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WEED SCIENCE

Palmer Amaranth (*Amaranthus palmeri*) Control in Dicamba-Tolerant Cotton (*Gossypium hirsutum*) when Applied with Various Dicamba + Insecticide Tank-Mixtures

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ABSTRACT

Postemergence herbicide application timings for Palmer amaranth (*Amaranthus palmeri*) often coincide with foliar insecticide applications in cotton (*Gossypium hirsutum*). Combining multiple pesticides into a single application increases efficiency while reducing overall application cost. Multiple foliar insecticides are now labeled for dicamba tank-mixes. However, there is limited literature with respect to efficacy of dicamba on Palmer amaranth control when applied with insecticides. Field experiments were conducted from 2018 to 2020 to evaluate the effect of carrier volume and insecticide on the efficacy of dicamba (XtendiMax^{TM} with VaporGrip^{TM}) to control Palmer amaranth in XtendFlex™ cotton production systems. Dicamba was tank-mixed with acephate and dimethoate to four-leaf cotton and with thiamethoxam and sulfoxaflor just prior to bloom. Applications were made at carrier volumes of 140 and 280 L ha^{-1} and with a single spray droplet size of 800 µm. Palmer amaranth control 7 d after treatment was negatively impacted when applications included dimethoate; however, no corresponding response in seedcotton yield was observed relative to dicamba applied alone. However, when pooled over carrier volume, applications containing dicamba + acephate resulted in higher seedcotton yield than applications of dicamba + dimethoate. Additionally, pre-bloom applications of dicamba + thiamethoxam or sulfoxaflor increased Palmer amaranth efficacy relative to dicamba applied alone. Although certain insecticides are known to increase herbicidal crop response, the impact of insecticides on herbicide efficacy to control specific weed species is largely unknown. Therefore, we conclude that multiple dicamba + acephate, thiamethoxam, or sulfoxaflor tank-mixtures provide similar control of Palmer amaranth compared to dicamba alone.

Palmer amaranth. Palmer amaranth (*Amaranthus palmeri*, S. Wats) is one of the most troublesome weed species throughout the southeastern U.S. (Ward et al., 2013). In 2009, Palmer amaranth was ranked as the single most troublesome weed in cotton production systems (Webster and Nichols, 2012) and is currently one of the most economically damaging glyphosate-resistant weed species in the U.S. (Beckie, 2006). Biologically, Palmer amaranth is a competitive and opportunistic species characterized by rapid germination and growth and is capable of proliferous seed production (Ward et al., 2013).

Palmer amaranth possesses an impressive capacity to develop resistance to multiple herbicides (Ward et al., 2013) with documented resistance to a total of 10 herbicide sites of action (SOA) to date: acetolactate synthase (ALS) inhibitors, 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase inhibitor, 4-hydoxyphenylpyruvate dioxygenase (HPPD) inhibitors, protoporphyrinogen oxidase (PPO) inhibitors, microtubule assembly inhibitors, very long-chain fatty acid (VLCFA) synthesis inhibitors, photosystem II (PSII) inhibitors (D1 serine and D1 histidine binders), synthetic auxins, and glutamine synthetase inhibitors (Heap, 2023). Additionally, certain Palmer amaranth biotypes possess resistance to multiple modes of action (Burgos et al., 2001; Culpepper et al., 2006; Gaeddert et al., 1997; Heap, 2023; Horak and Peterson, 1995; Norsworthy et al., 2008; Sosnoskie et al., 2011; Sprague et al., 1997; Steckel et al., 2008; Thompson et al., 2012; Wise et al., 2009). In Mississippi, Palmer amaranth biotypes resistant to group 14 (PPO), 3 (microtubule inhibitors), 9 (ALS), 2 (EPSP), and biotypes that are cross-resistant to glyphosate, ALS, and PPO herbicides limit options available to

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producers after crop emergence. Prior to 2017, glufosinate was the only option available to producers for control of multiple-resistant Palmer amaranth after crop emergence. However, with the introduction of Roundup Ready Xtend® (Bayer, Leverkusen, Germany) and Enlist® (Corteva Agriscience, Wilmington, DE) cotton varieties, dicamba and 2,4-D and are now federal- and state-labelled options for Palmer amaranth control. Effective POST control options for glyphosate- and multiple-resistant Palmer amaranth are available; however, selection pressure for Palmer amaranth resistance to these limited options persists.

Pesticide Application Factors. The application and subsequent efficacy of pesticides in agriculture production systems is a complex process and involves a series of factors that dynamically affect pesticide application efficacy. These factors include the physical and chemical properties of the carrier itself (water), droplet formation at the nozzle orifice, transport from the nozzle to the plant surface, leaf impaction and retention, deposition, plant uptake, and plant biological response (Brazes et al., 1991; Ebert and Downer, 2008; Merritt et al., 1989; Reichard, 1988).

