Antitranspirants Partially Mitigate Auxin Herbicide Injury on Tomato Plants

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Abstract. The use of dicamba and 2,4-D products on herbicide-tolerant crops has resulted in numerous cases of off-target movement and injury to sensitive plants, including tomato (*Solanum lycopersicon* L.). Two greenhouse studies were conducted to determine whether ‘Big Beef’ (‘BB’) or ‘Florida 91’ (‘FL’) tomato plants pre-treated with an antitranspirant, including Moisture-Loc (ML) at 100 mL·L⁻¹, Trans-Film (TF) at 50 g·L⁻¹, or Wilt-Pruf (WP) at 100 mL·L⁻¹, mitigated injury from synthetic auxin herbicides. Dicamba or 2,4-D was applied at a rate corresponding to 1/200 of the manufacturer’s labeled rate of 0.56 kg ae/ha or 1.06 kg ae/ha, respectively. At 2 weeks after treatment (WAT), plants treated with ML or WP before either herbicide exhibited injury symptoms, but they were always less severe than those treated with the herbicide alone for both cultivars. However, shoot length measurements indicated that none of the antitranspirants consistently provided protection against herbicide injury at 2 WAT. By 12 WAT, ML or WP used before either herbicide increased the number of live reproductive organs compared with dicamba or 2,4-D alone for both cultivars. Floral abortion on tomato plants was also reduced when ML or WP was applied before an herbicide treatment by 12 WAT. Although WP and ML did not provide complete protection against synthetic auxin herbicide injury, the concept of using film-forming barriers may be useful in mitigating some of the short-term effects of drift on plants.

Auxin herbicides have been registered for postemergence control of broadleaf weeds in agricultural crops for more than 50 years (Peterson et al., 2016). Since their initial development, different formulations of auxin herbicides, such as 2,4-D and dicamba, were created to decrease their volatility in the environment (Sosnoskie et al., 2015). The diglycolamine salt of dicamba and choline salt of 2,4-D choline are two formulations that have been used on genetically modified soybeans and cotton in production areas where long-term use of glyphosate has resulted in resistant weed species (Gage et al., 2019). Although these auxin herbicides were formulated for reduced off-target movement via particle drift and volatility, injury occurs on sensitive crops at very low rates (Culpepper et al., 2018; Knezevic et al., 2018; Kruger et al., 2012; Mohseni-Moghadam and Doo-han, 2015). Drift reduction agents, ambient temperature, wind speed, nozzle type, and boom height at the time of application influence drift, whereas volatilization is affected by air temperature, relative humidity, and

vapor pressure (Alves et al., 2017; Bish et al., 2019; Egan and Mortensen 2012; Jones et al., 2019; Mueller and Steckel, 2019; Nordby and Skuterud, 1974; Sosnoskie et al., 2015).

In the eastern United States, tomatoes (*Solanum lycopersicon* L.) are a high-value crop often grown in close proximity to soybean or cotton fields where dicamba or 2,4-D may be used for weed control. In 2017, more than 2200 cases of alleged dicamba-related injury on several crops were investigated by regulatory agencies in various states (Bradley, 2017). In Missouri alone, 335 complaints of dicamba injury were reported, which included 7650 ha of tomato (Missouri Department of Agriculture, 2017).

Tomato plants are highly sensitive to dicamba and 2,4-D (Hemphill and Montgomery, 1981; Knezevic et al., 2018). Common symptoms of synthetic auxin herbicide injury include epinasty, deformed leaflets, split stems, plant stunting, flower and fruit loss, and malformed fruit with delayed maturity (Bauerle et al., 2015; Bennet, 1989; Hemphill and Montgomery, 1981; Robbins and Taylor, 1957). However, two important factors that influence the degree of injury are herbicide dosage and growth stage of sensitive plants. Kruger et al. (2012) estimated that dicamba applied with a nonionic surfactant and ammonium sulfate at 2.4, 4.8, and 13.3 g ae/ha resulted in 5%, 10%, and 25% flower loss, respectively, when applied at an early vegetative stage on tomato. However, lower rates of dicamba (1.5, 2.7, and 6.4 g ae/ha) caused similar percentages of flower loss when

applied at early bloom. In other studies, 2,4-D rates as low as 1.8 to 2.1 g ae/ha applied at early bloom reduced tomato yield and distorted fruit shape (Hemphill and Montgomery, 1981; Robbins and Taylor, 1957). Herbicide rates used in the previous two studies are consistent with those that can occur in off-target drift (1/200 = 2.8 g ae/ha dicamba and 5.3 g ae/ha 2,4-D) (Egan and Mortensen, 2012; Kruger et al., 2012).

The severity of injury in response to auxin herbicides is also genotype-dependent. ‘Glamour’, ‘Heinz 1439’, ‘Moreton Hybrid’, and ‘Roma’ exhibited high tolerance to 2,4-D injury when 60 commercial tomato cultivars were sprayed at first bloom and evaluated (Coyne and Burnside, 1968). Also, three wild tomato accessions exhibiting less dicamba and 2,4-D injury than two commercially-available cultivars (‘Money Maker’ and ‘Better Boy’) were recently identified, which may be used for the future development of herbicide-tolerant tomato plants (Zangouinejad et al., 2019).

