003	0.1637	0.3257	<0.0001
Site-year by variety	0.1061	0.0457	0.0353	0.1613	0.0602	0.0031
Site-year by timing	0.0652	0.0003	0.2695	0.9214	0.9063	0.5026
Timing by variety	0.2491	0.0064	0.5048	0.5237	0.9202	0.0349
Site-year by variety by timing	0.9204	0.7964	0.8961	0.3289	0.9918	0.9914

[a]5.6 g ae ha^{-1} dicamba.

Table 8. Soybean main stem nodes per plant relative to the plants in the nontreated control as a result of varying soybean varieties exposed to dicamba[a] at multiple application timings at Manhattan, KS in 2018 and 2019, and in Ottawa, KS in 2019.[b,c]

	Site-year			Variety			
Timing of application	MHK18	MHK19	OTT19	AG4135	CR3841	CR4748	ST40B
	%						
V3	98 a	72 ab	95 a	98 ab	78 bcd	87 abc	89 ab
R1	64 ab	63 ab	59 b	67 de	68 cde	53 e	57 e

[a]5.6 g ae ha^{-1} dicamba.
[b]Abbreviations: AG4135, Asgrow AG4135; CR3841, Credenz 3841LL; CR4748, Credenz 4748LL; MHK18, Manhattan, KS in 2018; MHK19, Manhattan, KS in 2019; OTT19, Ottawa, KS in 2019; ST40B, Stine 40BA02.
[c]Means separated within site-year and means followed by the same letter within a column are not statistically different according to Fisher's protected LSD ($\alpha = 0.05$).

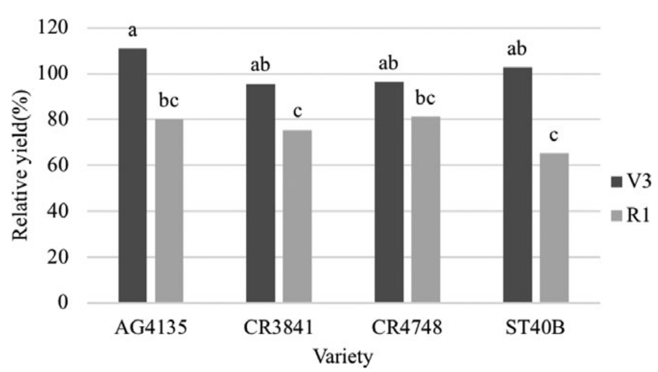

Figure 1. Soybean yield relative to nontreated plots for each variety following dicamba application at V3 and R1 at Manhattan, KS in 2018 and 2019, and at Ottawa, KS in 2019.Means followed by the same letter are not statistically different according to Fisher's protected LSD ($\alpha = 0.05$). AG4135, Asgrow AG4135, nontreated plot yield = 3,837 kg ha^{-1}; CR3841, Credenz 3841LL, nontreated plot yield = 3,769 kg ha^{-1}; CR4748, Credenz 4748LL, nontreated plot yield = 3,904 kg ha^{-1}; ST40B, Stine 40BA02, nontreated plot yield = 3,635 kg ha^{-1}.

reproductive nodes per square meter when soybeans were treated at V3, V5, and R2 with dicamba rates ranging from 0.073 to 2.72 g ae ha^{-1}. There were no significant differences observed among relative seed weight, pods per plant, and relative seeds per pod (data not shown).

There were significant interactions between site-year and variety and application timing and variety for relative yield (Table 7); however, means within site-years were similar for all varieties (data not shown). When pooled across site-years, dicamba application at V3 resulted in 95% or greater relative yield, regardless of the variety, whereas dicamba at R1 resulted 81% to 66% relative yield, with significant yield losses occurring in all varieties except for CR4748 (Figure 1). Yields in the nontreated checks for each variety ranged from 3,635 to 3,904 kg ha^{-1}. Yield loss observed in this study is similar to yield loss reported by Foster and Griffin (2018) and McCown et al. (2018).

Correlations with Yield

There was a strong, negative correlation between yield and soybean injury 4WAT and at senescence (Table 9). Robinson et al. (2013) indicated that height reduction may be a quick way to estimate potential yield loss as a result of dicamba exposure. This was supported by these data, which show that in addition to a strong correlation, a linear relationship existed between soybean height and yield loss. As height increased by 31 cm, yield increased by 1 kg ha^{-1} (Figure 2).