Additionally, active ingredient (Creech et al., 2016; Knoche, 1994; Meyer et al., 2015), spray nozzle (Berger et al., 2014; Etheridge et al., 2001; Johnson et al., 2006; Klein et al., 2009; Miller and Ellis, 2000; Nuyttens et al., 2007; van de Zande et al., 2002; Yates et al., 1985), application pressure (Creech et al., 2015; Nuyttens et al., 2007), and carrier volume (Berger et al., 2014; Knoche, 1994; Reed and Smith, 2001; Shaw et al., 2000; Whisenant et al., 1993) all affect the characteristics of spray droplets themselves.

Nozzles used in agriculture production systems commonly produce spray droplets ranging in size from 10 to greater than 1000 µm (Bouse et al., 1990), with droplets < 150 µm (Yates et al., 1985) and 200 µm (Etheridge et al., 2001) classified as droplets with a propensity to drift off-site. Smaller spray droplets with a lower kinetic energy result in greater spray droplet retention on the leaf surface relative to larger droplets. Consequently, larger spray droplets with higher kinetic energy are poorly retained on the leaf surface and yield minimal coverage of leaf surface tissue (Forster et al., 2005; Spillman, 1984).

Whereas smaller droplets maximize target coverage and spray droplet retention, larger spray droplets minimize off-target movement. Therefore, pesticide application factors that maximize pesticide application efficacy and minimize off-target pesticide movement are often incongruous elements.

Impact of Carrier Volume and Spray Droplet Size on Herbicide Efficacy. Optimal herbicide efficacy is a function of target coverage and/or interception, and chemical deposition, retention, and absorption of the material applied. For herbicide applications, size of the spray droplet spectra is of unique importance to overall application efficacy due to its impact on spray droplet deposition and drift (Hewitt, 2000; Maybank et al., 1978; Taylor et al., 2004; Whisenant et al., 1993; Yates et al., 1976). Furthermore, there is an inverse relationship between spray droplet size and herbicide efficacy (Creech et al., 2015; Henry et al., 2014; Knoche, 1994).

Specifically, a meta-analysis on herbicide efficacy x spray droplet size revealed that in 71% of experiments, herbicide efficacy was increased as droplet size decreased (Knoche, 1994). Creech et al. (2016) reported that spray droplet sizes of < 300µm and > 750µm optimize herbicide efficacy for contact and systemic chemistries, respectively. Conversely, (with the exception of glyphosate) there is generally a positive relationship between carrier volume and herbicide efficacy (Knoche, 1994). Consequently, these data indicate that specific carrier volume and droplet size effects on herbicide efficacy likely vary across herbicides and their intended objective, and as a function of their mode of action.

Impact of Insecticide Tank-Mixtures on Herbicide Efficacy. To date, research evaluating the impact of insecticide tank-mixtures on herbicide performance has largely focused on crop safety of labeled herbicide applications. Ahrens (1990) reported increased injury to soybean following applications of thifensulfuron + carbaryl, chlorpyrifos, malathion, and methomyl relative to thifensulfuron or insecticides applied alone. In addition, soybean injury was observed to be positively correlated with insecticide rate when applied at 140 to 560 g ai ha^{-1} with thifensulfuron. Ahrens and Panaram (1997) reported enhanced thifensulfuron injury to corn when applied with chlorpyrifos and malathion and to soybean when applied with chlorpyrifos.

Conversely, there is a paucity of data with respect to herbicide efficacy on specific weed species when applied with insecticides. However, Ahrens (1990) observed thifensulfuron efficacy on yellow foxtail (*Setaria pumila* [Poir.] Roem. & Schult.) was enhanced by all insecticides with the exception of carbaryl. The increase in thifensulfuron injury to both corn (Ahrens and Panaram, 1997) and soybean (Ahrens, 1990; Ahrens and Panaram, 1997), and increased efficacy with yellow foxtail (Ahrens, 1990) suggests some insecticides could inhibit the metabolism and detoxification of thifensulfuron. However, the synergistic or antagonistic effects on herbicide efficacy to control specific weeds is largely unknown. To date, no research has reported the impact of insecticide tank-mixtures on the efficacy of herbicides to control Palmer amaranth.