Most commercially grown tomato cultivars do not possess natural or engineered tolerance to dicamba and 2,4-D. Thus, solutions to mitigate injury concerns associated with off-target movement of these herbicides are needed for sensitive crops. One potential solution is the application of film-forming antitranspirant products. These antitranspirants provide a transient water-impermeable coating on plant surfaces and increase resistance to water vapor loss (Sutherland and Waters, 2002). Historically, film-forming polymers have been used as antitranspirants to reduce water loss of bare-root woody plants during postharvest handling or shipping (Englert et al., 1993), to minimize dehydration of fruits during cold storage (Plaut, 2008), to improve reestablishment of transplants (Goreta et al., 2007; Nitzsche et al., 1991), and to prevent plant infection from foliar pathogens (Han, 1990; Walters 1992). Three types of film-forming antitranspirants include a latex emulsion (ML, formerly known as Moisturin), an emulsion of polyethylenes and polyterpenes (TF), and a β-pinene polymer (WP), which have been labeled for various crops (Ondi Enterprises, 2020; Gordon, 2017; Wilt-Pruf Products, 2020).

Hummel (1990) reported that the β-pinene polymer antitranspirant was noninjurious to ‘Early Giant’ tomato and improved plant water status. However, film-forming products typically begin to lose their effectiveness in reducing transpiration ≈7 to 10 d after application (Anderson and Kreith, 1978; Kreith et al., 1975). Temporary negative effects of film-forming antitranspirants include impaired gas exchange, decreased photosynthesis, and increased leaf temperature (Davenport et al., 1974; Davies and Kozlowski, 1974; Gale, 1961; Williamson, 1963). The layer of film formed at application degrades over time with plant growth (Albrigo, 1972; Funk, 1979).

Because tomato plants are highly sensitive to synthetic auxin herbicides, this species was selected as a model crop to ascertain if film-forming antitranspirants provide transient protection against dicamba and 2,4-D drift

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injury on two different cultivars with similar days to maturity (72 to 73 d). The objective of this study was to determine if pretreating semideterminate 'Big Beef' ('BB') or determinate 'Florida 91' ('FL') tomato plants with ML, TF, or WP antitranspirant mitigated injury from dicamba or 2,4-D herbicides.

Materials and Methods

Expt. 1. 'BB' and 'FL' (Tomato Growers Supply, Fort Myers, FL) tomato seeds were sown in trays (20 × 27 cm size) that contained a commercial growing medium of sphagnum moss, vermiculite, and perlite (ProMix BX; Premier Tech Horticulture, Québec, Canada) in late May 2019 and placed in a greenhouse maintained at 26 °C day/20 °C night cycle under natural lighting. After germination, seedlings were transplanted at the two-leaf stage into 0.5-L containers in the same growing medium, hand-watered as needed, and maintained in the greenhouse under conditions described earlier.

'BB' and 'FL' tomato plants had eight and seven leaves per plant, respectively, and were ≈25 cm-tall with no visible floral buds when treated with an antitranspirant. Treatments included each antitranspirant alone, each herbicide alone, and each antitranspirant followed by either dicamba or 2,4-D. On 27 June, antitranspirant treatments, including ML (Zorro Technology, Clackamas, OR), TF (PBI Gordon, Shawnee, KS), or WP (Wilt-Pruf Products, Essex, CT) were applied by immersing the shoot growth in a product solution for 5 s. Both ML and WP solutions (100 mL·L⁻¹) were mixed according to the manufacturers' labeled concentration. Because a TF solution of 100 mL·L⁻¹ caused phytotoxicity on tomato leaves in a preliminary test (M.R. War-mund, unpublished data), a lower concentration of 50 mL·L⁻¹ was used for this study.

On 28 June, dicamba (Xtendimax with Vapor Grip; Bayer CropScience, St. Louis, MO) or 2,4-D (Enlist One with Colex-D; Dow AgroSciences, Indianapolis, IN) treatments were applied. Each herbicide was applied at 1/200 the manufacturer's recommended use rate (0.56 kg ae/ha dicamba or 1.06 kg ae/ha 2,4-D). Nontreated control plants (i.e., no antitranspirant and no herbicide) were also included for comparison. Herbicides were applied outdoors at 43 cm above the leaf canopy of tomato plants using a CO₂-pressurized backpack sprayer equipped with 8002 flat fan nozzles (TeeJet Technologies, Urbandale, IA) at 140 L·ha⁻¹ and 193 kPa. Plants treated with dicamba, 2,4-D, and nontreated controls were isolated by treatment in three greenhouses (≈15 m-apart) to minimize herbicide cross-contamination among plants. One week later, plants were transplanted into 8.5-L polyethylene containers using the same growing medium just described and placed in a greenhouse at 26 °C day/20 °C night cycle under natural light for duration of the study. Plants were hand-watered and fertilized as needed with 275 g·L⁻¹ of 21N-5P-20K (Peters Excel; Everris NA, Dublin, OH). The experiment was a split plot design in a

factorial arrangement (2 cultivars × 4 antitranspirant treatments × 3 herbicide treatments) with seven replications of each treatment. The main plot consisted of cultivar and replication and subplots were antitranspirant and herbicide treatments.

