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Evaluating efficacy of dicamba and dicamba/tembotrione with and without ammonium sulfate for broadleaf weed control

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Abstract

Mixing ammonium sulfate (AMS) can increase dicamba volatility. Therefore, AMS cannot be used with dicamba products in dicamba-resistant soybean. However, most dicamba products applied in corn are labeled to mix with AMS. The objectives of this study were to evaluate broadleaf weed control with dicamba (DiFlexx®) and dicamba/tembotrione (DiFlexx® DUO) applied alone or with AMS or AMS substitute and their effect on broadleaf weed density and biomass. Field experiments were conducted in Illinois, Missouri, and Nebraska in 2018 and 2019. In Illinois and Nebraska, mixing AMS + crop oil concentrate (COC) with dicamba applied at 1,120 g ae ha^{-1} increased the control of Palmer amaranth and waterhemp (*Amaranthus* species) from 78% to 92% and velvetleaf from 73% to 96% compared with dicamba applied alone 14 d after application (DAA); however, Missouri data showed no difference. Mixing AMS + COC with dicamba/tembotrione at 597 and 746 g ai ha^{-1} did not improve broadleaf weed control 14 DAA at any site compared with dicamba/tembotrione applied alone. Control of *Amaranthus* species was increased from 82% with dicamba applied at 840 g ae ha^{-1} to 96% when mixed with AMS + COC 28 DAA in Illinois; however, control was similar to dicamba applied at 1,120 g ae ha^{-1}. Broadleaf weed control did not differ among dicamba or dicamba/tembotrione 28 and 56 DAA in Missouri and Nebraska. Broadleaf weed density decreased from 64 plants m^{-2} to 24 plants m^{-2} with dicamba at 1,120 g ae ha^{-1} with AMS + COC 14 DAA in Nebraska; however, no differences were observed in broadleaf weed density or biomass 56 DAA in any state. The results suggest that dicamba or dicamba/tembotrione can be applied without AMS or AMS substitute, especially at higher rates, without losing broadleaf weed control efficacy.

Keywords: Dicamba injury; dicamba volatility; herbicide mixture; off-target movement; weed management.

Introduction

Since the 1960s, dicamba has been a widely used herbicide to control broadleaf weeds in row crops, rangeland and pasture, and non-crop areas (Caux et al. 1993; Schweizer et al. 1978; Shaner 2014). Dicamba-resistant soybean and cotton (*Gossypium hirsutum* L.) were commercialized in 2017 for effectively managing herbicide-resistant broadleaf weeds, especially glyphosate-resistant broadleaf weeds, which became widespread due to repeated use of glyphosate in glyphosate-resistant crops (Dodson et al. 2021; Peterson et al. 2018). Dicamba is an effective option for controlling glyphosate-resistant broadleaf weeds such as common ragweed (*Ambrosia artemisiifolia* L.) (Byker et al. 2017), waterhemp (Johnson et al. 2010; Spaunhorst et al. 2014), giant ragweed (*Ambrosia trifida* L.) (Johnson et al. 2010; Spaunhorst et al. 2014; Vink et al. 2012), horseweed (*Erigeron canadensis* L.) (Johnson et al. 2010), and Palmer amaranth (de Sanctis and Jhala 2021; Johnson et al. 2010; McDonald et al. 2021). Due to dicamba's effectiveness in managing glyphosate-resistant weeds, dicamba-resistant crops were rapidly adopted by growers, as evidenced by a 69% increase in the adoption of dicamba-resistant cotton from 2016 to 2019 (Dodson et al. 2021) and a 43% increase in adoption of dicamba-resistant soybean from 2016 to 2018 (Wechsler et al. 2019). Concomitantly, dicamba use in dicamba-resistant soybean increased from about 3.4 to 7.2 million kg from 2017 to 2019 (USGS 2019), indicating the preference of growers for using dicamba as an effective postemergence herbicide. Werle et al. (2018) reported that dicamba was used on 80% of dicamba-resistant soybean planted in Nebraska in 2017, with 93% of surveyed growers agreeing that dicamba improved broadleaf weed control.

The increasing use of dicamba for broadleaf weed control in dicamba-resistant crops became controversial in the United States in 2017 (US-EPA 2017) when approximately 2,700 cases of dicamba-related off-target broadleaf crop injuries were reported that affected about 1.4 million ha of dicamba-sensitive soybean fields (Bradley 2017). Werle et al. (2018) surveyed soybean growers in Nebraska and found that 51% of respondents had observed dicamba off-target injury on dicamba-sensitive soybean. A report from the U.S. Environmental Protection Agency indicates that about 4% of soybean growers representing 65 thousand fields, equating to 1.7 million ha observed off-target dicamba injury symptoms in 2018 (US-EPA 2020). Many reports of off-target dicamba injury came from Nebraska and Illinois, where almost one out of thirteen fields were injured (Wechsler et al. 2019). In 2018, the Nebraska Department of Agriculture received 106 dicamba-related off-target injury complaints, and 280 complaints by Nebraska Extension (Jhala et al. 2019). Likewise, 250 complaints were received in 2017 by the Minnesota Department of Agriculture, affecting about 107,242 ha of sensitive soybean (Gunsolus 2021).