RESEARCH OBJECTIVES

In mid-southern and southeastern cotton production systems, postemergence herbicide applications for Palmer amaranth control often coincide with foliar insecticide applications for controlling various insect pests throughout the growing season. Combining separate herbicide and insecticide applications into a single pesticide application would increase application efficiency while reducing overall application cost. However, as herbicide selection pressure persists and resistance increases on remaining options for glyphosate-, PPO-, and ALS-resistant Palmer amaranth, any decrease in efficacy due to dicamba + insecticide antagonism is unacceptable to producers. Therefore, pesticide application factors that maintain or maximize pesticide efficacy are required.

Multiple foliar-applied insecticides are now labeled for dicamba tank-mixes. However, there is a paucity of data with respect to the efficacy of dicamba when tank-mixed with insecticides on control of Palmer amaranth. Consequently, the efficacy of dicamba for Palmer amaranth control when tank-mixed with these insecticides is unknown. The objective of this research was to evaluate the impact of carrier volume and insecticide mixtures on the efficacy of dicamba for Palmer amaranth control. If efficacious, a single-pass application would increase overall pesticide application efficiency.

MATERIALS AND METHODS

Field experiments were conducted during 2018, 2019, and 2020 to evaluate the effect of carrier volume and tank-mixed insecticide on Palmer amaranth control with dicamba (XtendiMax^{TM} with VaporGrip^{TM}; Bayer, Leverkusen, Germany) in XtendFlex™ upland cotton production systems. Two separate experiments were conducted each year to evaluate Palmer amaranth control. Both experiments consisted of a single field location: Hood Farms in Dundee, MS. In each experiment, four row plots were planted to DP 1646 B2XF (Bayer, Leverkusen, Germany) at a population of 108,726 seed ha^{-1}. No at-planting preemergence herbicide was used to ensure adequate Palmer amaranth populations at the desired application timing. However, the second experiment was maintained weed free until approximately 2 wk prior to bloom to allow for a new flush of Palmer amaranth to establish prior to treatment applications.

For experiment one, Palmer amaranth control was evaluated after application of a tank-mix of various insecticides commonly used for foliar thrips (Thysanoptera: Thripidae) control. Applications were made to approximately four-leaf cotton when Palmer amaranth reached a height of 6 cm. For experiment two, Palmer amaranth control was evaluated when applied with various insecticides commonly used for tarnished plant bug (*Lygus lineolaris* [Palisot de Beauvois]) control. Therefore, applications were initiated when Palmer amaranth reached a height of 6 cm immediately prior to bloom. Plot dimensions were 3.9 x 9.1 m and 3.9 x 15.2 m for experiments one and two, respectively.

Applications were made using a Capstan Ag Systems (Topeka, KS) Pinpoint Pulse-Width Modulation (PWM) sprayer on a Bowman MudMaster (Bowman Manufacturing, Newport, AR) traveling at a ground speed of 14.5 km h^{-1}. In a PWM system, flow and output are controlled by the relative proportion of time that each electronically actuated solenoid valve is open and is referred to as the duty cycle (Giles and Comino, 1990). The duty cycle of a PWM sprayer is documented as having minimal effects on the spray droplet size of the emitted droplet spectra when compared to conventional pressure regulated systems (Butts et al., 2018), and is therefore uniquely suited for both pesticide application research and minimizing pesticide drift.

In both experiments, dicamba (XtendiMax with VaporGrip) was applied at 560 g ae ha^{-1} (Table 1). For experiment 1, acephate (Acephate 97UP; United Phosphorus, Inc.; King of Prussia, PA) and dimethoate (Dimethoate 4 EC; Drexel Chemical Company, Memphis, TN) were applied at 204 and 224 g ai ha^{-1}, respectively (Table 1). For experiment 2, thiamethoxam (Centric 40 WG; Syngenta, Basel, Switzerland) and sulfoxaflor (Transform WG; Corteva, Wilmington, DE) were applied at 56 and 53 g ai ha^{-1}, respectively (Table 1). Both experiments used two carrier volumes: 140 and 280 L ha^{-1}, and a single spray droplet size of 800 µm to comply with dicamba label restrictions.

Table 1. Treatment combinations for Palmer amaranth control when applied with insecticides for thrips and tarnished plant bug control