Plant height and the number of leaves per plant were recorded at treatment. At 2 WAT, herbicide injury ratings from 0 (no injury) to 10 (plant death) were recorded and the total length of all shoots per plant were measured to calculate the increase in shoot length from the date of treatment. The increase in the number of leaves from the date of treatment, and the number live and aborted flowers and buds were recorded at 4 WAT. The number of live reproductive organs (flower buds and flowers) were then calculated. Flowers that withered without setting a fruit were considered aborted. Throughout the study, ripe tomatoes were harvested and fresh weights were obtained. At 12 WAT, plants were harvested, roots were washed free of potting medium, and plant tissue was oven-dried at 65 °C to determine plant dry weights. Also, the number of live reproductive organs (flower buds, flowers, ripe and unripe fruit), aborted flowers and buds, and the fresh weight of all remaining immature fruit from plants were recorded at 12 WAT.

Data were analyzed using PROC GLIMMIX in SAS (SAS Institute, Cary, NC). A rank transformation was performed on herbicide injury ratings, excluding treatments (i.e., nontreated controls) that did not exhibit injury. However, results from back-transformed injury ratings are presented because results were similar. A

Poisson distribution was used to analyze the numbers of leaves and reproductive organs. Replication and replication × cultivar were considered random effects and antitranspirant, herbicide, and all other interactions were considered fixed effects. The odds (i.e., probability) of aborted flowers as a proportion of all reproductive organs were calculated, using the GLMMIX procedure with a link = logit function for a binomial distribution. Odds were calculated from the antilog of the logit value and back-transformed [% floral abortion = odds/(1 + odds)] for reporting percent floral abortion for each cultivar/herbicide treatment combination. Means were separated using Fisher's protected least significant difference test ($P \leq 0.05$).

Expt. 2. In early June 2019, tomato seeds were sown, and the previous experiment was repeated. However, because the TF treatments appeared less promising than the other two antitranspirants, these treatments were eliminated from this study. 'BB' and 'FL' tomato plants were dipped in ML or WP solutions on 9 July 2019, and herbicides were applied 24 h later. Other experimental procedures and data analyses were performed as previously described.

Results

Expt. 1: Plant injury symptoms

None of the plants treated with an antitranspirant alone exhibited any injury symptoms at 2 WAT (Table 1). Because results for antitranspirants used alone were often similar to nontreated controls, only limited reference to these treatments are made hereafter. Dicamba

Table 1. Expt. 1: 'Big Beef' and 'Florida 91' plant injury ratings at 2 WAT following antitranspirant and herbicide applications.^z

	Antitranspirant	Herbicide		
		Dicamba	2,4-D	None
Cultivar				
Big Beef	Moisture-Loc	5.9 Ba	2.6 Cb	—
	Wilt-Pruf	5.8 Ba	3.5 Ba	—
	Transfilm	7.0 Aa	5.7 Ab	—
	None	6.8 A	5.6 Ab	—
Florida 91	Moisture-Loc	5.0 B	2.8 Bb	—
	Wilt-Pruf	4.8 Ba	2.6 Bb	—
	Transfilm	6.1 Aa	3.8 Ab	—
	None	6.0 Aa	3.9 Ab	—
Significant effects				
Cultivar (C)			**	
Antitranspirant (A)			***	
Herbicide (H)			***	
C × A			NS	
C × H			NS	
A × H			*	
C × A × H			*	

^zAntitranspirants were applied to tomato plants 24 h before herbicide treatments. The shoot growth of each plant was dipped in a solution of Moisture-Loc or Wilt-Pruf at 100 g·L⁻¹ or Transfilm at 50 g·L⁻¹ for 5 s. Herbicides were applied at 1/200 of the labeled rate (dicamba 0.56 kg ae/ha or 2,4-D 1.06 kg ae/ha). Values represent seven replications of each treatment. Visual rating scale was 0 (no plant injury) to 10 (plant mortality). WAT = weeks after treatment. Means for each cultivar and herbicide treatment within a column followed by the same uppercase letters and means within a row followed by the same lowercase letters are not significantly different by Fisher's protected least significant difference test, $P \leq 0.05$.

Dash (—) indicates no plant injury observed.

NS, ***, **, *Indicate nonsignificance or statistical significance at $P \leq 0.001$, 0.01, or 0.05, respectively.

Fig. 1. (A) An elongated and distinctly acuminate leaflet on a 'Big Beef' plant treated with dicamba at 1/200 the labeled rate and (B) nontreated control leaflet at 2 weeks after treatment.

alone caused reflexed foliar cupping and distortion on both tomato cultivars by 2 WAT. The terminal apices of leaflets on both cultivars treated with dicamba or 2,4-D were also more elongated and distinctly acuminate compared with nontreated control leaflets (Fig. 1). The apical portion of the main stem present at the time of treatment was swollen and stunted with an undersized leaf on both dicamba-treated cultivars by 2 WAT (Fig. 2). Both herbicides induced stem epinasty and promoted the development of adventitious root initials on the main stems of plants (Fig. 3). Tomato plants treated with 2,4-D developed swollen nodes on

the primary stem. Twisting and malformation of leaflets were also observed on 2,4-D-treated plants of both cultivars.

There was a cultivar $\times$ antitranspirant $\times$ herbicide interaction for plant injury ratings (Table 1). All plants treated with an antitranspirant and an herbicide exhibited injury by 2 WAT. However, when ML or WP was used before either herbicide on 'BB' plants, injury ratings were lower than each associated herbicide used alone. Similar results were observed on 'FL' plants. For both cultivars,

injury ratings for plants treated with dicamba only were higher than those for plants treated with 2,4-D only.

