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Field Evaluation of Auxin Herbicide Volatility Using Cotton and Tomato as Bioassay Crops

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Research was conducted to compare cotton and tomato response to volatility of 2,4-D, dicamba, and triclopyr formulations. Herbicide treatments were applied to tilled soil during August and September, and potted plants were placed in the center of treated strips. To quantify injury, leaf cupping/crinkling/drooping; leaf rolling/strapping; stem epinasty; and stem swelling/cracking were each visually rated on an injury scale of 0 to 5 (0 = none, 1 = slight, 2 = slight to moderate, 3 = moderate, 4 = moderate to severe, and 5 = severe). Leaf cupping/crinkling/drooping injury averaged across herbicide treatments at 1× rates was 1.0 for cotton and 2.0 for tomato 14 d after treatment (DAT). Averaged across crops, leaf cupping/crinkling/drooping injury for the 1× rates 14 DAT was equivalent for the 2,4-D dimethylamine (DMA) salt, 2,4-D acid, dicamba DMA salt, dicamba diglycolamine (DGA) salt, dicamba acid, and triclopyr acid formulations and ranged from 1.1 to 1.8. For tomato, the only herbicide treatments with injury 14 DAT no greater than for the nontreated were 1× rates of 2,4-D DMA and 2,4-D acid for leaf rolling/strapping (1.0); 2,4-D acid, dicamba DMA, dicamba acid, and triclopyr acid for stem epinasty (0.3 to 0.7); and 2,4-D DMA, 2,4-D acid, dicamba DMA, dicamba DGA, dicamba acid, and triclopyr acid for stem swelling/cracking (0.1 to 0.2). A weighted factor assigned to each injury criterion provided an overall total injury estimate of 0 to 100%. When applied at 1× rates, total injury for 2,4-D isooctyl ester was 10% for cotton and 36% for tomato and for triclopyr butoxyethyl ester was 11% for cotton and 50% for tomato. For the 2,4-D DMA, 2,4-D acid, dicamba DMA, dicamba DGA, dicamba acid, and triclopyr acid formulations, total injury was 4 to 8% for cotton and 20 to 24% for tomato, and for both crops, injury was no greater than for the nontreated.

Nomenclature: 2,4-D, dicamba, triclopyr; cotton, *Gossypium hirsutum* (L.); tomato, *Solanum lycopersicum* (L.).

Key words: Herbicide-resistant crops, off-target movement, spray drift, visual rating system.

Se realizó una investigación para comparar la respuesta del algodón y el tomate a la volatilidad de formulaciones de 2,4-D, dicamba, y triclopyr. Los tratamientos de herbicidas fueron aplicados durante Agosto y Septiembre, a suelo labrado, y plantas en potes fueron puestas en el centro de las franjas tratadas con el herbicida. Para cuantificar el daño, se evaluó visualmente el acucharamiento/arrugamiento/caída de las hojas, el enrollamiento de las hojas, la epinastia del tallo, y el engrosamiento/aparición de fisuras en el tallo, usando una escala de daño para cada variable de 0 a 5 (0 = nada, 1 = poco, 2 = poco a moderado, 3 = moderado, 4 = moderado a severo, y 5 = severo). El daño acucharamiento/arrugamiento/caída de hojas promediando los tratamientos de herbicidas a dosis de 1× fue 1.0 para algodón y 2.0 para tomate 14 d después del tratamiento (DAT). Promediando los cultivos, este mismo tipo de daño para dosis de 1× 14 DAT, fue equivalente para las formulaciones de sal de 2,4-D dimethylamine (DMA), ácido de 2,4-D, sal de dicamba DMA, sal de dicamba diglycolamine (DGA), ácido de dicamba, y ácido de triclopyr, y varió entre 1.1 y 1.8. En el tomate, los únicos tratamientos de herbicidas que tuvieron un daño que no fue mayor al testigo sin tratamiento a 14 DAT, fueron dosis 1× de 2,4-D DMA y ácido de 2,4-D, para el daño de enrollamiento de hojas (1.0); ácido de 2,4-D, dicamba DMA, ácido de dicamba, y ácido de triclopyr, para el daño de epinastia de tallo (0.3 a 0.7); y 2,4-D DMA, ácido de 2,4-D, dicamba DMA, dicamba DGA, ácido de dicamba, y ácido de triclopyr para el daño de engrosamiento del tallo (0.1 a 0.2). Un factor ponderado asignado para cada criterio de daño brindó un estimado general del total de daño de 0 a 100%. Cuando se aplicó la dosis de 1×, el daño total de 2,4-D isooctyl ester fue 10% para algodón y 36% para tomate, y para triclopyr butoxyethyl ester fue 11% para algodón y 50% para tomate. Para las formulaciones de 2,4-D DMA, ácido de 2,4-D, dicamba DMA, dicamba DGA, ácido de dicamba, y ácido de triclopyr, el daño total fue 4 a 8% para algodón y 20 a 24% para tomate, y para ambos cultivos, el daño no fue superior al del testigo sin tratamiento.

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Introduction of glyphosate-resistant crops in the mid-1990s allowed growers to effectively manage problem weeds that had limited production in the past. Continuous long-term use of glyphosate, however, has selected for glyphosate-resistant weeds (Heap 2014). Novel weed management systems to address herbicide-resistant weed management are currently under investigation. Soybean (*Glycine max* L. Merr.) and cotton cultivars are being developed with a trait that confirms resistance to dicamba (Roundup Ready Xtend Crop System; Monsanto Co., St. Louis, MO) (Arnevik et al. 2014). Crop tolerance is achieved through enzyme deactivation of dicamba to the nonherbicidal 3,6-dichloro salicylic acid. A herbicide premix will be marketed containing monoethanolamine glyphosate and the diglycolamine (DGA) salt of dicamba as well as a standalone product containing the DGA dicamba salt, each containing a proprietary technology that reduces dicamba DGA volatility compared with other formulations (MacInnis et al. 2014). Dicamba as a BAPMA [*N*,*N*-bis-(aminopropyl)methylamine], a tridentate amine salt that provides strong and effective binding of dicamba spray residues to suppress volatilization (Xu et al. 2012), will also be available for use with the dicamba-resistant crop technology. Additionally, several crops including soybean will contain a trait that confers 2,4-D resistance (Enlist Weed Control System; Dow AgroSciences, Indianapolis, IN) (Skelton et al. 2014). Crop resistance is achieved through insertion of the *aad-12* gene, which encodes a bacterial aryloxyalkanoate dioxygenase enzyme allowing transgenic plants to metabolize 2,4-D rapidly to dichlorophenol. A herbicide premix will be marketed that contains glyphosate and 2,4-D choline, a quaternary ammonium salt with reduced volatility (Perry et al. 2013).