Active Ingredient	Formulated Product	Application Rate	Carrier Volume	Droplet Size[z]	Nozzle	Application Pressure
Experiment 1 – Four-leaf application			**L ha^{-1}**	**µm**	**Wilger[y]**	**kPa**
dicamba	**XtendiMax**	**560 g ae ha^{-1}**	**140**	**800**	**UR11006**	**338**
dicamba **acephate**	**XtendiMax** **Acephate 97 UP**	**560 g ae ha^{-1}** **204 g ai ha^{-1}**	**140**	**800**	**UR11006**	**345**
dicamba **dimethoate**	**XtendiMAX** **Dimethoate 4EC**	**560 g ae ha^{-1}** **224 g ai ha^{-1}**	**140**	**800**	**UR11008**	**345**
dicamba **acephate**	**XtendiMax** **Acephate 97 UP**	**560 g ae ha^{-1}** **204 g ai ha^{-1}**	**280**	**800**	**UR11006**	**345**
dicamba **dimethoate**	**XtendiMax** **Dimethoate 4EC**	**560 g ae ha^{-1}** **224 g ai ha^{-1}**	**280**	**800**	**UR11006**	**255**
Experiment 2 – Pre-bloom application						
dicamba	**XtendiMax**	**560 g ae ha^{-1}**	**140**	**800**	**UR11006**	**337**
dicamba **thiamethoxam**	**XtendiMax** **Centric 40WG**	**560 g ae ha^{-1}** **56 g ai ha^{-1}**	**140**	**800**	**UR11006**	**379**
dicamba **sulfoxaflor**	**XtendiMax** **Transform WG**	**560 g ae ha^{-1}** **53 g ai ha^{-1}**	**140**	**800**	**UR11006**	**338**
dicamba **thiamethoxam**	**XtendiMax** **Centric 40WG**	**560 g ae ha^{-1}** **56 g ai ha^{-1}**	**280**	**800**	**UR11006**	**386**
dicamba **sulfoxaflor**	**XtendiMax** **Transform WG**	**560 g ae ha^{-1}** **53 g ai ha^{-1}**	**280**	**800**	**UR11006**	**345**

[z] **All applications containing dicamba were made with 800 µm spray droplets.**

[y] **All nozzles used in this study were Wilger Industries (Wilger Industries, Lexington, TN).**

Dicamba was applied alone and in combination with insecticides. A non-treated and weed-free control were included for comparison purposes. A randomized complete block design was used and contained four replications of seven treatment combinations that included a non-treated check and a season-long weed-free control. All plots were maintained weed and insect free after herbicide or herbicide + insecticide application. However, within each experiment an additional factorial arrangement of treatments analysis was performed that included dicamba + insecticide tank-mix (Factor A; A1 = acephate, A2 = dimethoate) x carrier volume (Factor B; B1 = 140 L ha^{-1}, B2 = 280 L ha^{-1}) that were fully crossed. Dicamba was not applied alone at the 280 L ha^{-1} carrier volume because it was determined that this is not a practical option for producers. Conversely, a carrier volume of 280 L ha^{-1} was chosen for dicamba + insecticide applications to assess the efficacy of insecticide performance while being confined to the ultra-coarse droplet sizes required for dicamba applications.

The intended spray droplet sizes for each product or tank-mix treatment combination at each carrier volume were obtained by using a combination of spray nozzle (Wilger Industries, Lexington, TN), nozzle flow rate, and spray application pressure. The methods for this process were identical to those described by Creech et al. (2016) and Henry et al. (2014). The spray droplet spectrum for each pesticide material at each carrier volume was evaluated using the low-speed wind tunnel (LSWT) at the Precision Application Technology (PAT) Laboratory in North Platte, NE. Elements in the LSWT include a 7.5-hp axial flow fan, an expansion chamber, a honeycomb straightener use to produce laminar air flow, and eight 1.2 x 1.2 x 2.4-m sections. A scrubber system and a 10-hp electric axial flow fan is attached to the terminal section for removing spray droplets and vapors from the exhaust air.

The droplet spectrum for each treatment combination was analyzed using a Sympatec HELOS-VARIO/KR laser diffraction system with the R7 lens (Sympatec Inc.; Clausthal, Germany). The laser is controlled by WINDOX 5.7.0.0 software (Sympatec Inc.; Clausthal, Germany), which is operated on a computer adjacent to the wind tunnel. This lens is capable of detecting droplets in a range from 9 to 3,700 µm. The laser consists of two main components: an emitter housing containing the optical box, the source of the laser, and a receiver housing containing the lens and the detector element. The two laser housings are separated by 1.2 m on each side of the wind tunnel and mounted on aluminum optical bench rail that is connected underneath the wind tunnel to ensure proper laser alignment. The spray plume was oriented perpendicular to the laser beam by means of a mechanical linear actuator. The actuator moves the nozzle at a constant speed of 0.2 m s^{-1} such that the entire spray plume will pass through the laser beam spaced 30 cm from the nozzle. Treatments in this study were compared using the $D_{V0.5}$ parameter, which represents a droplet size such that 50% of the spray volume is contained in droplets of equal or smaller values, respectively. The spray classifications used in this document reflect the reference curves created from reference nozzle data at the PAT Lab as described by ASABE 572.1 (ASABE, 2009).