Height reduction was also correlated with main stem nodes per plant, pods per plant, and seed weight, similar to that reported by Robinson et al. (2013). There were also strong correlations between yield components and relative yield. Relative pods per plant, seed weight, and seeds per pod were positively correlated to relative yield. Robinson et al. (2013) noted that seeds per square meter, pods per square meter, and nodes per square meter need to be characterized in order to understand the total effect of dicamba exposures on non-DR soybean.

Effects on Offspring

There were no significant differences among site-years, variety, and timing of application for reduction in germination, reduction in offspring emergence, number of offspring injured, offspring soybean injury, and reduction in offspring height (data not shown). No injury was observed in offspring and there were no differences from the nontreated check. Previous studies have shown reduced germination, emergence, and vigor and increased injury to offspring of soybean treated with dicamba and that the response became more severe as dicamba rate increased (Auch and Arnold 1978; Jones et al. 2018; Thompson and Egli 1973; Wax et al. 1969).

Table 9. Pearson correlation coefficients and corresponding P-values for soybean trait response to a reduced rate[a] of dicamba at multiple timings at Manhattan, KS in 2018 and 2019, and in Ottawa, KS in 2019.[b]

	2 WAT	4 WAT	At senescence	Relative height	Relative yield	Relative pods per plant	Relative nodes per plant	Relative seed weight	Relative seeds per pod
2WAT	1								
4WAT	**0.50*****[c,d]	1							
At senescence	0.26**	**0.93*****	1						
Relative height	−0.29**	**−0.69*****	**−0.73*****	1					
Relative yield	−0.22*	**−0.57*****	**−0.58*****	**0.83*****	1				
Relative pods plant^{-1}	−0.17	−0.14	−0.09	0.48***	**0.57*****	1			
Relative nodes plant^{-1}	−0.24*	**−0.56*****	**−0.55*****	**0.74*****	**0.75*****	**0.51*****	1		
Relative seed weight^{-1}	0.01	−0.09	−0.10	**0.63*****	**0.61****	**0.54****	0.49***	1	
Relative seeds pod^{-1}	−0.13	−0.28**	−0.31**	**0.73*****	**0.69*****	**0.54*****	**0.57*****	**0.67*****	1

[a]5.6 g ae ha^{-1} dicamba.
[b]Abbreviation: WAT = weeks after treatment.
[c]Bolded text indicates strong correlations with levels of significance ≤0.05, Correlation coefficients were nonsignificant or significant at *P ≤ 0.05, **P ≤ 0.01 or ***P ≤ 0.001.
[d]Pearson coefficient: <0.3 = weak correlation, >0.3 but <0.5 = moderate correlation, >0.5 = strong correlation.

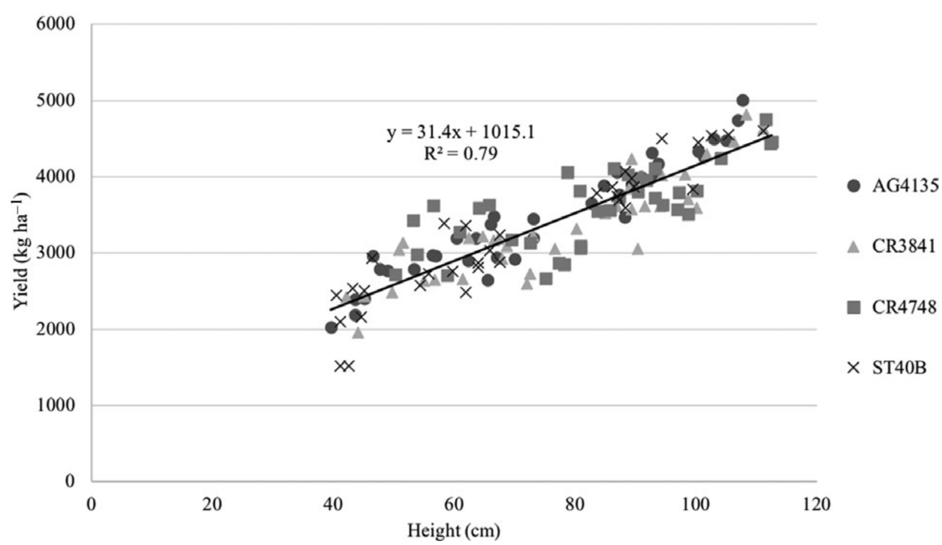

Figure 2. Linear regression of yield and height as a result of varying soybean varieties exposed to dicamba at varying application timings at Manhattan, KS in 2018 and 2019, and at Ottawa, KS in 2019. AG4135, Asgrow AG4135; CR3841, Credenz 3841LL; CR4748, Credenz 4748LL; ST40B, Stine 40BA02.