All herbicides are susceptible to off-target movement through physical drift of the liquid spray solution. Wind speed, spray pressure, and nozzle height above the intended target are primary contributors to herbicide drift (Hatterman-Valenti et al. 1995). Off-target movement of some herbicides can also occur through volatility. Que Hee and Sutherland (1974) stated that when considering off-target movement of 2,4-D, volatilization would contribute two to three orders of magnitude less than spray (physical) drift. They also reported that vapor drift of 2,4-D could be essentially eliminated by use of amine salts. Dicamba volatilization losses for the unformulated acid of 29% occurred during 7 d at 35 C (Burnside and Lavy 1966). Baur et al. (1973) reported 58% loss of 2,4-D acid during 4 d at 30 C. Behrens and Lueschen (1979) reported 92% of dicamba acid had volatilized at 12 h compared with 43% for the dimethylamine (DMA) salt. In a field study in which potted soybean was placed in corn (*Zea mays* L.) treated with dicamba DMA salt, significant soybean injury from volatility was observed for 3 d after application. Symptoms caused by dicamba vapors were observed on soybean placed up to 60 m downwind of treated corn. Use of less volatile dicamba salt formulations, diethanolamine and tallow amine, did not eliminate dicamba injury symptoms on soybean. Vapor injury in the field was due to degradation of the DMA salt to free dicamba acid.

Egan and Mortensen (2012) in a field study detected vapor drift of dicamba DMA salt at a mean concentration of 0.56 g ae ha^{-1} 21 m away from the treated plot. The extent and severity of vapor drift for the DMA salt was positively correlated with air temperature and relative humidity at time of application. Vapor drift was reduced for the dicamba DGA formulation compared with the DMA but was not eliminated. In a study to evaluate cotton response to volatility of 2,4-D, potted plants left in the field for 48 h after application at 2.2 kg ae ha^{-1} were injured less than 2% when placed 1.5 and 3 m from where the amine salt formulation was applied, and visual injury was not detected with the choline salt at either distance (Sosnoskie et al. 2012). Cotton injury due to volatility of 2,4-D ester was 57% when placed 3 m from the treated area. In another study, 2,4-D and dicamba–treated soil in greenhouse flats watered to field capacity was placed between rows of cotton and soybean to evaluate volatility (Hayden et al. 2013). Within 0.9 m of the treated soil, cotton injury was 12 to 15% for 2,4-D ester compared with no more than 3% for 2,4-D choline and 2,4-D amine. Differences in soybean injury due to volatility were not observed among the 2,4-D ester, 2,4-D amine, and 2,4-D choline formulations and injury was equal to the nontreated. In research to compare volatility of the proprietary blend of DGA salt of dicamba with monoethanolamine salt of glyphosate, which included VaporGrip technology (Monsanto Co., St.

Louis, MO), and dicamba DMA salt plus potassium salt of glyphosate, differences in soybean and cotton plant height and yield were not observed when compared with the nontreated (Hayden et al. 2014).

In an attempt to quantify volatility and to model herbicide rate vs. injury, extreme variability in plant response to 2,4-D, dicamba, and triclopyr was observed for data collected before 14 d after treatment (DAT), and data were more variable in the field than the greenhouse (Sciumbato et al. 2004b). For the field study, injury to cotton from volatilization was greater for 2,4-D DMA than for dicamba DGA, but both herbicides were less volatile than triclopyr butoxyethyl ester.

Future use of 2,4-D and dicamba in herbicide-resistant crops should offer viable weed management alternatives. Although physical drift of auxin herbicides can cause significant injury and yield losses (Griffin et al. 2013; Johnson et al. 2012), there is also concern as to potential off-target movement from herbicide volatility. For the dicamba and 2,4-D–resistant crop technologies currently under development, it is uncertain as to whether dicamba formulations other than the DGA and tridentate amine salts and 2,4-D formulations other than the choline salt will be allowed for in-crop use. The objectives of this research were to compare volatility of various formulations of 2,4-D, dicamba, and triclopyr under field conditions using cotton and tomato as bioassay crops and to develop and evaluate a visual rating system to quantify overall injury based on injury criteria associated with exposure to auxin herbicides.

Material and Methods

Research was conducted at the Louisiana State University (LSU) AgCenter Central Research Station, Ben Hur Research Farm in Baton Rouge, LA, to evaluate cotton and tomato response to volatility of various formulations of 2,4-D, dicamba, and triclopyr. Cotton and tomato seeds were planted in 15-cm pots in the greenhouse and after emergence were thinned to one plant per pot. Plants were fertilized weekly with 15 : 30 : 15 ($N : P_2O_5 : K_2O$) (Scotts Miracle-Gro Products Inc., Marysville, OH) until cotton had three to six leaves and tomato had 3 to 10 leaves. The variability in leaf size coincided with when field and weather conditions were conducive to experiment initiation. Plants were moved from the greenhouse to the research farm 5 d before application and were watered as needed to allow plants time to acclimate. In fields planted to corn or in noncrop fallowed areas, strips 4.6 m wide and 46 m long were mowed, disked, and smoothed. Untilled 4.6-m-wide border areas with corn or weeds present on each side of the tilled strips served as buffers. Soil type was a Mhoon silt loam (fine, silty, mixed, nonacid, thermic Typic Fluvaquent) with pH 6.3 and 1.9% organic matter. The 2,4-D formulations isooctyl ester (Weedone LV4, Nufarm Inc., Burr Ridge, IL), DMA salt (Weedar 64, Nufarm Inc.), and acid (Unison, Helena Chemical Company, Collierville, TN) at 1,120 (1×) and 2,240 (2×) g ae ha^{-1}; the dicamba formulations DMA salt (Banvel, Arysta LifeScience North America LLC, Cary, NC), DGA salt (Clarity, BASF Corporation, Research Triangle Park, NC), and acid (Vision, Helena Chemical Company) at 560 (1×) and 1,120 (2×) g ae ha^{-1}; and the triclopyr formulations butoxyethyl ester (Garlon, Dow AgroSciences LLC, Indianapolis, IN) and acid (Trycera, Helena Chemical Company) at 1,680 (1×) and 3,360 (2×) g ae ha^{-1} were applied in the center of each tilled strip to an area 1.8 m wide. A CO_2-pressurized backpack sprayer equipped with 11002 XR flat fan nozzles (TeeJet Technologies, Wheaton, IL) and calibrated to deliver 140 L ha^{-1} spray volume at 166 to 207 kPA was used. A nontreated tilled strip was included for comparison. After each herbicide treatment was applied, spray hoses and spray boom were flushed with a 2% solution of ammonia and water. Knee-high rubber boots worn by the applicator were rinsed with the ammonia solution to avoid cross-contamination. Wind speed at application was no more than 3.2 km h^{-1}.