Off-target movement of dicamba has been associated with spray/particle drift, application techniques, tank mixtures, spray tank contamination, and environmental conditions (Boerboom 2009; Riter et al. 2021). Among all factors, dicamba volatility is a well-documented mode of secondary movement of dicamba (Behrens and Lueschen 1979; Bish et al. 2019; Jones et al. 2019; Sall et al. 2020; Soltani et al. 2020). Seminal work by Behrens and Lueschen (1979) detected volatility up to three days after dicamba application in a corn field in Missouri. Similarly, Bish et al. (2019) detected dicamba in the air for three days after application under field conditions in Missouri. Soltani et al. (2020) reported secondary movement of dicamba through vapor drift at five out of six sites in the Midwestern United States. Moreover, Werle et al. (2018) reported that 31% of Nebraska growers stated volatilization as the reason for dicamba off-target injury. Dicamba may volatilize owing to its high vapor pressure and favorable meteorological conditions (Riter et al. 2021), even if applied following label instructions (Hartzler 2017; Norsworthy et al. 2018). In addition, volatilization combined with sensitive broadleaf crops in proximity increases the potential of dicamba off-target injury (Hartzler 2017).

Spray adjuvants and mixing partners influence the volatility potential of dicamba (Bish et al. 2019; Ferreira et al. 2020; Striegel et al. 2021). Ammonium sulfate (AMS) is a commonly used water conditioning adjuvant that improves spray solution properties (McMullan 2000). Ammonium sulfate negates the antagonistic effects of cations present in the spray solution (Bradley et al. 2000; Hart et al. 1992; Zollinger et al. 2011) and improves weed control efficacy of certain foliar-applied herbicides, especially weak acid herbicides such as glyphosate (Devkota et al. 2016; Hart et al. 1992; Kent et al. 1991; Ramsdale et al. 2003) and dicamba (Roskamp et al. 2013). Ammonium sulfate has remained a common adjuvant for improving the weed control efficacy of dicamba, glyphosate, and glufosinate (Riter et al. 2021); however, mixing AMS increases dicamba volatility (Riter et al. 2021; Sall et al. 2020). Protons dissociated from AMS in the dicamba spray solution can combine with dicamba anions to form volatile dicamba acid (Riter et al. 2021). Therefore, new dicamba products [Engenia® (N,N-Bis-(3-aminopropyl) methylamine salt of 3,6-dichloro-o-anisic acid)], Tavium® (diglycolamine salt of dicamba/*S*-metolachlor), and XtendiMax® [diglycolamine salt of dicamba (3,6-dichloro-o-anisic acid)] registered for use in dicamba-resistant crops prohibit the addition of AMS (Anonymous 2020b; 2020c; 2021b), though the majority of dicamba products applied in corn are labeled to apply with AMS to improve postemergence broadleaf weed control (Anonymous 2006; 2010; 2022) which can potentially increase dicamba volatility and injure nearby dicamba-sensitive broadleaf crops. Dicamba (DiFlexx) is labeled from 210 to 560 g ae ha^{-1} for postemergence application in corn and up to 1,120 g ae ha^{-1} for biennial and perennial broadleaf weed control in fallow (Anonymous 2020a).

Research was required to determine if dicamba applied without AMS will reduce broadleaf weed control efficacy or if replacing AMS with a substitute can provide a similar level of broadleaf weed control. Multi-state field experiments were conducted in Illinois, Missouri, and Nebraska to understand these outcomes. The objectives of this study were to evaluate the broadleaf weed control efficacy of dicamba [DiFlexx (diglycolamine salt of dicamba (3,6-dichloro-o-anisic acid)] and dicamba/tembotrione [DiFlexx DUO (diglycolamine salt of dicamba (3,6-dichloro-o-anisic acid)/tembotrione)] with and without AMS or with AMS substitute (Class Act® Ridion®) and their effect on broadleaf weed density and biomass.

Materials and Methods

Site Descriptions

Field experiments were conducted in Illinois, Missouri, and Nebraska in 2018 and 2019. Information about soil type, pH, organic matter, and tillage practices for each state/site is presented in Table 1. Major broadleaf weeds at all research sites included Palmer amaranth, waterhemp (collectively referred to as *Amaranthus* spp.), and velvetleaf (*Abutilon theophrasti* Medik.). In addition, common ragweed, and cocklebur (*Xanthium strumarium* L.) were present in Missouri. A low level of glyphosate-resistant Palmer amaranth was present at the study sites in Nebraska and Illinois. Broadleaf weeds evaluated in this study at all the sites were sensitive to dicamba.

Experimental Design and Treatments

The experiments were conducted in a randomized complete block design with three replications in Illinois and four replications in Missouri and Nebraska. Research plots were 3 m wide and 4 to 14 m long, depending on the state (Table 2). Corn was seeded at 80,000 seeds ha^{-1} in Missouri and at 86,000 seeds ha^{-1} in Illinois and Nebraska. The dates for corn planting, preemergence, and postemergence herbicide applications for each site/year are presented in Table 2.

The experiment consisted of fourteen treatments, including a no- postemergence herbicide and a weed-free control. Herbicide treatments included dicamba (DiFlexx, Bayer Crop Science, St. Louis, MO) at 840 and 1,120 g ae ha^{-1} and dicamba/tembotrione (DiFlexx DUO, Bayer Crop Science, St. Louis, MO) at 597 and 746 g ai ha^{-1} applied alone or with AMS and COC (crop oil concentrate) or AMS substitute i.e., Class Act Ridion (Winfield United, St. Paul, MN 55164) (Table 3). Dicamba (DiFlexx) can be applied in the range of 210 to 560 g ae ha^{-1} in corn; however, it is labeled up to 1,120 g ae ha^{-1} for broadleaf weed control in fallow (Anonymous 2020a). Dicamba/tembotrione (DiFlexx DUO) is labeled from 447 to 746 g ai ha^{-1} for postemergence application in corn (Anonymous 2021a). These products contain the safener cyprosulfamide (Anonymous 2020a), which provides better corn safety (Barnes et al. 2020).