Data collection for both experiments included visual estimate of Palmer amaranth control (0-100%) at 7, 14, 21, and 28 d after treatment (DAT). Visual Palmer amaranth control for the non-treated and weed-free controls were always rated at 0 and 100%, respectively. Therefore, treatment response of visual herbicide symptomology was rated relative to both controls. The weed-free and non-treated controls were included in these experiments for visual comparison purposes only. Therefore, these treatments were removed from the data set prior to statistical analyses.

Finally, seedcotton yield was collected from the center two rows of each plot using a spindle picker modified for plot research. Data were subjected to analyses of variance using PROC GLIMMIX in SAS© v9.4 (SAS Institute Inc.; Cary, NC), and means were separated using Fisher's Protected LSD at an alpha level of 0.05.

RESULTS AND DISCUSSION

Four-Leaf Cotton Application. Palmer amaranth control at 7 DAT was significantly different due to treatment ($p = 0.0020$; Table 2). Dicamba applied alone at a carrier volume of 140 L ha^{-1} or as a tank-mixture with acephate at 140 or 280 L ha^{-1} resulted in Palmer amaranth control of 78 to 82%. Conversely, dicamba applied with dimethoate at a carrier volume of either 140 or 280 L ha^{-1} resulted in Palmer amaranth control of 70 to 71%. Palmer amaranth control did not vary due to treatment at 14, 21, or 28 DAT and ranged from 69 to 89% (Table 2).

These data indicate that Palmer amaranth control 7 DAT was greater when dicamba was applied alone at a carrier volume of 140 L ha^{-1} or with acephate at either 140 or 280 L ha^{-1}. Independent of carrier volume, application of dicamba + dimethoate resulted in the least Palmer amaranth control. Consequently, these data indicate that independent of carrier volume, a dicamba + dimethoate tank-mixture resulted in less Palmer amaranth control than dicamba + acephate at 7 DAT but not by 28 DAT.

Table 2. Palmer amaranth control following application^{z} of dicamba + acephate and dicamba + dimethoate at 140 and 280 L ha^{-1} to cotton at the four-leaf growth stage. Data were pooled across years 2018 to 2020

Herbicide	Insecticide	Carrier Volume	Droplet Size	7 DAT	14 DAT	21 DAT	28 DAT
		L ha^{-1}	µm	Percent Control^{y,x}			
dicamba	none	140	800	82 a	77	76	76
dicamba	acephate	140	800	78 a	72	70	69
dicamba	dimethoate	140	800	71 b	73	76	76
dicamba	acephate	280	800	80 a	80	86	89
dicamba	dimethoate	280	800	70 b	74	69	70
p value				0.0020	0.2076	0.2097	0.1041

[z] Application to four-leaf cotton coincided with ~ 10 cm Palmer amaranth.

[y] Evaluated as percent control (0-100%) relative to non-treated and weed-free controls.

[x] Means within each column followed by the same letter are not significantly different at $p \geq 0.05$.

Palmer amaranth control 7 DAT also varied due to insecticide tank-mixture (p = 0.0073; Table 3). Pooled over carrier volume, application of dicamba + acephate resulted in 78% Palmer amaranth control, 8% greater than following the application of dicamba + dimethoate (Table 3). Palmer amaranth control 28 DAT varied due to an insecticide tank-mixture x carrier volume interaction (p = 0.0313; Table 3). Dicamba + acephate applied at a carrier volume of 280 L ha^{-1} resulted in 89% Palmer amaranth control, which was similar to that observed following application of dicamba + dimethoate at 140 L ha^{-1} (76%) (Table 3). Application of dicamba + acephate at 140 L ha^{-1} or dicamba + dimethoate at 280 L ha^{-1} resulted in 69 and 70% Palmer amaranth control, respectively, and were also similar to that observed following application of dicamba + dimethoate at 280 L ha^{-1} (Table 3).

These data indicate application of dicamba + acephate resulted in greater Palmer amaranth control at 7 DAT than following applications of dicamba + dimethoate. However, these data indicate Palmer amaranth control did not vary due to carrier volume when dicamba was applied with acephate and dimethoate, and therefore disagree with Knoche (1994), who reported herbicide efficacy to be positively correlated with carrier volume.