Because of the size of the experimental area needed, the 1× and 2× rates were evaluated separately and each run represented a single replication. For the 1× rate tests, herbicide treatments were applied August 9, 2010, August 25, 2011, August 9, 2012, and September 20, 2012. Herbicide treatments for the 2× rates were applied September 13, 2010, September 27, 2011, August 9, 2012, and September 20, 2012. Applications for both the 1× and 2× tests were made between 8 and 9 A.M. Data for rainfall before herbicide application

Table 1. Rainfall before herbicide application and average air and soil temperature and relative humidity at herbicide application for the volatility study evaluating 1× and 2× herbicide rates.

Application date	Rainfall before application	Average air temperature	Average soil temperature	Average relative humidity
	mm	C	C	%
August 9, 2010 (1× rate)	44 within 4 d	24	31	96
September 13, 2010 (2× rate)	13 within 7 d	22	33	83
August 25, 2011 (1× rate)	21 within 7 d	26	33	86
September 27, 2011 (2× rate)	13 within 9 d	26	29	86
August 9, 2012 (1×, 2× rates)	36 within 9 d	28	27	88
September 20, 2012 (1×, 2× rates)	34 within 4 d	21	21	87

and average air and soil temperature and relative humidity at herbicide application are presented in Table 1. Total rainfall, average minimum/maximum air and soil temperature, and relative humidity for the period 0 to 4 d after herbicide application for each of the runs are presented in Table 2.

One hour was allowed to pass after herbicide applications so that spray droplets would disperse and any herbicide effects on the indicator plants could be attributed to volatilization (Sciumbato et al. 2004b). As soon as the hour had elapsed, an all-terrain vehicle (ATV) equipped with a side-mounted platform traveled in the nontreated area adjacent to each treated strip, and 15 by 15 cm ceramic tiles were placed on the soil surface 1.5 m apart in the center of each treated strip. During the same operation, pots containing cotton and tomato were placed alternately on top of the tiles to prevent direct contact with the soil. Depending on the run, 10 to 15 pots of cotton and tomato were present in each of the treated and nontreated strips. Because of limited soil moisture (Tables 1 and 2) plants were watered by hand using the ATV for the runs on September 13, 2010 and August 25, 2011. At 4 DAT plants were removed from the field and placed under a 30% shade cloth enclosure with overhead irrigation.

For each individual pot, plants were visually rated 1 and 2 DAT in the field with care taken to avoid foot traffic in treated strips. Ratings at 7 and 14 DAT were made under the shade enclosure. Injury was quantified using the following criteria from least severe to most severe: (1) leaf cupping/crinkling (irregular leaf surface)/drooping (petiole droop), (2) leaf rolling/strapping, (3) stem epinasty, and (4) stem base swelling/cracking. These criteria were selected because they encompass the range of injury symptoms that would be expected from plants exposed to phenoxy, benzoic acid, and pyridine carboxylic herbicides (Griffin et al. 2013; Johnson et al. 2012; Sciumbato et al. 2004a). Because the level of injury among the herbicides would be expected to vary based on rate and crop, severity of injury for each of the criterion was based on a scale of injury ranging from 0 to 5, with 0 = none, 1 = slight, 2 = slight to moderate, 3 = moderate, 4 = moderate to severe, and 5 = severe. To obtain total injury for the herbicide treatments, the injury criteria were weighted as follows: leaf cupping/crinkling/drooping = 2, leaf rolling/strapping = 4, stem epinasty = 6, and stem swelling/

Table 2. Rainfall, average minimum (min.) and maximum (max.) air and soil temperatures, and average relative humidity 0–4 d after herbicide application (DAA) for the volatility study evaluating 1× and 2× herbicide rates.

Application date	Rainfall within 4 DAA	Average min./max. air temperature	Average min./max. soil temperature	Average min./max. relative humidity
	mm	C	C	%
August 9, 2010 (1× rate)	42	24/33	29/35	54/94
September 13, 2010 (2× rate)	0	19/33	28/36	35/94
August 25, 2011 (1× rate)	0	22/35	29/36	33/90
September 27, 2011 (2× rate)	19	17/29	24/30	41/93
August 9, 2012 (1×, 2× rates)	27	23/32	27/31	55/95
September 20, 2012 (1×, 2× rates)	0	17/31	23/31	40/95

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cracking = 8. The weighted values were chosen to represent the minimal effect that might occur, for example, from slight cupping of leaves to most detrimental injury associated with stem epinasty (Sciumbato et al. 2004a) and cracking. Assuming a maximum severity injury of 5 for all injury criteria and weighting each accordingly would result in total injury of 100%.

For this study, the sprayed strips of each herbicide and rate served as experimental units/plots and the four runs served as replications for each experiment. Crop response data collected on the cotton and tomato plants within each plot were considered subsamples. Crop response data within each herbicide/rate experiment were subjected to ANOVA using the MIXED procedure of SAS/STAT software (SAS Institute Inc., Cary, NC). Four runs of each experiment were considered four replications and were treated as a random effect. Plant species and herbicides were considered fixed effects and were tested for significance at alpha = 0.05. The residuals were tested for normality using UNIVARIATE procedure of SAS/STAT software (SAS Institute Inc., Cary NC) and homogeneity of residuals was inspected graphically. Because residuals were not normally distributed, data were subjected to square root transformation to normalize the residuals. LSD ($P \leq 0.05$) was used for mean separation and letter groupings were generated on nontransformed data using the PDMIX800 macro in SAS/STAT software (Saxton 1998).

Results and Discussion

For each of the runs when herbicides were applied at the 1× and 2× rates, the soil surface was slightly moist because of a light to heavy dew. Rainfall of at least 13 mm was received within 9 d preceding application (Table 1). For the 1× run in 2010 and for the 1× and 2× runs in September 2012, rainfall of 44 and 34 mm, respectively, was received 4 d before application. Average air temperature and soil temperature at application ranged from 21 to 28 C and from 21 to 33 C, respectively (Table 1). Relative humidity at application ranged from 83 to 96% (Table 1).

For the 0- to 4-d period after herbicide application and before plants were removed from the field, rainfall of 42, 19, and 27 mm was received for the 1× run in 2010, the 2× run in 2011, and the 1× and 2× runs in August 2012, respectively (Table 2). Rainfall was not received during the 4-d period after application for the other runs. Maximum air temperature for the 0- to 4-d period for the runs ranged from 29 to 35 C, and maximum soil temperature ranged from 30 to 36 C. Maximum relative humidity was 90 to 95%. Behrens and Lueschen (1979) reported that temperature and relative humidity at application can affect dicamba volatility. Rainfall after dicamba application can greatly reduce subsequent volatilization.