Vegetative growth. All two-way interactions were significant for the increase in shoot length at 2 WAT (Table 2). The cultivar $\times$ herbicide interaction revealed that 'BB' plants treated with 2,4-D, dicamba, or nontreated controls had 36%, 45%, or 25% more shoot elongation, respectively, than comparable treatments on 'FL' plants (data not shown). The antitranspirant $\times$ herbicide interaction was also significant for increase in shoot length. For both cultivars, shoot length was decreased by dicamba alone and increased by 2,4-D alone compared with the nontreated controls. The only antitranspirant followed by herbicide treatment combination that had less shoot growth than dicamba alone was TF followed by dicamba for both cultivars. None of the antitranspirants followed by 2,4-D treatment combinations differed in shoot length from 2,4-D alone on 'BB' and 'FL' plants.

The main effect of cultivar was significant for the increase in leaf number by 4 WAT (Table 2). 'BB' plants produced more new leaves (8.4) than those of 'FL' (8.0). The interaction of antitranspirant-by-herbicide was also significant for the increase in leaf number by 4 WAT (Table 2). Plants of both cultivars treated with dicamba alone or 2,4-D alone had a 19% or 37% increase in leaf number, respectively, compared with nontreated controls. None of the antitranspirants used before dicamba suppressed the increased leaf numbers caused by dicamba alone. However, the proliferation of foliar growth associated with the application of 2,4-D alone was suppressed when 'BB' and 'FL' plants were treated with ML or WP before the 2,4-D application.

By 12 WAT, none of the plants receiving a 2,4-D treatment exhibited symptoms of injury on young distal leaflets of 'BB' plants, whereas all dicamba-treated 'BB' plants still displayed minor distortions on new leaflets. For 'FL', the only plants that had distorted distal leaflets were those pretreated with TF before 2,4-D or those sprayed with dicamba.

For plant dry weight, only the effects of cultivar and herbicide were significant by 12 WAT. 'BB' plants had greater mean dry weight (93 g) than 'FL' plants (58 g) ($P < 0.0001$). Dicamba alone and 2,4-D alone reduced dry weight by 35% and 20% compared with nontreated control plants ($P < 0.0001$). None of the antitranspirants mitigated the negative effect of either herbicide on plant dry weight.

Reproductive growth. The effects of cultivar, antitranspirant, and herbicide were significant for the number of live reproductive organs at $P = 0.0012$, $P < 0.0001$, and $P < 0.0001$, respectively, whereas all interactions were nonsignificant by 4 WAT. The mean number of live reproductive organs for all 'BB' plants was 9.1, whereas 'FL' plants averaged 12.6 reproductive organs. Among antitranspirant treatments, plants treated with ML and WP had more live reproductive organs (12 to 13) than those treated with TF or nontreated controls

Fig. 2. Swollen and stunted main stem of a 'Florida 91' plant treated with dicamba at 1/200 the labeled rate at 2 weeks after treatment.

Fig. 3. Swollen nodes and adventitious root initials on a stem of a 'Big Beef' plant treated with 2,4-D at 1/200 of the labeled rate at 2 weeks after treatment.

Table 2. Expt. 1: Increase in shoot length at 2 WAT and increase in leaf number at 4 WAT after antitranspirant and herbicide applications on 'Big Beef' and 'Florida 91' tomato plants.^z

	Shoot length (cm)			Leaf no.		
	Herbicide			Herbicide		
	Dicamba	2,4-D	None	Dicamba	2,4-D	None
Antitranspirant						
Moisture-Loc	23.9 Ab	46.6 Ba	43.8 Aa	27.0 Aa	24.2 Ba	17.7 Ab
Wilt-Pruf	24.5 Ac	51.0 Aa	42.4 ABb	29.4 Aa	24.5 Bb	19.2 Ac
Transfilm	17.7 Bc	49.4 ABa	40.0 Bb	26.5 Aa	27.6 ABa	17.4 Ab
None	24.6 Ac	48.7 ABa	36.7 Cb	23.6 Bb	30.2 Aa	19.0 Ac
Significant effects						
Cultivar (C)		***			**	
Antitranspirant (A)		*			NS	
Herbicide (H)		***			***	
C × A		*			NS	
C × H		**			NS	
A × H		**			**	
C × A × H		NS			NS	

^zAntitranspirants were applied to tomato plants 24 h before herbicide treatments. The shoot growth of each plant was dipped in a solution of Moisture-Loc or Wilt-Pruf at 100 g·L⁻¹ or Transfilm at 50 g·L⁻¹ for 5 s. Herbicides were applied at 1/200 of the labeled rate (dicamba 0.56 kg ae/ha or 2,4-D 1.06 kgae/ha). Values represent seven replications of each treatment. WAT = weeks after treatment. Means within a column followed by the same uppercase letters and means within a row followed by the same lowercase letters are not significantly different by Fisher's protected least significant difference test, $P \leq 0.05$.

NS, ***, **, *Indicate nonsignificance or statistical significance at $P \leq 0.001$, 0.01, or 0.05, respectively.

(9). For all herbicide treatments, nontreated and 2,4-D-treated plants had 41% and 47% more live reproductive organs, respectively, than dicamba-treated plants.

By 12 WAT, all two-way interactions for the number of live reproductive organs were significant (Table 3). The cultivar × herbicide interaction revealed that 'BB' plants treated with 2,4-D, dicamba, or nontreated controls had 52%, 60%, or 36% more live reproductive organs, respectively, than comparable treatments on 'FL' plants (data not shown). The antitranspirant × herbicide interaction revealed that either herbicide applied alone reduced the

number of live reproductive organs compared with the nontreated controls by nearly 50% (Table 3). However, plants treated with any antitranspirant before dicamba had more live reproductive organs than those treated with dicamba alone. Similar results were obtained when an antitranspirant was used before 2,4-D compared with 2,4-D alone.