Seedcotton Yield. Seedcotton yield varied due to treatment ($p \leq 0.0281$; Table 4). Dicamba + acephate applied at a carrier volume of 280 L ha^{-1} resulted in 3,528 kg seedcotton ha^{-1} and was similar to that following application of dicamba with or without acephate at 140 L ha^{-1}. Conversely, the non-treated control resulted in 2,375 kg seedcotton ha^{-1} and was also similar to that observed following applications of dicamba + dimethoate at either 140 (2,663 kg ha^{-1}) or 280 (2,778 kg ha^{-1}) L ha^{-1} (Table 4). Seedcotton yield also varied due to insecticide tank-mix ($p \leq 0.0194$; Table 5). Pooled over carrier volume, application of dicamba + acephate resulted in 3,288 kg seedcotton ha^{-1}, 273 kg seedcotton ha^{-1} more than following the application of dicamba + dimethoate. Finally, although Palmer amaranth control 28 DAT varied due to an insecticide tank-mixture x carrier volume interaction (Table 3), we observed no corresponding response in seedcotton yield. Although a 20% differential in Palmer amaranth control is not to be considered inconsequential, in this study it was found to be insufficient to produce a corresponding yield response.

Pre-Bloom Application. Palmer amaranth control at 14, 21, and 28 DAT varied due to treatment ($p \leq 0.0008$; Table 6). At 14 DAT, dicamba applied alone at a carrier volume of 140 L ha^{-1} resulted in 71% Palmer amaranth control and was at least 6% less than all other treatments (Table 6).

Table 3. Palmer amaranth control following application^{z} of dicamba + acephate and dicamba + dimethoate at 140 and 280 L ha^{-1} to cotton at the four-leaf growth stage. Data were pooled across years 2018 to 2020

Effect		7 DAT	14 DAT	21 DAT	28 DAT
Insecticide Tank-Mixture		**Percent Control^{y,x}**			
dicamba + acephate		**78 a**	**76**	**78**	**79**
dicamba + dimethoate		**70 b**	**73**	**73**	**73**
***p* value**		**0.0073**	**0.3070**	**0.3469**	**0.2843**
Carrier Volume					
140 L ha^{-1}		**74**	**72**	**73**	**73**
280 L ha^{-1}		**75**	**77**	**77**	**79**
***p* value**		**0.6582**	**0.1115**	**0.4702**	**0.2540**
Insecticide Tank-Mixture * Carrier Volume					
dicamba + acephate	**140 L ha^{-1}**	**76**	**72**	**70**	**69 b**
	280 L ha^{-1}	**80**	**80**	**86**	**89 a**
dicamba + dimethoate	**140 L ha^{-1}**	**71**	**73**	**76**	**76 ab**
	280 L ha^{-1}	**70**	**74**	**69**	**70 b**
***p* value**		**0.3779**	**0.2438**	**0.0540**	**0.0313**

[z] Application to four-leaf cotton coincided with ~ 10 cm Palmer amaranth.

[y] Evaluated as percent control (0-100%) relative to non-treated and weed-free controls.

[x] Means within each column followed by the same letter are not significantly different at $p \geq 0.05$.

Table 4. Seedcotton yield following application of dicamba + acephate and dicamba + dimethoate at 140 and 280 L ha^{-1} to cotton at the four-leaf growth stage. Data were pooled across years 2018 to 2020

Herbicide	Insecticide	Carrier Volume	Droplet Size	Seedcotton Yield
		L ha^{-1}	µm	kg ha^{-1} [z]
dicamba	none	140	800	3,037 ab
dicamba	acephate	140	800	3,048 ab
dicamba	dimethoate	140	800	2,663 bc
dicamba	acephate	280	800	3,528 a
dicamba	dimethoate	280	800	2,788 bc
non-treated	non-treated	-	-	2,375 c
		p value		0.0281

[z] Means within each column with the same letter are not significantly different at $p \geq 0.05$.

Table 5. Seedcotton yield following application of dicamba + acephate and dicamba + dimethoate at 140 and 280 L ha^{-1} to cotton at the four-leaf growth stage. Data were pooled across years 2018 to 2020

Effect		Seedcotton Yield
Insecticide Tank-Mixture		kg ha^{-1} [z]
dicamba + acephate		3,288 a
dicamba + dimethoate		2,725 b
p value		0.0914
Carrier Volume		
140 L ha^{-1}		3,158
280 L ha^{-1}		2,855
p value		0.1913
Insecticide Tank-Mixture * Carrier Volume		
dicamba + acephate	140 L ha^{-1}	3,528
	280 L ha^{-1}	3,048
dicamba + dimethoate	140 L ha^{-1}	2,788
	280 L ha^{-1}	2,663
p value		0.4391

[z] Means within each column with the same letter are not significantly different at $p \geq 0.05$.