Leaf Cupping/Crinkling/Drooping Injury. For each of the ratings at 1, 2, 7, and 14 DAT significant plant type (cotton and tomato) and herbicide treatments effects were observed for both 1× and 2× rates, but the plant type by herbicide interactions were not significant (Table 3). Averaged across herbicide treatments, severity of injury on a scale of 0 to 5, with 0 = none, 1 = slight, 2 = slight to moderate, 3 = moderate, 4 = moderate to severe, and 5 = severe, was greater for tomato than for cotton at all ratings and at both rates (Table 4). For 1× rates, average cotton injury increased from 0.1 at 1 DAT to 0.3 at 2 DAT and by 14 DAT was 1.0. Injury to tomato at 1× rates increased from 0.7 at 1 DAT to 2.0 at 14 DAT. For the 2× rates, cotton and tomato injury 1 DAT averaged 0.2 and 1.7, respectively, and by 14 DAT, injury for tomato averaged around twice that of cotton (2.9 vs. 1.4, respectively).

Averaged across cotton and tomato, leaf cupping/crinkling/drooping injury 1 DAT was greatest at both 1× and 2× rates for 2,4-D ester (0.8 and 1.9, respectively) and for triclopyr ester (1.4 and 2.4, respectively) (Table 4). Injury for the other herbicide treatments 1 DAT was no more than 0.3 for the 1× rates and 0.8 for the 2× rates. By 2 DAT differences among the herbicide treatments were more apparent. For the 1× rate, injury for 2,4-D ester averaged 1.4 and was equal to 2,4-D DMA (1.0) but was greater than for 2,4-D acid (0.5). For the 2× rate, injury 2 DAT for 2,4-D ester averaged 2.7 and was greater than for the 2,4-D DMA and acid formulations; injury was less for 2,4-D acid compared with the DMA (0.6 vs. 1.4). For the 1× and 2× rates, injury 2 DAT for the dicamba formulations was equivalent and ranged from 0.8 to 1.3. Triclopyr ester injury 2 DAT averaged 1.8 for the 1× rate and 2.9 for the 2× rate, and for both rates, injury was greater than for triclopyr acid (0.7

Table 3. Results of analysis of variance for the effect of plant type, herbicide, and plant type × herbicide interaction for four injury criteria (0–5 rating scale) and total injury (0–100%) 1, 2, 7, and 14 d after treatment (DAT) for 1× and 2× herbicide rates.[a]

		Injury criteria				
Data collection	Source of variation	Leaf cupping/crinkling/drooping	Leaf rolling/strapping[b]	Stem epinasty[b]	Stem swelling/cracking[b]	Total injury[c]
DAT		P value				
1× Rate						
1	Plant type (cotton, tomato)	< 0.0001	—	—	—	< 0.0001
	Herbicide (9 treatments)	< 0.0001	0.0211	0.0684	—	0.0007
	Plant type by herbicide	0.3468	—	—	—	0.0028
2	Plant type (cotton, tomato)	< 0.0001	—	—	—	< 0.0001
	Herbicide (9 treatments)	0.0014	0.0461	0.0004	—	0.0003
	Plant type by herbicide	0.4599	—	—	—	0.0003
7	Plant type (cotton, tomato)	< 0.0001	—	—	—	< 0.0001
	Herbicide (9 treatments)	0.0030	0.0470	0.0005	0.2128	0.0004
	Plant type by herbicide	0.1643	—	—	—	0.0144
14	Plant type (cotton, tomato)	< 0.0001	—	—	—	< 0.0001
	Herbicide (9 treatments)	0.0006	0.0589	0.0019	0.0210	0.0001
	Plant type by herbicide	0.0742	—	—	—	0.0475
2× Rate						
1	Plant type (cotton, tomato)	< 0.0001	—	—	—	< 0.0001
	Herbicide (9 treatments)	0.0003	0.0015	0.0010	—	0.0003
	Plant type by herbicide	0.3076	—	—	—	0.0002
2	Plant type (cotton, tomato)	< 0.0001	—	—	—	< 0.0001
	Herbicide (9 treatments)	< 0.0001	0.0032	< 0.0001	0.1012	< 0.0001
	Plant type by herbicide	0.6854	—	—	—	0.0001
7	Plant type (cotton, tomato)	< 0.0001	—	—	—	< 0.0001
	Herbicide (9 treatments)	< 0.0001	0.0018	< 0.0001	< 0.0001	< 0.0001
	Plant type by herbicide	0.8200	—	—	—	0.0002
14	Plant type (cotton, tomato)	< 0.0001	—	—	—	< 0.0001
	Herbicide (9 treatments)	< 0.0001	0.0028	0.0003	< 0.0001	< 0.0001
	Plant type by herbicide	0.8729	—	—	—	0.0002

[a] Plant type included cotton and tomato and herbicides included 2,4-D isooctyl ester, dimethylamine salt, and acid; dicamba dimethylamine salt, diglycolamine salt, and acid; and triclopyr butoxyethyl ester and acid formulations applied at 1× and 2× rates.

[b] Leaf rolling/strapping, stem epinasty, and stem swelling/cracking injury were not observed for cotton at any of the rating dates; P values are representative for only tomato.

[c] Total injury P values include cotton data for only the leaf cupping/crinkling/drooping injury.

and 1.3 for 1× and 2× rates, respectively). By 14 DAT, injury with 2,4-D ester averaged 2.1 for the 1× rate and 3.1 for the 2× rate. Injury observed for the 2,4-D DMA and acid formulations at both rates was equivalent and less than for the ester at the 2× rate. Injury 14 DAT was equivalent for the dicamba DMA, DGA, and acid formulations and ranged from 1.1 to 1.8 for the 1× rate and 2.0 to 2.1 for the 2× rate. For triclopyr ester, injury 14 DAT averaged 2.5 for the 1× rate and 3.1 for the 2× rate, and injury was at least 1.6 times that of the triclopyr acid formulation.