The cultivar × herbicide interaction was significant for flower abortion by 4 WAT and 12 WAT (Table 3). The cultivar × herbicide interaction revealed that 'BB' plants treated with 2,4-D, dicamba, or nontreated controls had 41%, 46%, or 45%

more aborted flowers, respectively, than comparable treatments on 'FL' plants by 12 WAT (data not shown). The interaction of antitranspirant-by-herbicide was also significant for flower abortion by 4 WAT and 12 WAT. Plants of both cultivars treated with dicamba alone had greater percentages of flower abortion than those treated with 2,4-D alone at both evaluation dates. The negative effect of dicamba alone on flower abortion was mitigated by the application of ML or WP before dicamba treatment. The adverse effect of 2,4-D alone was reduced when ML, TF, or WP was applied before the application of 2,4-D.

The three-way interaction was significant for total fruit weight by 12 WAT (Table 4). Nontreated control plants and those treated with 2,4-D alone produced similar total fruit weights for both cultivars. However, the application of dicamba alone reduced total fruit weight of 'BB' and 'FL' by 91 and 58%, respectively, compared with nontreated controls. 'BB' plants treated with TF before the application of either herbicide produced only small immature fruit during the experimental period. Also, none of the plants pretreated with ML or WP before either herbicide produced greater total fruit weight than dicamba or 2,4-D alone. However, 'FL' plants treated with WP before 2,4-D had more fruit weight than plants treated with 2,4-D alone.

Expt. 2: Plant injury symptoms

The interaction of antitranspirant × herbicide was significant for injury ratings by 2 WAT, but the three-way interaction was not significant (Table 5). Plants of both cultivars treated with dicamba alone exhibited more injury than those treated

Table 3. Expt. 1: Number of reproductive organs at 12 WAT and percent flower abortion at 4 and 12 WAT following antitranspirant and herbicide applications on 'Big Beef' and 'Florida 91' tomato plants.^z

	No. of live reproductive organs			Aborted flowers at 4 WAT (%) ^y			Aborted flowers at 12 WAT (%) ^y		
	Herbicide			Herbicide			Herbicide		
	Dicamba	2,4-D	None	Dicamba	2,4-D	None	Dicamba	2,4-D	None
Antitranspirant									
Moisture-Loc	34.6 ABc	44.2 Ab	56.0 Aa	30.8 Ba	23.8 BCb	17.7 Bb	50.3 Ca	45.8 Cb	38.4 Bc
Wilt-Pruf	37.5 Ab	43.2 Aa	46.0 Ba	31.0 Ba	21.8 Cb	15.7 Bb	53.1 BCa	48.2 BCb	40.9 ABc
Transfilm	34.0 Bc	39.0 Ab	44.9 Ba	53.1 Aa	29.3 Bb	26.3 Ab	57.0 Ba	51.3 Bb	43.9 Ac
None	27.0 Cb	29.8 Bb	57.1 Aa	53.5 Aa	37.1 Ab	14.5 Bc	71.3 Aa	66.1 Ab	28.4 Cc
Significant effects									
Cultivar (C)		***			NS				
Antitranspirant (A)		***			***			**	
Herbicide (H)		***			***			***	
C × A		***			**			***	
C × H		***			*			***	
A × H		***			*			***	
C × A × H		NS			NS			NS	

^zAntitranspirants were applied to tomato plants 24 h before herbicide treatments. The shoot growth of each plant was dipped in a solution of Moisture-Loc or Wilt-Pruf at 100 g·L⁻¹ or Transfilm at 50 g·L⁻¹ for 5 s. Herbicides were applied at 1/200 of the labeled rate (dicamba 0.56 kg ae/ha or 2,4-D 1.06 kg ae/ha). Live reproductive organs include flower buds, flowers, and ripe and unripe fruit. Values represent seven replications of each treatment. WAT = weeks after treatment. Means within a column followed by the same uppercase letters and means within a row followed by the same lowercase letters are not significantly different by Fisher's protected least significant difference test, $P \leq 0.05$.

^yPROC GLIMMIX using a link = logit function for binomial distributions was used to analyze floral abortion data as proportion of the total number of reproductive organs. Back transformed data [% flower abortion = odds/(1 + odds)] are presented.

NS, ***, **, *Indicate nonsignificance or statistical significance at $P \leq 0.001$, 0.01, or 0.05, respectively.