S-metolachlor (Dual II Magnum, Syngenta Crop Protection, Greensboro, NC 27419) at 1,670 g ai ha^{-1} was applied preemergence to achieve early-season weed control. Weed-free control received preemergence application of a premix of atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron®; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,928 g ai ha^{-1} and a postemergence application of glyphosate (Roundup® PowerMAX; Bayer Crop Science, St. Louis, MO) at 1,576 g ae ha^{-1} plus acetochlor (Warrant®; Bayer Crop Science, St. Louis, MO) at 1,260 g ai ha^{-1}. Herbicides were applied using a CO_2-pressurized backpack sprayer. The sprayer boom had six flat-fan nozzles with 51 cm spacing in Illinois, eight flat-fan nozzles with 38 cm spacing in Missouri, and five flat-fan nozzles with 51 cm in Nebraska. The sprayer was calibrated to deliver 140 L ha^{-1} at 221 kPa in Illinois, 117 kPa in Missouri, and 276 kPa in Nebraska. The Turbo TeeJet Induction 11025, 11002, and 11015 nozzles (Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60187) were used in Illinois, Missouri, and Nebraska, respectively.

Data Collection

Broadleaf weed control at 14, 28, and 56 d after application (DAA) was evaluated visually using a scale of 0% to 100%, where 0% represents no control and 100% represents complete plant death. Broadleaf weed densities were assessed at 14, 28, and 56 DAA by randomly placing two 0.5 m^2 quadrats in each plot. Broadleaf weed biomass was collected 56 DAA by harvesting above-ground shoots of broadleaf weeds from two randomly placed 0.5 m^2 quadrats in each plot. The biomass was bagged and dried to a constant weight in an oven at 70 C. Crop injury was evaluated visually at 7, 14, and 21 DAA on a scale of 0% to 100%, where 0% represents no injury and 100% represents complete plant death. The two central rows of corn from each plot were harvested with a plot combine, and grain yields were adjusted to 15.5% moisture content.

Data Analysis

Data were subjected to ANOVA using *agricolae* package of R version 3.5.1 (Mendiburu 2021; R Core Team 2019). ANOVA assumption of normal distribution was tested with the Shapiro-Wilk test using the *shapiro.test* function, and equal variances were tested using the Bartlett test using the *bartlett.test* function and the Fligner-Killen test using the *flinger.test* function (Kniss and Streibig 2018). Data failing the assumption of normal distribution were transformed with arcsine and logit transformation, and tables are presented with back-transformed data for easy interpretation. In the ANOVA model, site and herbicide treatments were considered fixed effects, and the year nested within the site constituted a random effect. If the effect of site or year was significant, data were analyzed and presented separately. When differences between states were non-significant, data were combined for the respective states. Fisher's protected least significant (LSD) test was applied using the *LSD.test* function to separate the treatment means at $P\text{-}value \leq 0.05$.

Results and Discussion

Broadleaf Weed Control

Broadleaf weed control varied with dicamba and dicamba/tembotrione rates, and the presence or absence of adjuvants 14, 28, and 56 DAA at least in one of the sites (Table 3 and 4; $P < 0.001$ for all significant cases). In Illinois and Nebraska, control of *Amaranthus* spp. at 14 DAA ranged from 75% to 93%, and control of velvetleaf ranged from 73% to 96% with dicamba and dicamba/tembotrione (Table 3). Dicamba at 840 g ae ha^{-1} provided 84% control of *Amaranthus* spp. and 87% control of velvetleaf, which was similar to 78% control of *Amaranthus* spp. and 73% control of velvetleaf with dicamba at 1,120 g ae ha^{-1}. Similarly, Priess et al. (2022) reported 80% control of Palmer amaranth (< 10 cm tall) with dicamba at 560 g ae ha^{-1} 14 DAA in fallow in Arkansas. Similarly, McDonald et al. (2021) and de Sanctis and Jhala (2021) reported 75% to 86% control of Palmer amaranth and velvetleaf with dicamba (560 g ae ha^{-1}) 14 DAA in Nebraska. Mixing AMS and COC with dicamba at 840 g ae ha^{-1} improved control of *Amaranthus* spp. and velvetleaf by 18% compared with mixing AMS substitute (Class Act Ridion). Mixing AMS and COC with dicamba at 1,120 g ae ha^{-1} improved control of *Amaranthus* spp. by 14% and velvetleaf by 23% compared to dicamba applied alone (Table 3). However, broadleaf weed (*Amaranthus* spp., common ragweed, and common cocklebur) control 14 DAA did not differ between dicamba and dicamba/tembotrione with or without adjuvants in Missouri. Relatively less hard water and low historic use of dicamba at Missouri site compared to Nebraska and/or Illinois sites might have played a role in the lack of improvement in broadleaf weed control when AMS was added to dicamba in Missouri. Likewise, broadleaf weed control 14 DAA at any site was not improved by mixing AMS and COC or Class Act Ridion to either rate of dicamba/tembotrione (Table 3). No corn injury was observed from any treatment (data not shown).