Although buffer areas were present between herbicide-treated strips, and hygienic procedures were followed during and after application, slight to moderate leaf cupping/crinkling/drooping injury was observed for both cotton and tomato in nontreated strips (Table 4). When 2× herbicide rates were applied, injury 14 DAT for the nontreated averaged 0.5 for cotton and 1.7 for tomato. This response was not unexpected since some of the herbicides are highly volatile and the buffer strips would not be expected to eliminate cross-contamination completely. Variability in evaluating volatility in field trials can also be attributed to external

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Table 4. Cotton and tomato leaf cupping/crinkling/drooping injury (0–5 scale) and their means (Avg.) associated with volatility of 2,4-D, dicamba, and triclopyr formulations applied at 1× and 2× rates to bare soil and evaluated 1, 2, 7, and 14 d after treatment (DAT).[a]

			Leaf cupping/crinkling/drooping injury (0–5)[b]											
			1 DAT			2 DAT			7 DAT			14 DAT		
Treatment	Formulation	Rate	Cotton	Tomato	Avg.	Cotton	Tomato	Avg.	Cotton	Tomato	Avg.	Cotton	Tomato	Avg.
1× Rate														
2,4-D	Ester	1×	0.6	1.1	0.8 ab[c]	1.1	1.7	1.4 ab	1.3	2.0	1.6 ab	2.2	2.0	2.1 ab
2,4-D	DMA	1×	0.0	0.3	0.1 c	0.5	1.5	1.0 bc	0.8	1.8	1.3 abc	1.7	1.8	1.7 abc
2,4-D	Acid	1×	0.0	0.4	0.1 c	0.1	1.2	0.5 cd	0.2	1.7	0.8 cd	0.5	1.8	1.1 cd
Dicamba	DMA	1×	0.1	0.7	0.3 bc	0.2	1.7	0.8 bc	0.4	1.9	1.0 bcd	0.8	1.9	1.3 bcd
Dicamba	DGA	1×	0.0	0.6	0.2 c	0.5	1.7	1.1 abc	0.8	1.9	1.3 abc	1.6	2.1	1.8 abc
Dicamba	Acid	1×	0.0	0.3	0.1 c	0.3	1.5	0.8 bc	0.6	1.2	0.9 cd	1.0	1.2	1.1 cd
Triclopyr	Ester	1×	0.3	3.3	1.4 a	0.7	3.6	1.8 a	0.8	3.6	2.0 a	1.6	3.7	2.5 a
Triclopyr	Acid	1×	0.0	0.5	0.1 c	0.2	1.6	0.7 bc	0.5	2.0	1.1 abc	0.6	2.4	1.4 bcd
Nontreated	—	—	0.0	0.2	0.1 c	0.0	0.4	0.1 d	0.0	1.4	0.5 d	0.2	1.5	0.7 d
Average			0.1 b[c]	0.7 a	—	0.3 b	1.6 a	—	0.5 b	1.9 a	—	1.0 b	2.0 a	—
2× Rate														
2,4-D	Ester	2×	1.3	2.7	1.9 ab	1.9	3.7	2.7 a	2.1	3.8	2.9 a	2.5	3.8	3.1 a
2,4-D	DMA	2×	0.1	1.4	0.5 cd	0.6	2.4	1.4 b	0.8	2.8	1.7 bc	1.2	2.9	1.9 b
2,4-D	Acid	2×	0.0	1.2	0.4 cd	0.1	1.7	0.6 c	0.4	2.2	1.1 cd	1.0	2.3	1.6 bc
Dicamba	DMA	2×	0.0	1.8	0.6 cd	0.5	2.5	1.3 b	0.9	3.0	1.8 b	1.3	3.1	2.1 b
Dicamba	DGA	2×	0.1	1.8	0.7 c	0.6	2.4	1.3 b	1.2	2.7	1.9 b	1.4	2.8	2.1 b
Dicamba	Acid	2×	0.0	1.6	0.5 cd	0.5	2.4	1.2 b	1.0	2.7	1.7 bc	1.5	2.7	2.0 b
Triclopyr	Ester	2×	1.5	3.5	2.4 a	2.0	3.9	2.9 a	2.2	3.9	3.0 a	2.3	3.9	3.1 a
Triclopyr	Acid	2×	0.1	2.1	0.8 bc	0.4	2.7	1.3 b	0.8	2.9	1.7 bc	1.0	3.0	1.9 b
Nontreated	—	—	0.1	0.2	0.1 d	0.1	1.2	0.5 c	0.2	1.6	0.7 d	0.5	1.7	1.0 c
Average			0.2 b	1.7 a	—	0.6 b	2.5 a	—	1.0 b	2.8 a	—	1.4 b	2.9 a	—

[a] Herbicide rates (1× and 2×) were 1,120 and 2,240 g ae ha^{-1} for 2,4-D isooctyl ester (Ester), dimethylamine salt (DMA), and acid formulations (Acid); 560 and 1,120 g ae ha^{-1} for dicamba dimethylamine salt (DMA), diglycolamine salt (DGA), and acid formulations; and 1,680 and 3,360 g ae ha^{-1} for triclopyr butoxyethyl ester (Ester) and acid formulations.

[b] Severity of injury based on a scale of 0 = none; 1 = slight; 2 = slight to moderate; 3 = moderate; 4 = moderate to severe; 5 = severe.

[c] Herbicide means (averaged across plant types) and plant type effects (averaged across herbicide treatments) followed by the same letter are not significantly different using LSD at $P \leq 0.05$.

Table 5. Tomato leaf rolling/strapping injury (0–5 scale) associated with volatility of 2,4-D, dicamba, and triclopyr formulations applied at 1× and 2× rates to bare soil and evaluated 1, 2, 7, and 14 d after treatment (DAT).[a]

Treatment	Formulation	Rate	Leaf rolling/strapping (0–5)[b]			
			1 DAT	2 DAT	7 DAT	14 DAT
1× Rate						
2,4-D	Ester	1×	0.3 b[c]	0.9 abc	1.2 ab	1.4 ab
2,4-D	DMA	1×	0.2 b	0.6 bc	0.9 bc	1.0 bc
2,4-D	Acid	1×	0.2 b	0.5 bc	0.9 bc	1.0 bc
Dicamba	DMA	1×	0.3 b	0.6 bc	1.4 ab	1.4 ab
Dicamba	DGA	1×	0.3 b	0.9 abc	1.5 ab	1.5 ab
Dicamba	Acid	1×	0.2 b	1.1 ab	1.4 ab	1.5 ab
Triclopyr	Ester	1×	1.3 a	1.7 a	1.9 a	2.0 a
Triclopyr	Acid	1×	0.2 b	0.6 bc	1.2 ab	1.4 ab
Nontreated	—	—	0.1 b	0.3 c	0.6 c	0.7 c
2× Rate						
2,4-D	Ester	2×	1.6 ab	2.6 ab	3.0 ab	3.1 ab
2,4-D	DMA	2×	0.2 c	1.0 cd	2.1 bc	2.2 bc
2,4-D	Acid	2×	0.2 c	0.4 d	1.6 c	1.7 cd
Dicamba	DMA	2×	0.6 bc	1.1 bcd	2.4 abc	2.5 abc
Dicamba	DGA	2×	0.4 bc	0.9 cd	2.3 abc	2.4 abc
Dicamba	Acid	2×	0.5 bc	1.8 abc	2.5 abc	2.6 abc
Triclopyr	Ester	2×	2.9 a	3.1 a	3.4 a	3.7 a
Triclopyr	Acid	2×	0.4 bc	1.2 bcd	2.2 bc	2.2 bc
Nontreated	—	—	0.0 c	0.3 d	0.7 d	0.9 d

[a] Herbicide rates (1× and 2×) were 1,120 and 2,240 g ae ha^{-1} for 2,4-D isooctyl ester (Ester), dimethylamine salt (DMA), and acid formulations (Acid); 560 and 1,120 g ae ha^{-1} for dicamba dimethylamine salt (DMA), diglycolamine salt (DGA), and acid formulations; and 1,680 and 3,360 g ae ha^{-1} for triclopyr butoxyethyl ester (Ester) and acid formulations.