Table 4. Expt. 1: Total fruit weight in grams of 'Big Beef' and 'Florida 91' at 12 WAT following antitranspirant and herbicide applications.^z

		Herbicide		
		Dicamba	2,4-D	None
Antitranspirant		(g)		
Cultivar				
Big Beef	Moisture-Loc	41.5 Aa	29.8 Aa	34.5 Ca
	Wilt-Pruf	18.5 Aa	63.0 Aa	70.5 BCa
	Transfilm	2.2 Ab	3.3 Ab	162.2 Aa
	None	11.8 Ab	70.0 Aab	126.6 Aa
Florida 91	Moisture-Loc	63.0 Ab	118.6 Bab	190.0 Ba
	Wilt-Pruf	58.8 Ab	233.5 Aa	287.4 Aa
	Transfilm	122.1 Ab	122.7 Bb	203.0 Ba
	None	78.3 Ab	160.3 Ba	186.7 Ba
Significant effects				
Cultivar (C)			***	
Antitranspirant (A)			NS	
Herbicide (H)			***	
C × A			NS	
C × H			NS	
A × H			*	
C × A × H			*	

^zAntitranspirants were applied to tomato plants 24 h before herbicide treatments. The shoot growth of each plant was dipped in a solution of Moisture-Loc or WP at 100 g·L⁻¹ or Transfilm at 50 g·L⁻¹ for 5 s. Herbicides were applied at 1/200 of the labeled rate (dicamba 0.56 kg ae/ha or 2,4-D 1.06 kg ae/ha). Values represent 7 replications of each treatment. WAT = weeks after treatment. Means for each cultivar and herbicide treatment within a column followed by the same uppercase letters and means within a row followed by the same lowercase letters are not significantly different by Fisher's protected least significant difference test, $P \leq 0.05$.

NS, ***, *Indicate nonsignificance or statistical significance at $P \leq 0.001$ or 0.05, respectively.

with 2,4-D alone. Also, plants with either antitranspirant applied before dicamba had lower injury ratings than plants treated

with dicamba alone. Similar results were obtained for antitranspirants used with 2,4-D.

Vegetative growth. The three-way interaction was significant for shoot length at 2 WAT (Table 6). For 'BB', dicamba alone or 2,4-D alone resulted in a 40% or 70% increase in shoot length, respectively, compared with nontreated controls at 2 WAT. 'BB' plants treated with WP before dicamba had less shoot growth than those treated with dicamba alone. For 'FL', all dicamba treatments had similar increases in shoot length. However, ML or WP applied before 2,4-D mitigated the stimulated shoot growth caused by 2,4-D alone on 'FL' plants.

Both herbicides used alone on 'BB' and 'FL' plants stimulated foliar growth when compared with the nontreated controls by 4 WAT (Table 7). Neither antitranspirant used before dicamba suppressed the increased foliar growth caused by dicamba. However, plants treated with ML or WP before 2,4-D had fewer leaves than those sprayed with 2,4-D only.

By 12 WAT, herbicide injury symptoms on young distal leaflets of all 'BB' plants were not apparent (data not shown). Injury symptoms on young leaflets were only visible on 'FL' plants treated with an antitranspirant before dicamba or dicamba alone.

For plant dry weight, the interaction of antitranspirant-by-herbicide was significant at 12 WAT (Table 8). The antitranspirant-by-herbicide interaction revealed that herbicides applied alone reduced plant dry weights by 33% compared with nontreated controls. However, plants treated with WP before dicamba had greater dry weight than those sprayed with dicamba alone. In contrast, plants treated with

ML before 2,4-D had greater dry weight than those treated with 2,4-D alone.

Reproductive growth. By 4 WAT, plants treated with dicamba alone developed fewer live reproductive organs than the nontreated controls of both cultivars (Table 9). Antitranspirants applied alone reduced the number of live reproductive organs compared with the nontreated controls for both cultivars and did not mitigate herbicide injury by 4 WAT. However, plants treated with ML or WP before either herbicide developed more live reproductive organs than those treated with dicamba or 2,4-D alone by 12 WAT (Table 9).

The three-way interaction for aborted flowers was significant at 4 WAT (Table 10). For 'BB', plants treated with dicamba alone had higher percentages of flower abortion than nontreated controls. However, ML or WP applied before dicamba reduced 'BB' flower abortion by 49% or 47%, respectively, compared with dicamba alone. Antitranspirants had no effect on flower abortion caused by dicamba alone on 'FL' plants. For both cultivars, percentages of flower abortion were increased by 2,4-D alone compared with the nontreated control plants. For 'FL' plants only, ML or WP mitigated the effect of 2,4-D alone on flower abortion.

Only the effects of antitranspirant ($P = 0.0001$) and herbicide ($P = 0.0003$) were significant for flower abortion by 12 WAT. Across all treatments, plants treated with ML or WP antitranspirant had less flower abortion (38% and 40%, respectively) than plants not treated with an antitranspirant (52%). Also, dicamba- or 2,4-D-treated plants had more flower abortion (52% and 50%, respectively) than non-herbicide-treated plants (29%).

For total fruit weight, only the effects of cultivar ($P = 0.0084$) and herbicide ($P < 0.0001$) were significant at 12 WAT. 'FL' plants averaged 386 g total fruit weight while 'BB' averaged only 296 g. Plants treated with 2,4-D had greater total fruit weight (413 g) than nontreated plants (309 g) and those treated with dicamba (280 g).