Differences in experimental parameters, specifically dicamba application rates and the environment in which offspring were tested, may explain the contrasting results obtained in this study.

In conclusion, yield loss due to dicamba was influenced by application timing, but not variety. Application at V3 resulted in minimal to no yield loss, but application at R1 resulted in 19% to 34% yield loss. Of the yield components impacted, the greatest effects were observed in main stem nodes per plant, where V3 applications resulted in less severe reduction than R1 applications. Pods per plant, seeds per pod, and seed weight did not result in significant reductions regardless of variety or timing of application. These data support additional label restrictions for use of dicamba in dicamba-resistant soybean to reduce the risk of injury during reproductive growth stages.

Acknowledgments. We thank the Kansas Soybean Commission for funding this project. We also thank Cathy Minihan for her assistance. No conflicts of interest have been declared. This publication is contribution no. 21-047-J from the Kansas Agricultural Experiment Station, Manhattan, KS.

References

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

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

Association of Official Seed Analysts [AOSA] (2019) Rules for testing seeds. Vol. 1. Washington, DC: Association of Official Seed Analysts

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

Behrens R, Lueschen WE (1979) Dicamba volatility. Weed Sci 27:486–493

Fehr WR, Caviness CE (1977) Stages of soybean development. Special Report 80. Ames: Iowa State University of Science and Technology, Cooperative Extension Service, Agriculture and Home Economics Experiment Station

Foster MR, Griffin JL (2018) Injury criteria associated with soybean exposure to dicamba. Weed Technol 32:608–617

France OW, Norsworthy JK, Ross J, Castner MC, Barber T (2019) Does sensitivity among soybean cultivars vary due to a low dose of dicamba? Page 69 *in* Proceedings of the Southern Weed Science Society 72nd Annual Meeting. Oklahoma City, OK, February 3–6, 2019

Jones GT, Norsworthy JK, Barber T, Gbur E, Kruger GR (2018) Effect of low doses of dicamba alone and in combination with glyphosate on parent soybean and offspring. Weed Technol 33:17–33

Jones GT, Norsworthy JK, Barber T (2019) Response of soybean offspring to a dicamba drift event the previous year. Weed Technol 33:41–50

Kniss AR (2018) Soybean response to dicamba: A meta-analysis. Weed Technol 32:507–512

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

McCown S. Barber T, Norsworthy JK (2018) Response of non–dicamba-resistant soybean to dicamba as influenced by growth stage and herbicide rate. Weed Technol 32:513–519

Mukaka MM (2012) Statistics Corner: A guide to appropriate use of correlation coefficient in medical research. Malawi Med J 24:79–71

Osipitan OA, Scott JE, Knezevic SZ (2019) Glyphosate-resistant soybeans to micro-rates of three dicamba-based herbicides. Agrosyst Geosci Environ 2:180052. https://acsess.onlinelibrary.wiley.com/doi/10.2134/age2018.10.0052. Accessed: February 16, 2020

Robinson AP, Simpson DM, Johnson WG (2013) Response of glyphosate-tolerant soybean yield components to dicamba exposure. Weed Sci 61:526–536

Sciumbato AS, Chandler JM, Senseman SA, Bovey RW, Smith KL (2004) Determining exposure to auxin-like herbicides. II. Practical application to quantify volatility. Weed Technol 18:1135–1142

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

Soltani N, Nurse RE, Sikkema PH (2016) Response of glyphosate-resistant soybean to dicamba spray tank contamination during vegetative and reproductive growth stages. Can J Plant Sci 96:160–164

Thompson L Jr, Egli DB (1973) Evaluation of seedling progeny of soybeans treated with 2,4-D, 2,4-DB, and dicamba. Weed Sci 21:141–144

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

Weidenhamer JD, Triplett GB, Sobotka FE (1989) Dicamba injury to soybean. Agron J 81:637–643

https://doi.org/10.1017/wet.2021.4 Published online by Cambridge University Press