Control of *Amaranthus* spp. 28 DAA ranged between 67% to 96% in Illinois, 89% to 99% in Missouri, and 80% to 99% in Nebraska (Table 4). In Illinois, a lower rate of dicamba (840 g ae ha^{-1}) provided 82% control of *Amaranthus* spp., which did not significantly differ from 90% control with dicamba at 1,120 g ae ha^{-1}. The level of control was similar to Merchant et al. (2013), who reported 83% control of Palmer amaranth with dicamba (1,120 g ae ha^{-1}) in fallow 28 DAA. Broadleaf weed control was similar to Vyn et al. (2006), who reported 87% to

92% control of waterhemp with dicamba at 600 g ae ha^{-1} in corn 28 DAA. Mixing AMS and COC with dicamba at 840 g ae ha^{-1} improved control of *Amaranthus* spp. by 14% and 18% compared with dicamba applied alone and dicamba + Class Act Ridion, respectively. Similarly, control of *Amaranthus* spp. increased from 67% with a lower rate of dicamba/tembotrione (597 g ai ha^{-1}) to 96% when AMS and COC were mixed, a notable increase of 29%. At the higher rate, control improved (17%) with dicamba/tembotrione but not with dicamba. A higher labeled rate of dicamba/tembotrione (746 g ai ha^{-1}) without adjuvant achieved 78% control of *Amaranthus* spp. compared with 95% control when AMS and COC were mixed 28 DAA in Illinois (Table 4).

Consistent with the control of *Amaranthus* spp. 28 DAA, control at 56 DAA in Illinois improved by 13% to 15% when mixing AMS and COC with dicamba at 840 g ae ha^{-1}; control improved from 83% to 85% with dicamba applied alone or with Class Act Ridion to 98% by mixing with AMS and COC (Table 4). Similarly, mixing AMS and COC to dicamba at 1,120 g ae ha^{-1} provided 98% control of *Amaranthus* spp. compared to 88% with dicamba without adjuvant, a numerical increase of 10%. Moreover, mixing AMS and COC (96% to 98% control) instead of Class Act Ridion (83% to 85% control) to dicamba/tembotrione regardless of the application rates improved control of *Amaranthus* spp. by 13%. Mixing AMS and COC rather than Class Act Ridion with dicamba at 840 g ae ha^{-1} improved velvetleaf control from 80% to 93% 56 DAA in Illinois. Similarly, mixing AMS and COC with dicamba at 1,120 g ae ha^{-1} improved velvetleaf control by 11%, as dicamba provided 87% control compared to 98% control when AMS and COC were mixed (Table 4). Control of *Amaranthus* spp. 28 DAA in Missouri, 56 DAA in Missouri and Nebraska, and velvetleaf control 56 DAA in Nebraska was similar across treatments, except for the no-postemergence herbicide and weed-free control.

Results indicate that mixing AMS with dicamba and dicamba/tembotrione did not often improve late-season broadleaf weed control, except for in one location (Table 3 and Table 4). Interestingly, 14% to 23% better broadleaf weed control was observed 14 DAA in Illinois and Nebraska when AMS and COC were mixed with dicamba at 1,120 g ae ha^{-1} (Table 3; $P < 0.001$), or later in the season in Illinois 28 and 56 DAA when AMS and COC were mixed with dicamba at 840 g ae ha^{-1} (Table 4; $P < 0.001$). Results of this study were comparable with earlier studies where dicamba efficacy was initially improved with the addition of AMS. For instance, Roskamp et al. (2013) reported a 9% to 13% increase in common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.) control with the inclusion of AMS to dicamba. Late-season broadleaf weed control was not improved by mixing AMS with dicamba or dicamba/tembotrione in two out of the three states. Broadleaf weed control 56 DAA was improved by mixing AMS with dicamba at 840 g ae ha^{-1} in Illinois. Moreover, broadleaf weed control 56 DAA with a higher rate of dicamba or dicamba/tembotrione was similar to a lower rate of dicamba or dicamba/tembotrione with AMS and COC. This confirms that if AMS were to improve the efficacy of a lower rate of dicamba or dicamba/tembotrione, similar control can be achieved by using a higher rate of dicamba (in fallow croplands) or dicamba/tembotrione (in corn) without AMS. Hence, mixing AMS or its substitute with dicamba or dicamba/tembotrione may not serve its intended purpose of improving broadleaf weed control. In fact, adding AMS with dicamba products such as dicamba/tembotrione in corn may cause off-target injuries to nearby sensitive broadleaf crops that result from an increase in dicamba volatility. Sall et al. (2020) reported the highest volatility from dicamba field trials that included AMS. Further research is needed to confirm and quantify the vapor drift from corn fields where dicamba and dicamba/tembotrione should be applied with and without AMS.

Certain ammonium-based tank-mix partners such as AMS and dimethylamine salt of glyphosate can decrease the pH of dicamba solutions (Mueller and Steckel 2019; Striegel et al. 2021), thereby favoring the formation of volatile dicamba acid (Riter et al. 2021). Hence, the likelihood of dicamba volatility increases as more protons are available to form volatile dicamba acid as pH decreases. However, the change in pH of dicamba in a solution with AMS is reported to be slight (< 0.5 units) and depends on the dicamba formulation, application rate, tank-mix partner, water source, and initial pH (Mueller and Steckel 2019; Striegel et al. 2021). This could indicate that currently unknown mechanisms may be responsible for enhancing dicamba volatility (Hayden 2020). Although knowledge about the underlying mechanisms is incomplete, the potential for AMS to increase dicamba volatility is well documented (Hayden 2020; Latorre et al. 2017).