[b] Severity of injury based on a scale of 0 = none; 1 = slight; 2 = slight to moderate; 3 = moderate; 4 = moderate to severe; 5 = severe.

[c] Herbicide means for each rate/rating date followed by the same letter are not significantly different using LSD at $P \leq 0.05$.

factors such as wind, relative humidity, and temperature (Behrens and Lueschen 1979; Egan and Mortensen 2012; Xu et al. 2012).

Leaf Rolling/Strapping Injury. For the 1× and 2× herbicide rates, leaf rolling/strapping injury due to volatility of the herbicide treatments was not observed for cotton, but significant herbicide effects were noted for tomato (Table 3). Injury 1 DAT (0 to 5 scale) for the 1× herbicide treatments was greatest for triclopyr ester (1.3) and no more than 0.3 for the other treatments (Table 5). Injury was equivalent at all ratings for the 2,4-D and dicamba formulations at the 1× rates and was as high as 1.5 14 DAT. Although injury for triclopyr at the 1× rate was greater for the ester compared with the acid formulation 1 and 2 DAT, differences between the formulations were not observed 7 and 14 DAT.

For 2× rates, tomato leaf rolling/strapping injury for 2,4-D ester increased from 1.6 at 1 DAT to 3.1 at 14 DAT (Table 5). Injury for 2,4-D ester was equivalent to that of 2,4-D DMA and the dicamba formulations 14 DAT but greater than that for 2,4-D acid. For the dicamba DMA, DGA, and acid formulations at the 2× rate, injury did not differ at any of the ratings. For triclopyr ester at the 2× rate, injury 14 DAT was 3.7, 1.7 times that of triclopyr acid. For both rates of triclopyr acid 14 DAT, injury was no greater than for the 2,4-D or dicamba formulations. The only herbicide treatment with injury 14 DAT at both rates no greater than the nontreated was the 2,4-D acid formulation.

Stem Epinasty Injury. Stem epinasty injury was not observed for cotton, but herbicide effects were noted for tomato (Table 3). For tomato, stem epinasty 1 DAT (0 to 5 scale) for herbicide treatments at 1× rates was no greater than for the nontreated (Table 6). At 2 and 7 DAT, injury for only 2,4-D ester and triclopyr ester at 1× rates was greater than for the nontreated. At 14 DAT, injury for 2,4-D ester was 2.5 for the 1× rate, equivalent to 2,4-D DMA but greater than for 2,4-D acid. At the 2× rates 14 DAT, injury for the 2,4-D DMA and

Table 6. Tomato stem epinasty and stem swelling/cracking injury (0–5 scale) associated with volatility of 2,4-D, dicamba, and triclopyr applied at 1× and 2× rates to bare soil and evaluated 1, 2, 7, and 14 d after treatment (DAT).[a]

			Stem epinasty (0–5)[b]				Stem swelling/cracking (0–5)[b]			
Treatment	Formulation	Rate	1 DAT	2 DAT	7 DAT	14 DAT	1 DAT	2 DAT	7 DAT	14 DAT
1× Rate										
2,4-D	Ester	1×	0.4 a[c]	1.2 ab	2.1 ab	2.5 ab	—[d]	—	0.3 a[c]	0.5 ab
2,4-D	DMA	1×	0.0 a	0.5 bc	0.7 c	1.2 bc	—	—	0.0 a	0.1 bc
2,4-D	Acid	1×	0.0 a	0.0 d	0.1 c	0.3 cd	—	—	0.1 a	0.2 bc
Dicamba	DMA	1×	0.1 a	0.3 cd	0.4 c	0.7 cd	—	—	0.0 a	0.1 bc
Dicamba	DGA	1×	0.1 a	0.4 bcd	0.8 bc	1.3 abc	—	—	0.1 a	0.2 bc
Dicamba	Acid	1×	0.0 a	0.2 cd	0.3 c	0.7 cd	—	—	0.0 a	0.1 bc
Triclopyr	Ester	1×	0.7 a	2.3 a	2.7 a	2.9 a	—	—	0.4 a	1.1 a
Triclopyr	Acid	1×	0.0 a	0.1 cd	0.3 c	0.5 cd	—	—	0.0 a	0.2 bc
Nontreated	—	—	0.0 a	0.1 cd	0.1 c	0.2 d	—	—	0.0 a	0.0 c
2× Rate										
2,4-D	Ester	2×	1.1 a	3.0 a	3.4 a	3.5 a	—	0.2 a	1.9 a	2.3 a
2,4-D	DMA	2×	0.0 b	0.1 bc	0.7 cd	1.0 b	—	0.0 a	0.0 b	0.2 bc
2,4-D	Acid	2×	0.0 b	0.1 bc	0.6 cde	0.8 bc	—	0.0 a	0.1 b	0.1 c
Dicamba	DMA	2×	0.1 b	0.6 b	1.4 c	1.8 ab	—	0.1 a	0.3 b	0.7 b
Dicamba	DGA	2×	0.0 b	0.6 bc	1.2 cd	1.5 b	—	0.1 a	0.4 b	0.8 b
Dicamba	Acid	2×	0.0 b	0.4 bc	1.6 bc	2.0 ab	—	0.0 a	0.2 b	0.7 b
Triclopyr	Ester	2×	1.7 a	3.0 a	3.2 ab	3.4 a	—	0.4 a	2.3 a	3.1 a
Triclopyr	Acid	2×	0.0 b	0.1 bc	0.3 de	0.6 bc	—	0.0 a	0.2 b	0.3 bc
Nontreated	—	—	0.0 b	0.1 bc	0.1 e	0.1 c	—	0.0 a	0.0 b	0.1 c

[a] Herbicide rates (1× and 2×) were 1,120 and 2,240 g ae ha^{-1} for 2,4-D isooctyl ester (Ester), dimethylamine salt (DMA), and acid formulations (Acid); 560 and 1,120 g ae ha^{-1} for dicamba dimethylamine salt (DMA), diglycolamine salt (DGA), and acid formulations; and 1,680 and 3,360 g ae ha^{-1} for triclopyr butoxyethyl ester (Ester) and acid formulations.