Discussion

Results from this study reinforce that tomato plants are sensitive to low dose applications of dicamba and 2,4-D (Bauerle et al., 2015; Bennet, 1989). However, the effect of dicamba on vegetative growth differed from that of 2,4-D. Soon after dicamba application, the apical portion of the main stem of plants was visibly stunted with little additional growth from the stem apex (Fig. 2). By 4 WAT, dicamba stimulated vegetative growth from axillary buds on tomato plants (Tables 2 and 7). Visually, these plants appeared chemically pruned, expressing symptoms similar to the common practice of manually removing shoot tips to stimulate lateral growth on plants. In contrast, 2,4-D alone stimulated apical growth of the main stem by 2 WAT when compared with nontreated controls of each cultivar (Tables 2 and 6). The stimulated shoot growth caused by 2,4-D was especially

Table 5. Expt. 2: 'Big Beef' and 'Florida 91' plant injury ratings at 2 WAT following antitranspirant and herbicide applications.^z

	Visual ratings of injury		
	Herbicide		
	Dicamba	2,4-D	None
Antitranspirant			
Moisture-Loc	3.7 Ba	3.6 Ba	—
Wilt-Pruf	3.8 Ba	3.5 Ba	—
None	6.8 Ba	4.9 Ba	—
Significant effects			
Cultivar (C)		NS	
Antitranspirant (A)		***	
Herbicide (H)		***	
C × A		NS	
C × H		NS	
A × H		***	
C × A × H		NS	

^zAntitranspirants were applied to tomato plants 24 h before herbicide treatments. The shoot growth of each plant was dipped in a solution of Moisture-Loc or Wilt-Pruf at 100 g·L⁻¹ or Transfilm at 50 g·L⁻¹ for 5 s. Herbicides were applied at 1/200 of the labeled rate (dicamba 0.56 kg ae/ha or 2,4-D 1.06 kg ae/ha). Values represent seven replications of each treatment. WAT = weeks after treatment; NI = no injury. Means within a column followed by the same uppercase letters and means within a row followed by the same lowercase letters are not significantly different by Fisher's protected least significant difference test, $P \leq 0.05$.

Dash (—) indicates no plant injury observed.

NS, ***, *Indicate nonsignificance or statistical significance at $P \leq 0.001$, respectively.

Table 6. Expt. 2: Increase in shoot length at 2 WAT following antitranspirant and herbicide applications on 'Big Beef' and 'Florida 91' tomato plants.^z

	Antitranspirant	Shoot length (cm)		
		Herbicide		
		Dicamba	2,4-D	None
Cultivar				
Big Beef	Moisture-Loc	56 ABb	77 Aa	65 Aab
	Wilt-Pruf	40 Bb	79 Aa	35 Bb
	None	69 Aa	83 Aa	49 ABb
Florida 91	Moisture-Loc	11 Ab	34 Ba	26 Aab
	Wilt-Pruf	18 Aa	32 Ba	20 Aa
	None	18 Ac	61 Aa	35 Ab
Significant effects				
Cultivar (C)			**	
Antitranspirant (A)			**	
Herbicide (H)			***	
C × A			NS	
C × H			*	
A × H			NS	
C × A × H			*	

^zAntitranspirants were applied to tomato plants 24 h before herbicide treatments. The shoot growth of each plant was dipped in a solution of Moisture-Loc or Wilt-Pruf at 100 g·L⁻¹ or Transfilm at 50 g·L⁻¹ for 5 s. Herbicides were applied at 1/200 of the labeled rate (dicamba 0.56 kg ae/ha or 2,4-D 1.06 kg ae/ha). Values represent seven replications of each treatment. WAT = weeks after treatment. Means for each cultivar and herbicide treatment within a column followed by the same uppercase letters and means within a row followed by the same lowercase letters are not significantly different by Fisher's protected least significant difference test, $P \leq 0.05$.

NS, ***, **, *Indicate nonsignificance or statistical significance at $P \leq 0.001$, 0.01, or 0.05, respectively.

pronounced on 'BB', likely due to its vigorous semideterminate growth habit.

Both herbicides caused stem epinasty in our experiments, which has been widely

Table 7. Expt. 2: Increase in leaf number at 4 WAT following antitranspirant and herbicide applications on 'Big Beef' and 'Florida 91' tomato plants.^z

	Leaf no.		
	Herbicide		
	Dicamba	2,4-D	None
Antitranspirant			
Moisture-Loc	31.9 Aa	27.8 Ba	18.9 Ab
Wilt-Pruf	34.8 Aa	27.5 Bb	18.5 Ac
None	28.3 Aa	34.6 Aa	20.6 Ab
Significant effects			
Cultivar (C)		NS	
Antitranspirant (A)		NS	
Herbicide (H)		***	
C × A		NS	
C × H		**	
A × H		*	
C × A × H		NS	

^zAntitranspirants were applied to tomato plants 24 h before herbicide treatments. The shoot growth of each plant was dipped in a solution of Moisture-Loc or Wilt-Pruf at 100 g·L⁻¹ or Transfilm at 50 g·L⁻¹ for 5 s. Herbicides were applied at 1/200 of the labeled rate (dicamba 0.56 kg ae/ha or 2,4-D 1.06 kg ae/ha). Values represent seven replications of each treatment. WAT = weeks after treatment. Means within a column followed by the same uppercase letters and means within a row followed by the same lowercase letters are not significantly different by Fisher's protected least significant difference test, $P \leq 0.05$.

NS, ***, **, *Indicate nonsignificance or statistical significance at $P \leq 0.001$, 0.01, or 0.05, respectively.

reported (Bauerle, 2015; Bennet, 1989; Coyne and Burnside, 1968; Hemphill and Montgomery, 1981; Knezevic et al., 2018). Also, dicamba and 2,4-D treatments promoted the development of adventitious root initials on the main stems of plants (Fig. 3). Adventitious root formation often occurs on tomato stems after wounding. In the tomato pericycle, wounding induces auxin transporters, resulting in auxin accumulation in founder cell initiation sites that differentiate and develop into adventitious roots capable of breaking through the epidermis (Guan et al.,

2019). This wound response may therefore parallel the response to low dose auxin-type herbicides by inducing expression of genes that ultimately result in the development of root initials.