Broadleaf Weed Density and Biomass

In Nebraska, the density of *Amaranthus* spp. 14 DAA was decreased to 24 plants m^{-2} when AMS and COC were mixed to the higher rate of dicamba (1,120 g ae ha^{-1}) compared with 64 plants m^{-2} with dicamba without adjuvants (Table 5; $P < 0.001$). De Sanctis and Jhala (2021) and Barnes et al. (2020) reported that dicamba at 560 g ae ha^{-1} with AMS or Class Act Ridion along with other adjuvants (non-ionic surfactant and drift reduction agent i.e., Intact™; Precision Laboratories LLC, Waukegan, IL 60085) reduced velvetleaf density from 40 to 60 plants m^{-2} to 11 to 17 plants m^{-2} 14 DAA and from 83 plants m^{-2} to 5 plants m^{-2} 28 DAA, respectively. There were no differences in the density of *Amaranthus* spp. and biomass of broadleaf weeds across herbicide rates with or without AMS or AMS substitute 56 DAA in Illinois, Missouri, and Nebraska. Dicamba or dicamba/tembotrione, irrespective of rates or adjuvants, decreased the density of *Amaranthus* spp. from 32 to 37 plants m^{-2} to 0 to 3 plants m^{-2} compared to no-postemergence herbicide 56 DAA. Likewise, broadleaf weed biomass decreased from 68 g m^{-2} to 0 to 6 g m^{-2}. Similarly, Kumar et al. (2021) reported that dicamba at 560 g ae ha^{-1} reduced Palmer amaranth biomass from 242 to 47 g m^{-2} 42 DAA in postharvest wheat stubble in Kansas. Similarly, de Sanctis et al. (2021) reported that dicamba at 560 g ae ha^{-1} reduced Palmer amaranth density from 37 to 54 plants m^{-2} to 2 to 5 plants m^{-2} and biomass from 223 to 336 g m^{-2} to 16 to 24 g m^{-2} 21 DAA in Nebraska. Similar to the broadleaf weed control ratings, these results indicate that AMS did not improve broadleaf weed density or biomass suppression potential of dicamba or dicamba/tembotrione. No corn injury was observed in any treatment at any site location across three states (data not shown) despite dicamba (DiFlexx; diglycolamine salt of 3,6-dichloro-o-anisic acid) applied at higher rates. This might be because the product contains corn safener– cyprosulfamide (Anonymous 2020a).

Corn Yield

Corn yield differed among sites ($P < 0.001$); therefore, data are presented separately for each state (Table 6). In Illinois, corn yield was similar across herbicides, except for the no-postemergence control (9,237 kg ha^{-1}), which lost an average of 36% corn yield. Similarly, Vyn et al. (2006) reported 6% to 36% corn yield loss due to waterhemp interference when not controlled with dicamba at 600 g ae ha^{-1}. In Missouri, corn yield was not improved by mixing AMS and COC or Class Act Ridion regardless of the application rate of dicamba or dicamba/tembotrione. In Nebraska, no- postemergence herbicide control (13,136 kg ha^{-1}) had a similar corn yield to other treatments (12,381 to 14,655 kg ha^{-1}) because an additional postemergence herbicide application was made this site (Table 6). No corn yield differences were observed by mixing AMS with dicamba or dicamba/tembotrione because AMS was often not effective for improving broadleaf weed control (Table 3 and Table 4) or decreasing broadleaf weed density or biomass, especially later in the season (Table 5).

Practical Implications

The results of multi-state study suggest that AMS can be excluded from dicamba (DiFlexx in fallow croplands) and dicamba/tembotrione (DiFlexx DUO in corn) without reducing efficacy for broadleaf weed control, especially when applying at higher rates. Likewise, mixing AMS substitute (Class Act Ridion) with dicamba or dicamba/tembotrione did not improve late-season broadleaf weed control (28 and 56 DAA), except for one instance. Dicamba (DiFlexx) rates used in this study were greater than labeled for a single postemergence herbicide application in corn; however, these rates were within/equivalent to the maximum labeled rate (1,120 g ae ha^{-1}) for broadleaf weed control in fallow croplands (Anonymous 2020a). Therefore, observed broadleaf weed control with dicamba in this study applies to fallow croplands and needs to be evaluated for corn in the future at the rates labeled in corn.

Although AMS has been commonly used as a water conditioning agent for dicamba products labeled in corn, new dicamba products (Engenia, Tavium, and XtendiMax) labeled in dicamba-resistant soybean restrict the use of AMS (Anonymous 2020b; 2020c; 2021b). The experimental evidence of the potential role of AMS in dicamba volatilization (Hayden 2020; Latorre et al. 2017) supports the conclusion that AMS should not be added to dicamba products. In considering internal and external experimental evidence of dicamba volatilization with AMS and results of this study, Bayer Crop Science revised the label of dicamba (DiFlexx) and dicamba/tembotrione (DiFlexx DUO) and removed AMS from the list of spray additives that can be used in corn (Anonymous 2020a; 2021a). In contrast, other dicamba products [Banvel® [dimethylamine salt of dicamba (3,6-dichloro-o-anisic acid], Clarity® (diglycolamine salt of 3,6-dichloro-o-anisic acid), Status® (sodium salt of diflufenzopyr/sodium salt of dicamba)] labeled in corn have not yet made any change (Anonymous 2006; 2010; 2022). Dicamba off-target injuries are an ongoing issue, and hence, omitting AMS with dicamba will help to reduce at least one probable factor from the complex equation of dicamba off-target movement.

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Competing Interests

The authors declare none.

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Table 1: Soil and tillage description of experimental sites in Illinois, Missouri, and Nebraska.

Site and Year	Soil type	pH	Percent organic matter	Tillage type
Urbana, Illinois (2018)	Silty clay loam	5.8	3.4	Conventional
Champaign, Illinois (2019)	Silty clay loam	6.6	3.5	Conventional
Columbia, Missouri (2018-19)	Silt loam	5.8	2.1	No-till
Clay Center, Nebraska (2018-19)	Silt loam	6.5	3.0	No-till

Table 2: Plot description and dates of management practices for field experiments conducted in 2018 and 2019 in Illinois, Missouri, and Nebraska.