Table 6. Palmer amaranth control following application[z] of dicamba + thiamethoxam and dicamba + sulfoxaflor at 140 and 280 L ha^{-1} to cotton at the pre-bloom stage. Data were pooled across years 2018 to 2020

Herbicide	Insecticide	Carrier Volume	Droplet Size	7 DAT	14 DAT	21 DAT	28 DAT
		L ha^{-1}	µm	Percent Control[y,x]			
dicamba	none	140	800	75	71 b	79 c	79 c
dicamba	thiamethoxam	140	800	78	77 a	84 ab	84 b
dicamba	sulfoxaflor	140	800	74	78 a	86 a	85 ab
dicamba	thiamethoxam	280	800	79	80 a	87 a	88 a
dicamba	sulfoxaflor	280	800	79	79 a	82 bc	85 ab
	p value			0.0918	<0.0001	0.0008	0.0004

[z] Pre-bloom application coincided with ~ 10 cm Palmer amaranth.

[y] Evaluated as percent control (0-100%) relative to non-treated and weed-free controls.

[x] Means within each column with the same letter are not significantly different at $p \geq 0.05$.

At 21 DAT, dicamba applied alone at a carrier volume of 140 L ha^{-1} resulted in 79% Palmer amaranth control and was at least 5% less than observed following all other treatments with the exception of dicamba + sulfoxaflor applied at 280 L ha^{-1} (82%; Table 6). Application of dicamba + thiamethoxam or sulfoxaflor at 140 L ha^{-1} or dicamba + thiamethoxam at 280 L ha^{-1} resulted in similar Palmer amaranth control of 82 to 84% (Table 6).

Finally, at 28 DAT dicamba applied alone at a carrier volume of 140 L ha^{-1} resulted in 79% Palmer amaranth control, which was at least 6% less than all other treatments (Table 6). Conversely, application of dicamba + thiamethoxam at 280 L ha^{-1} resulted in 88% Palmer amaranth control and was similar to that observed following application of dicamba + sulfoxaflor at 140 and 280 L ha^{-1} (85%; Table 6).

To date, no research has reported the impact on Palmer amaranth control when thiamethoxam or sulfoxaflor were applied with dicamba versus dicamba being applied alone. Additional research is needed to evaluate and characterize any variations in Palmer amaranth control with dicamba when various insecticides are added to the application. However, an increase in plant response due to a herbicide + insecticide interaction relative to when herbicides are applied alone is not without precedent.

Ahrens (1990) observed an increase in thifensulfuron injury to soybean with the addition of carbaryl, chlorpyrifos, malathion, and methomyl relative to when thifensulfuron was applied alone (Ahrens, 1990). Additionally, Ahrens and Panaram (1997) reported enhanced thifensulfuron injury to corn when applied with chlorpyrifos and malathion and to soybean when applied with chlorpyrifos. Thifensulfuron efficacy on yellow foxtail (*Setaria pumila*) was also enhanced when applied with chlorpyrifos, malathion, and methomyl (Ahrens, 1990).

The increase in thifensulfuron injury to corn (Ahrens and Panaram 1997) and soybean (Ahrens, 1990; Ahrens and Panaram, 1997) and efficacy to control yellow foxtail (Ahrens, 1990) was attributed to insecticidal activity inhibiting the metabolism and detoxification of thifensulfuron. Consequently, we hypothesize that thiamethoxam and sulfoxaflor could have inhibited the metabolism and detoxification of dicamba to result in the increase in observed injury to Palmer amaranth. Finally, our data indicate that multiple dicamba + insecticide tank-mix options are available that provide similar control of Palmer amaranth when compared to dicamba applied alone.

Palmer amaranth control 7 DAT also varied due to carrier volume ($p = 0.0285$; Table 7). Pooled over insecticide tank-mixture, a carrier volume of 280 L ha^{-1} resulted in 79% Palmer amaranth control, an increase of 3% than following applications at 140 L ha^{-1} (Table 7).

Table 7. Palmer amaranth control following application^{z} of dicamba + thiamethoxam and dicamba + sulfoxaflor at 140 and 280 L ha^{-1} to cotton at the pre-bloom stage. Data were pooled across years 2018 to 2020

Effect		7 DAT	14 DAT	21 DAT	28 DAT
Insecticide Tank-Mixture		Percent Control^{y,x}			
dicamba + thiamethoxam		78	79	86	86
dicamba + sulfoxaflor		76	79	84	85
p value		0.1429	1.000	0.4277	0.4655
Carrier Volume					
140 L ha^{-1}		76 b	78	85	85
280 L ha^{-1}		79 a	78	85	87
p value		0.0285	0.0943	0.7175	0.1138
Insecticide Tank-Mixture * Carrier Volume					
dicamba + thiamethoxam	140 L ha^{-1}	78	77	84 ab	84
	280 L ha^{-1}	79	80	87 a	88
dicamba + sulfoxaflor	140 L ha^{-1}	74	78	86 ab	85
	280 L ha^{-1}	79	79	83 b	86
p value		0.3120	0.3088	0.0217	0.1138

[z] Pre-bloom application coincided with ~ 10 cm Palmer amaranth.