[b] Severity of injury based on a scale of 0 = none; 1 = slight; 2 = slight to moderate; 3 = moderate; 4 = moderate to severe; 5 = severe.

[c] Herbicide means for each rate/rating date followed by the same letter are not significantly different using LSD at $P \leq 0.05$.

[d] Injury not observed.

acid formulations was less than for the ester. For both rates, injury 14 DAT was equivalent for 2,4-D DMA, 2,4-D acid, and the dicamba formulations. Stem epinasty with triclopyr ester at both rates 14 DAT was equivalent to 2,4-D ester and greater than for triclopyr acid. Injury for both rates of triclopyr acid 14 DAT was no greater than for 2,4-D DMA, 2,4-D acid, and the dicamba formulations. For both the 1× and 2× herbicide rates, the only treatments with injury 14 DAT no greater than the nontreated were the acid formulations of 2,4-D and triclopyr.

Stem Swelling/Cracking Injury. Stem swelling and cracking injury was not observed for cotton, but herbicide effects were noted for tomato at some of the ratings (Table 3). Injury to tomato was not observed 1 and 2 DAT for 1× rates and 1 DAT for 2× rates, and significant herbicide treatment effects were not observed 7 DAT for 1× rates and 2 DAT for 2× rates. At 7 DAT for 2× rates, injury (0 to 5 scale) was 1.9 for 2,4-D ester and 2.3 for triclopyr ester, and injury was greater than for the other herbicide treatments (Table 6). At 14 DAT, injury with 2,4-D ester was no greater than for 2,4-D DMA, 2,4-D acid, and the dicamba formulations at 1× rates, but at 2× rates, injury for 2,4-D ester was greater. At both 1× and 2× rates, injury 14 DAT was equivalent for 2,4-D DMA and the dicamba formulations and was no more than 0.8. For triclopyr ester, injury 14 DAT was 5.5 times that of triclopyr acid at the 1× rate and 10.3 times that of the acid at the 2× rate. For both 1× and 2× rates, the only herbicide treatments with injury 14 DAT no greater than for the nontreated were 2,4-D DMA, 2,4-D acid, and triclopyr acid.

Total Injury. Total injury (0 to 100%) was calculated based on the level of severity for each of the four injury criteria (Tables 4–6) and was weighted based on the overall effect of each criterion on plant growth. Weighting of injury criteria considered leaf cupping/crinkling/drooping least

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Table 7. Cotton and tomato total injury (0–100%) associated with volatility of 2,4-D, dicamba, and triclopyr applied at 1× and 2× rates to bare soil and evaluated 1, 2, 7, and 14 d after treatment (DAT).[a]

			Total injury (0–100%)[b]							
			1 DAT		2 DAT		7 DAT		14 DAT	
Treatment	Formulation	Rate	Cotton	Tomato	Cotton	Tomato	Cotton	Tomato	Cotton	Tomato
1× Rate										
2,4-D	Ester	1×	2 cde[c]	11 b	3 efg	19 b	4 e	30 b	10 efg	36 b
2,4-D	DMA	1×	0 e	4 cde	2 fg	13 bcd	2 e	18 cd	7 g	24 cd
2,4-D	Acid	1×	0 e	4 cde	1 g	8 cdef	1 e	16 cd	4 g	20 cde
Dicamba	DMA	1×	2 cde	7 bc	4 efg	13 bcd	4 e	17 cd	7 g	20 cde
Dicamba	DGA	1×	1 de	7 bc	4 efg	14 bc	4 e	21 bc	8 fg	22 cde
Dicamba	Acid	1×	1 de	5 cde	2 fg	13 bcd	3 e	17 cd	6 g	21 cde
Triclopyr	Ester	1×	3 cde	23 a	5 efg	34 a	5 e	41 a	11 efg	50 a
Triclopyr	Acid	1×	1 de	5 bcde	2 fg	10 cde	2 e	18 cd	4 g	24 cd
Nontreated	—	—	0 e	3 cde	0 g	6 defg	0 e	9 de	3 g	12 defg
2× Rate										
2,4-D	Ester	2×	4 cde	24 b	8 cde	41 a	13 cde	59 a	17 cde	64 a
2,4-D	DMA	2×	1 e	6 cde	3 e	14 bcd	3 e	23 bc	7 de	27 bc
2,4-D	Acid	2×	0 e	5 cde	0 e	8 cde	2 e	18 cd	6 e	21 cd
Dicamba	DMA	2×	0 e	12 c	1 e	20 b	3 e	32 b	5 e	40 b
Dicamba	DGA	2×	1 e	9 cd	3 e	19 b	4 e	33 b	7 de	39 b
Dicamba	Acid	2×	1 e	8 cde	2 e	17 bc	3 e	32 b	7 de	40 b
Triclopyr	Ester	2×	4 cde	33 a	6 de	48 a	7 de	64 a	8 de	71 a
Triclopyr	Acid	2×	1 e	7 cde	3 e	15 bcd	2 e	23 bc	4 e	28 bc
Nontreated	—	—	0 e	3 de	1 e	7 cde	1 e	10 cde	4 e	14 cde

[a] Herbicide rates (1× and 2×) were 1,120 and 2,240 g ae ha^{-1} for 2,4-D isooctyl ester (Ester), dimethylamine salt (DMA), and acid formulations (Acid); 560 and 1,120 g ae ha^{-1} for dicamba dimethylamine salt (DMA), diglycolamine salt (DGA), and acid formulations; and 1,680 and 3,360 g ae ha^{-1} for triclopyr butoxyethyl ester (Ester) and acid formulations.

[b] To obtain total injury, injury criteria data (Tables 4–6) were weighted as follows: leaf cupping/crinkling/drooping = 2; leaf rolling/strapping = 4; stem epinasty = 6; and stem swelling/cracking = 8. A maximum severity of 5 for all injury criteria and weighting each criterion accordingly would result in total injury of 100%.

[c] Herbicide by plant type means for each rate/rating date followed by the same letter are not significantly different.

detrimental and stem swelling/cracking most detrimental. Significant plant type by herbicide interactions were observed for total injury at each of the ratings for both the 1× and 2× herbicide rates (Table 3). For cotton, total injury was calculated based solely on leaf cupping/crinkling/drooping since that was the only injury observed (Table 4). For the herbicide treatments at both rates, cotton total injury was no more than 4% 1 DAT and 17% 14 DAT, and injury was no greater than for the nontreated (Table 7). Total injury to cotton for the herbicide treatments at each of the ratings was consistently lower compared with tomato.