Site	Plot size	Corn seeding rate	Corn hybrid (relative maturity)		Corn planting date		Preemergence herbicide		Postemergence herbicide	
		seeds ha^{-1}	2018	2019	2018	2019	2018	2019	2018	2019
Illinois	3×4 m	86,000	DKC62-08RIB (112)	Pioneer 1197 AMXT (113)	April 28	May 17	April 29	May 17	May 29	June 12
Missouri	3×14 m	80,000	Pioneer P1151AM (111)	NK-1239 (112)	April 19	May 15	April 20	May 17	June 1	June 18
Nebraska	3×9 m	86,000	Pioneer P1197AM (113)	Pioneer P1197AM (113)	April 27	April 23	April 27	April 24	June 5	June 12

Table 3. Broadleaf weed control affected by dicamba (DiFlexx) and dicamba/tembotrione (DiFlexx DUO) applied with or without ammonium sulfate (AMS) 14 d after application in corn in field experiments conducted in Illinois, Missouri, and Nebraska in 2018 and 2019.[a-c]

			Amaranthus spp.		Common ragweed	Common cocklebur	Velvetleaf
Herbicide[a]	Rate	Adjuvants[d, e]	Illinois and Nebraska	Missouri	Missouri	Missouri	Illinois and Nebraska
	g ae or ai ha^{-1}				%		
Weed-free control (glyphosate + acetochlor)[b]	1,576 + 1,260	AMS + COC	96 (±1.1) a	88 (±4.5) b	96 (±1.8) a	99 (±0) a	99 (±0.3) a
Dicamba	840	-	84 (±2.9) bcd	94 (+- 3.6) ab	91 (±2.7) ab	97 (±1.5) b	87 (±3.4) abc
Dicamba	1,120	-	78 (±6.3) cd	97 (±1.1) a	94 (±2.2) ab	99 (±0.5) ab	73 (±12.7) c
Dicamba	840	AMS + COC	93 (±2.2) ab	96 (±1.9) a	85 (±12.1) b	99 (±0) a	93 (±3.3) ab
Dicamba	1,120	AMS + COC	92 (±2.0) ab	97 (±1.8) a	94 (±1.2) ab	99 (±0.5) ab	96 (±1.2) a
Dicamba	840	Class Act® Ridion®	75 (±6.5) d	95 (±2.4) a	94 (±2.3) ab	99 (±0.5) ab	75 (±13.1) bc
Dicamba	1,120	Class Act Ridion	89 (±2.4) abc	98 (±1.1) a	95 (±1.4) ab	99 (±0) a	94 (±2.3) ab
Dicamba/tembotrione	597	-	76 (±5.2) d	95 (±1.8) a	93 (±1.9) ab	98 (±0.8) ab	93 (±1.8) ab
Dicamba/tembotrione	746	-	80 (±4.2) cd	98 (±0.7) a	94 (±1.7) ab	98 (±1.1) ab	92 (±3.5) ab
Dicamba/tembotrione	597	AMS +	85 (±6.8) bc	92 (±3.5) a	90 (±2.1) a	99 (±0.5) a	84 ab

		COC		d		b		b		b	(±14.0)	c
Dicamba/tembotrione	746	AMS + COC	89 (±2.2)	abc	96 (±1.9)	a	93 (±2.4)	ab	99 (±0)	a	95 (±3.4)	a
Dicamba/tembotrione	597	Class Act Ridion	78 (±4.8)	d	93 (±2.1)	ab	92 (±1.2)	ab	98 (±0.7)	ab	95 (±2.5)	a
Dicamba/tembotrione	746	Class Act Ridion	78 (±3.6)	cd	98 (±1.1)	a	97 (±1.9)	a	99 (±0)	a	92 (±1.6)	ab
P-value			< 0.001		< 0.001		< 0.001		< 0.001		< 0.001	

[a] *S*-metolachlor was applied preemergence at 1,670 g ai ha^{-1} to the entire research site for early season residual weed control.

[b] The weed-free control received an additional preemergence application of atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron®; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,928 g ai ha^{-1} and postemergence application of glyphosate (Roundup® PowerMAX; Bayer Crop Science, St. Louis, MO) at 1,576 g ae ha^{-1} plus acetochlor (Warrant®; Bayer Crop Science, St. Louis, MO) at 1,260 g ai ha^{-1}.

[c] Means presented within each column with no common letter (s) are significantly different as per Fisher's Protected LSD test at $P \leq 0.05$.

[d] AMS: Liquid N PAK AMS 3% v/v; COC: 1% v/v; Class Act Ridion: Water conditioner plus NIS: 1% v/v.

[e] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; NIS, non-ionic surfactant.

Table 4. Broadleaf weed control affected by dicamba (DiFlexx) and dicamba/tembotrione (DiFlexx DUO) applied with or without ammonium sulfate (AMS) 28 and 56 d after application in corn in field experiments conducted in Illinois, Missouri, and Nebraska in 2018 and 2019.[a-c]