[y] Evaluated as percent control (0-100%) relative to non-treated and weed-free controls.

[x] Means within each column with the same letter are not significantly different at $p \geq 0.05$.

Palmer amaranth control 21 DAT also varied due to an insecticide tank-mixture x carrier volume interaction (p = 0.0217; Table 7). Application of dicamba + thiamethoxam at 280 L ha^{-1} resulted in 87% Palmer amaranth control and was similar to that observed following application of dicamba + sulfoxaflor (86%) and dicamba + thiamethoxam (84%) at 140 L ha^{-1} (Table 7). Conversely, application of dicamba + sulfoxaflor at 280 L ha^{-1} resulted in 83% Palmer amaranth control but was also similar to that observed following application of dicamba + thiamethoxam or dicamba + sulfoxaflor at 140 L ha^{-1} (Table 7).

Pooled over insecticide tank-mixture, applications made at 280 L ha^{-1} resulted in greater Palmer amaranth control 7 DAT relative to those made at 140 L ha^{-1}. These data agree with Knoche (1994), who reported herbicide efficacy to be positively correlated with carrier volume. However, at 7 and 21 DAT, the variation in Palmer amaranth control observed was only 3 and 4%, respectively, and does not represent a sufficient increase in efficacy to justify the increase in water volume.

Seedcotton Yield. Seedcotton yield did not vary due to treatment, insecticide tank-mix, or carrier volume, and ranged from 2,909 to 4,347 kg ha^{-1} (Tables 8 and 9).

Table 8. Seedcotton yield following application of dicamba + thiamethoxam and dicamba + sulfoxaflor at 140 and 280 L ha^{-1}. Data were pooled across years 2018 to 2020

Herbicide	Insecticide	Carrier Volume	Droplet Size	Seedcotton Yield
		L ha^{-1}	µm	kg ha$^{-1\ z}$
dicamba	none	140	800	4,347
dicamba	thiamethoxam	140	800	3,408
dicamba	sulfoxaflor	140	800	3,917
dicamba	thiamethoxam	280	800	3,494
dicamba	sulfoxaflor	280	800	3,545
non-treated	non-treated	-	-	2,909
	p value			0.2858

^{z}Means within each column with the same letter are not significantly different at $p \geq 0.05$

Table 9. Seedcotton yield following application of dicamba + thiamethoxam and dicamba + sulfoxaflor at 140 and 280 L ha^{-1}. Data were pooled across years 2018 to 2020

Effect		Seedcotton Yield
Insecticide Tank-Mixture		kg ha$^{-1\ z}$
dicamba + thiamethoxam		3,731
dicamba + sulfoxaflor		3,451
p value		0.5321
Carrier Volume		
140 L ha^{-1}		3,663
280 L ha^{-1}		3,519
p value		0.7481
Insecticide Tank-Mixture * Carrier Volume		
dicamba + thiamethoxam	140 L ha^{-1}	3,917
	280 L ha^{-1}	3,545
dicamba + thiamethoxam	140 L ha^{-1}	3,494
	280 L ha^{-1}	3,408
p value		0.6081

^{z}Means within each column with the same letter are not significantly different at $p \geq 0.05$.

CONCLUSION

Palmer amaranth control 7 DAT was negatively impacted when dimethoate was included in the application relative to dicamba applied alone, but this decrease in efficacy was not observed at later evaluation (28 DAT) and did not correlate with any reduction in seedcotton yield relative to dicamba applied alone (Table 4). However, we did observe an increase in seedcotton yield following applications of dicamba + acephate relative to dicamba + dimethoate (Table 5).

Additionally, our data show neither thiamethoxam nor sulfoxaflor negatively impacted Palmer amaranth control or seedcotton yield when applied with dicamba at pre-bloom stage of cotton. With a single exception, multiple dicamba + thiamethoxam or sulfoxaflor treatments increased Palmer amaranth efficacy relative to dicamba applied alone. Therefore, we conclude dicamba + acephate or dimethoate, and dicamba + thiamethoxam or sulfoxaflor are efficacious options to control Palmer amaranth when compared to dicamba applied alone, and that their final utility as a dicamba tank-mix partner should be evaluated based on their ability to control thrips and tarnished plant bugs when applied according to dicamba label restrictions.

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