For tomato, total injury for both rates of the herbicides and at all ratings was generally greatest for the ester formulations of 2,4-D and triclopyr; injury for 2× rates 14 DAT was 64 and 71%, respectively (Table 7). The greater injury observed for the ester formulations is attributed primarily to the severity of stem epinasty and stem swelling/cracking observed (Table 6). For the 1× rates at all ratings, differences in total injury were not observed for 2,4-D DMA, 2,4-D acid, and the dicamba formulations. For 7 and 14 DAT for 2× rates, however, total injury was equivalent for 2,4-D DMA and 2,4-D acid, but injury for 2,4-D acid was less compared with the dicamba formulations. For triclopyr ester, tomato total injury 14 DAT was 2.1 times that of triclopyr acid at the 1× rate and 2.5 times that of the acid at the 2× rate. Total injury for triclopyr acid at both rates 14 DAT was no greater than for the 2,4-D DMA, 2,4-D acid, dicamba DMA, dicamba DGA, and dicamba acid formulations. The only herbicide treatments with total injury 14 DAT for both rates no greater than the nontreated were 2,4-D DMA, 2,4-D acid, and

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triclopyr acid. Based on total injury 14 DAT for 1× rates of the various herbicides and formulations, tomato was 2.8 to 6.0 times more sensitive than cotton.

Previous research has shown substantial losses of unformulated 2,4-D acid due to volatility (Baur et al. 1973; Behrens and Lueschen 1979; Burnside and Lavy 1966). The 2,4-D acid formulation evaluated in the present study contains proprietary surfactants that solubilize 2,4-D acid to form a water-miscible liquid that has very low volatility and is odorless (Helena Chemical Company). The manufacturer has also been successful in developing acid formulations of dicamba and triclopyr that were also included in the present study.

To allow for a direct comparison of crop response, the same acid equivalent rate of each herbicide was applied for each formulation evaluated. The 1× rates of 2,4-D at 1,120 g ha^{-1} and dicamba at 560 g ha^{-1}, commonly used for control of winter weeds preplant, were selected. For the acid formulations of 2,4-D and dicamba, however, the most common use rates preplant are 490 and 270 g ha^{-1}, respectively (Unison and Vision, Helena Chemical Company), which are 57 and 52% less than for the 1× rates evaluated in the present study. It is possible that crop injury due to volatility of the 2,4-D and dicamba acid formulations could have been less if the lower use rates had been evaluated. Lower use rates of the acid formulations would also contribute to a reduction in environmental loading of herbicide active ingredient.

Because of volatility concerns associated with the herbicide-resistant crop technologies currently under development, it is uncertain as to whether 2,4-D formulations other than the choline salt and dicamba formulations other than the DGA and tridentate salts will be allowed for in-crop use. It is probable that only the 2,4-D choline salt will be allowed for use in the 2,4-D–resistant crop technology, in part because of its lower volatility potential compared with other 2,4-D formulations (Perry et al. 2013). Likewise, dicamba use in the dicamba-resistant technology may be restricted to either the DGA salt formulation that includes proprietary technology to reduce volatility (MacInnis et al. 2014) or the tridentate amine salt formulation that provides binding of dicamba residues to suppress volatilization (Xu et al. 2012). In the present study, total injury 14 DAT for cotton and tomato because of volatility was not different between the 2,4-D acid and DMA formulations and among the dicamba acid, DGA, and DMA formulations. In other field research to evaluate volatility, extensive cotton injury was observed for 2,4-D ester, but results did not show differences in crop injury between the amine and choline salt formulations (Hayden et al. 2013; Sosnoskie et al. 2012). In soybean, differences in injury attributed to volatility were not observed among the 2,4-D ester, amine, and choline formulations, and injury was no greater than for the nontreated (Hayden et al. 2013). These findings along with those from the present study suggest that under field conditions, differences in volatility among 2,4-D and dicamba herbicide formulations may be of minimal importance with respect to off-target movement and injury to sensitive crops. Egan and Mortensen (2012) in a field study detected vapor drift of dicamba DMA salt at a concentration of 0.56 g ha^{-1} (1/1,000 of applied rate of 560 g ha^{-1}). Griffin et al. (2013) reported that application of dicamba at 0.56 g ha^{-1}, the exposure rate associated with volatility, resulted in soybean yield reduction of no more than 1%.

In most weed science research, weed control and crop injury assessments are based on a scale of 0 (no control or crop injury) to 100% (all plants dead). Often this statement is accompanied by a listing of various injury criteria observed and represented in the control/injury assessment. To assign a single injury rating would require that a level of severity be established for individual injury criteria and that criteria are ranked as to their overall contribution to total injury. This rating system would be subjective, and ratings would be expected to vary considerably among individuals. The present research was successful in identifying specific plant injury criteria representing the primary injury symptoms expected from exposure to auxin herbicides (Griffin et al. 2013; Johnson et al. 2012; Sciumbato et al. 2004a) and in developing a rating scale based on severity of injury. The rating system went a step further by weighting each injury criterion, and on the basis of the severity of each, total injury could be calculated on a 0 to 100% scale. The rating system proved effective in separating cotton and tomato response to auxin herbicides and in differentiating crop response among auxin herbicide formulations.

Sciumbato et al. (2004a) developed a method of quantifying injury from auxin herbicides that evaluated leaf and stem injury separately using a scale of 0 to 100, with 100 representing plant death. The values were then averaged to provide a single estimate of crop injury. This method was used to quantify cotton and soybean response to volatility of 2,4-D and dicamba salts and triclopyr ester (Sciumbato et al. 2004b). In the field portion of the study, exposure rates (estimation of volatility) of the DGA salt of dicamba and the DMA salt of 2,4-D for cotton were equivalent and less than for triclopyr ester. However for soybean, the DMA salt of 2,4-D appeared to be most volatile. The contrast in plant response to volatility of the auxin herbicides was explained by the relative difficulty in evaluating soybean injury compared with cotton when using the injury method developed by Sciumbato et al. (2004a).

As the 2,4-D– and dicamba-resistant technologies become available, it will be important that growers are aware of the sensitivity of nonresistant crops. When exposed to the volatility of 1× rates of 2,4-D DMA, 2,4-D acid, dicamba DMA, dicamba DGA, and dicamba acid formulations, total injury to cotton was 4 to 8% 14 DAT and no greater than for the nontreated. Total injury for tomato for the same treatments was 20 to 24% and also no greater than the nontreated. Results show that volatility of 2,4-D and dicamba can contribute to off-target movement to sensitive crops, but exposure from volatility would be of much less importance when compared with spray tank contamination and physical drift.

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