			28 DAA			56 DAA				
			Amaranthus spp.			*Amaranthus* spp.			Velvetleaf	
Herbicide[a]	Rate	Adjuvants[d, e]	Illinois	Missouri	Nebraska	2019[f] Illinois	2019[f] Missouri	Nebraska	2019[f] Illinois	Nebraska
	g ae or ai ha⁻¹		——————————————————— % ———————————————————							
Weed-free control (glyphosate + acetochlor)[b]	1,576 + 1,260	AMS + COC	96 (±1.9) a	89 (±4.5) b	99 (±0) a	99 (±0) a	74 (±3.8) b	99 (±0) a	99 (±0) a	99 (±0) a
Dicamba	840	-	82 (±4.8) bc	99 (±0) a	92 (±2.5) abc	83 (±6) c	99 (±0) a	99 (±0) a	85 (±5.0) cd	99 (±0) a
Dicamba	1,120	-	90 (±2.6) ab	99 (±0) a	83 (±11.9) bc	88 (±3.3) bc	99 (±0) a	99 (±0) a	87 (±4.4) bcd	99 (±0) a
Dicamba	840	AMS + COC	96 (±1.5) a	99 (±0) a	95 (±1.4) abc	98 (±1.3) ab	99 (±0) a	99 (±0) a	93 (±3) abc	99 (±0) a
Dicamba	1,120	AMS + COC	96 (±0.8) a	99 (±0) a	99 (±0.5) ab	98 (±1.3) ab	99 (±0) a	99 (±0) a	98 (±1.3) a	99 (±0) a
Dicamba	840	Class Act Ridion	78 (±4.4) bcd	98 (±1.1) a	82 (±11.8) c	85 (±5.0) c	99 (±0) a	99 (±0) a	80 (±5.0) d	99 (±0) a
Dicamba	1,120	Class Act Ridion	95 (±1.2) a	99 (±0) a	92 (±2.6) abc	99 (±0) a	99 (±0) a	99 (±0) a	93 (±4.2) abc	99 (±0) a
Dicamba/tembotrione	597	-	67 (±10.8) d	99 (±0) a	94 (±2.0) abc	92 (±3.3) abc	99 (±0) a	99 (±0) a	98 (±1.3) a	99 (±0) a

Dicamba/tembotrione	746	-	78 (±6.5)	bcd	99 (±0)	a	95 (±1.6)	abc	92 (±3.3)	abc	99 (±0)	a	99 (±0)	a	98 (±1.3)	a	99 (±0)	a
Dicamba/tembotrione	597	AMS + COC	96 (±2.3)	a	98 (±0.6)	a	80 (±11.7)	c	96 (±1.3)	ab	99 (±0)	a	99 (±0)	a	99 (±0)	a	99 (±0)	a
Dicamba/tembotrione	746	AMS + COC	95 (±4.0)	a	99 (±0)	a	94 (±2.0)	abc	98 (±1.3)	ab	99 (±0)	a	99 (±0)	a	99 (±0)	a	99 (±0)	a
Dicamba/tembotrione	597	Class Act Ridion	78 (±4.6)	bcd	97 (±1.8)	a	87 (±4.7)	abc	83 (±6.7)	c	99 (±0)	a	99 (±0)	a	98 (±1.3)	a	99 (±0)	a
Dicamba/tembotrione	746	Class Act Ridion	76 (±4.9)	cd	99 (±0)	a	92 (±2.7)	abc	85 (±5.8)	c	99 (±0)	a	99 (±0)	a	95 (±2.6)	ab	99 (±0)	a
P-value[e]			< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001		< 0.001	

[a] *S*-metolachlor was applied preemergence at 1,670 g ai ha^{-1} to the entire research site for early season residual weed control.

[b] The weed-free control received an additional preemergence application of a premix of atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,928 g ai ha^{-1} and postemergence application of glyphosate (Roundup PowerMAX; Bayer Crop Science, St. Louis, MO) at 1,576 g ae ha^{-1} plus acetochlor (Warrant; Bayer Crop Science, St. Louis, MO) at 1,260 g ai ha^{-1}..

[c] Means presented within each column with no common letter (s) are significantly different as per Fisher's Protected LSD test at $P \leq 0.05$.

[d] AMS: Liquid N PAK AMS 3% v/v; COC: 1% v/v; Class Act Ridion: Water conditioner plus NIS: 1% v/v.

[e] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; NIS, non-ionic surfactant.

[f] Data were collected for year 2019 only.

Table 5. Broadleaf weed density and biomass affected by dicamba (DiFlexx) and dicamba/tembotrione (DiFlexx DUO) applied with or without ammonium sulfate (AMS) 14, 28, and 56 d after application in corn in field experiments conducted in Illinois, Missouri, and Nebraska in 2018 and 2019.[a-c]

			Density					Biomass
			14 DAA		28 DAA	56 DAA		56 DAA
			Amaranthus spp.		*Amaranthus* spp.	*Amaranthus* spp.		Broadleaves
Herbicide[a]	Rate	Adjuvants[d, e]	Nebraska		Illinois, Missouri, and Nebraska	Illinois	Missouri and Nebraska	Nebraska
	g ae or ai ha^{-1}		——plants m^{-2}——					g m^{-2}
No-postemergence control	-	-	136 (±0)		53 (±11.2)	32 (±12.5)	37 (±12.5)	68 (±30.2)
Weed-free control (glyphosate + acetochlor)[b]	1,576 + 1,260	AMS + COC	0 (±0)	c	0 (±0)	0 (±0)	0 (±0)	9 (±6)
Dicamba	840	-	34 (±2.8)	ab	4 (±1.6)	3 (±0.5)	0 (±0)	3 (±1.7)
Dicamba	1,120	-	64 (±3.1)	a	8 (±4.5)	1 (±0.4)	0 (±0)	6 (±5.5)
Dicamba	840	AMS + COC	26 (±2.4)	bc	5 (±2.1)	0 (±0)	0 (±0)	1 (±0.3)
Dicamba	1,120	AMS + COC	24 (±2.6)	bc	3 (±1.3)	0 (±0)	0 (±0)	1 (±0.8)
Dicamba	840	Class Act Ridion	34 (±2.7)	ab	5 (±1.9)	0 (±0)	0 (±0)	1 (±0.5)
Dicamba	1,120	Class Act Ridion	38 (±2.5)	ab	4 (±1.7)	0 (±0)	0 (±0)	0 (±0)
Dicamba/tembotrione	597	-	50 (±2.3)	ab	4 (±2.9)	0 (±0)	0 (±0)	0 (±0.2)
Dicamba/tembotrione	746	-	54 (±5.2)	ab	2 (±1.1)	0 (±0)	0 (±0)	0 (±0)
Dicamba/tembotrione	597	AMS + COC	28 (±3.1)	bc	8 (±4.5)	0 (±0)	0 (±0)	1 (±0.7)
Dicamba/tembotrione	746	AMS + COC	44 (±3.4)	ab	3 (±1.6)	0 (±0)	0 (±0)	1 (±0.4)
Dicamba/tembotrione	597	Class Act Ridion	50 (±3.6)	ab	6 (±2.3)	0 (±0)	0 (±0)	0 (±0.2)

Dicamba/tembotrione	746	Class Act Ridion	52 (±2.1) ab	7 (±2.6)	0 (±0)	0 (±0)	2 (±2.0)
P-value [f]			<0.001	NS	NS	NS	NS

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[a] *S*-metolachlor was applied preemergence at 1,670 g ai ha^{-1} to the entire research site for early season residual weed control.

[b] Weed-free control received an additional preemergence application of a premix of atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,928 g ai ha^{-1} and a postemergence application of glyphosate (Roundup PowerMAX; Bayer Crop Science, St. Louis, MO) at 1,576 g ae ha^{-1} plus acetochlor (Warrant; Bayer Crop Science, St. Louis, MO) at 1,260 g ai ha^{-1}.

[c] Means presented within each column with no common letter(s) are significantly different as per Fisher's Protected LSD test at $P \leq 0.05$.

[d] AMS: Liquid N PAK AMS 3% v/v; COC: 1% v/v; Class Act Ridion: Water conditioner plus NIS: 1% v/v.

[e] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; NIS, non-ionic surfactant.

[f] Significance level: NS, non-significant.

Table 6. Corn yield affected by dicamba (DiFlexx) and dicamba/tembotrione (DiFlexx DUO) applied with or without ammonium sulfate (AMS) in corn in field experiments conducted in Illinois, Missouri, and Nebraska in 2018 and 2019.[a-c]

Herbicide[a]	Rate	Adjuvants[d, e]	Crop yield				
			Illinois[c]		Missouri[c]		Nebraska[c]
	g ae or ai ha^{-1}		kg ha^{-1}				
No-postemergence control	-		9,237 (±1,533)	b	7,268 (±602)	e	13,136 (±1,947)
Weed-free control (glyphosate + acetochlor)[b]	1,576 + 1,260	AMS + COC	15,436 (±1,204)	a	11,798 (±336)	a	14,289 (±2,661)
Dicamba	840		13,858 (±376)	a	10,093 (±477)	b	13,027 (±2,336)
Dicamba	1,120		14,249 (±655)	a	8,548 (±305)	cde	12,933 (±2,537)
Dicamba	840	AMS + COC	14,324 (±473)	a	9,297 (±473)	bcd	13,214 (±1,712)
Dicamba	1,120	AMS + COC	14,423 (±344)	a	8,329 (±974)	de	13,056 (±2,006)
Dicamba	840	Class Act Ridion	14,031 (±727)	a	9,376 (±324)	bcd	14,162 (±2,155)
Dicamba	1,120	Class Act Ridion	14,213 (±741)	a	9,184 (±506)	bcd	14,421 (±2,373)
Dicamba/tembotrione	597		15,301 (±715)	a	9,732 (±346)	bcd	14,417 (±2,208)
Dicamba/tembotrione	746		14,475 (±702)	a	10,114 (±373)	b	14,458 (±2,291)
Dicamba/tembotrione	597	AMS + COC	14,435 (±503)	a	8,372 (±524)	de	14,655 (±2,285)
Dicamba/tembotrione	746	AMS + COC	14,737 (±686)	a	8,937 (±282)	bcd	12,381 (±2,559)
Dicamba/tembotrione	597	Class Act Ridion	14,485 (±779)	a	10,190 (±489)	b	14,208 (±2,386)
Dicamba/tembotrione	746	Class Act Ridion	14,337 (±740)	a	9,807 (±617)	bc	13,981 (±2,103)
P-value[f]			< 0.001		< 0.001		NS

[a] *S*-metolachlor was applied preemergence at 1,670 g ai ha^{-1} to the entire research site for early season residual weed control.

[b] Weed-free control received an additional preemergence application of a premix of atrazine/bicyclopyrone/mesotrione/*S*-metolachlor (Acuron; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,928 g ai ha^{-1} and a postemergence application of glyphosate (Roundup PowerMAX; Bayer Crop Science, St. Louis, MO) at 1,576 g ae ha^{-1} plus acetochlor (Warrant; Bayer Crop Science, St. Louis, MO) at 1,260 g ai ha^{-1}.

[c] Means presented within each column with no common letter(s) are significantly different as per Fisher's Protected LSD test at $P \leq 0.05$.

[d] AMS: Liquid N PAK AMS 3% v/v; COC: 1% v/v; Class Act Ridion: Water conditioner plus NIS: 1% v/v.

[e] Abbreviations: AMS, ammonium sulfate; COC, crop oil concentrate; NIS, non-ionic surfactant.

[f] Significance level: NS, non-significant.