In both experiments, the appearance of new, undamaged terminal leaflets on the main stems indicated that 2,4-D-treated plants began to recover vegetatively from injury by 12 WAT.

Also, total fruit weight of 'FL' plants treated with 2,4-D alone was greater than those treated with dicamba alone in Expt. 1 (Table 4) and both cultivars in Expt. 2 by 12 WAT. Collectively, these results indicate that tomato plants may recover more rapidly from 2,4-D injury than from dicamba injury. Peterson et al. (2016) also reported that some plant species recover from exposure to low rates of auxin herbicides.

Overall, little fruit matured on plants during the 12-week experimental periods. However, 'FL' plants produced more total fruit weight than those of 'BB'. The cultivar difference in fruit weight is likely due to the productivity of 'FL' and its tendency to set tomatoes at warm temperatures (Koske et al., 2009).

The mitigation of dicamba and 2,4-D injury to tomato plants also varied among the film-forming antitranspirants. In the first experiment, TF provided no early protection against herbicide injury and its efficacy was inconsistent at 12 WAT (Tables 1 and 3). In contrast, the application of either ML or WP before an herbicide application partially mitigated plant injury symptoms at 2 WAT and resulted in more live reproductive organs when compared with the respective herbicide treatment alone at 12 WAT (Tables 1, 3, and 9). In other studies, auxin-type herbicides stimulated cell elongation of plants within an hour of treatment and enhanced the accumulation of potassium ions in guard cells, resulting in larger stomatal aperture size for 5 to 16 h and photosynthesis for 5 to 20 h after

Table 8. Expt. 2: Plant dry weight at 12 WAT following antitranspirant and herbicide applications on 'Big Beef' and 'Florida 91' tomato plants.

	Plant dry weight (g)		
	Herbicide		
	Dicamba	2,4-D	None
Antitranspirant			
Moisture-Loc	67.3 ABa	76.9 Aa	60.3 ABa
Wilt-Pruf	79.1 Aa	65.4 ABab	54.4 Bb
None	52.3 Bb	52.4 Bb	78.0 Aa
Significant effects			
Cultivar (C)		**	
Antitranspirant (A)		NS	
Herbicide (H)		NS	
C × A		NS	
C × H		NS	
A × H		***	
C × A × H		NS	

^zAntitranspirants were applied to tomato plants 24 h before herbicide treatments. The shoot growth of each plant was dipped in a solution of Moisture-Loc or Wilt-Pruf at 100 g·L⁻¹ or Transfilm at 50 g·L⁻¹ for 5 s. Herbicides were applied at 1/200 of the labeled rate (dicamba 0.56 kg ae/ha or 2,4-D 1.06 kg ae/ha). Values represent seven replications of each treatment. WAT = weeks after treatment. Means within a column followed by the same uppercase letters and means within a row followed by the same lowercase letters are not significantly different by Fisher's protected least significant difference test, $P \leq 0.05$.

NS, ***, **Indicate nonsignificance or statistical significance at $P \leq 0.001$ or 0.01, respectively.

Table 9. Expt. 2: The number of live reproductive organs at 4 and 12 WAT following antitranspirant and herbicide applications on 'Big Beef' and 'Florida 91' tomato plants.^z

	No. live repro. organs at 4 WAT			No. live repro. organs at 12 WAT		
	Herbicide			Herbicide		
	Dicamba	2,4-D	None	Dicamba	2,4-D	None
Antitranspirant						
Moisture-Loc	9.8 Ab	14.0 Aba	11.0 Bab	37.4 Aa	34.9 Aa	37.3 Aa
Wilt-Pruf	9.8 Ab	15.0 Aa	10.4 Bb	35.9 Aab	31.3 Ab	36.8 Aa
None	9.8 Ab	12.5 Bab	14.3 Aa	20.9 Bb	22.3 Bb	41.8 Aa
Significant effects						
Cultivar (C)		*			**	
Antitranspirant (A)		NS			***	
Herbicide (H)		**			***	
C × A		NS			NS	
C × H		NS			NS	
A × H		*			***	
C × A × H		NS			NS	

^zAntitranspirants were applied to tomato plants 24 h before herbicide treatments. The shoot growth of each plant was dipped in a solution of Moisture-Loc or Wilt-Pruf at 100 g·L⁻¹ or Transfilm at 50 g·L⁻¹ for 5 s. Herbicides were applied at 1/200 of the labeled rate (dicamba 0.56 kg ae/ha or 2,4-D 1.06 kg ae/ha). Live reproductive organs include flower buds, flowers, and ripe and unripe fruit. Values represent seven replications of each treatment. WAT = weeks after treatment. Means within a column followed by the same uppercase letters and means within a row followed by the same lowercase letters are not significantly different by Fisher's protected least significant difference test, $P \leq 0.05$.

NS, ***, **, *Indicate nonsignificance or statistical significance at $P \leq 0.001$, 0.01, or 0.05, respectively.

treatment (Cobb, 1992; Thompson, 1989). Thus, thorough coverage of enlarged stomatal apertures on leaf surfaces with an antitranspirant at a sufficient rate may be necessary to adequately mitigate plant injury caused by an auxin-type herbicide. Albrigo (1972) showed that a 3% spray of pinolene antitranspirant (i.e., WP) partially, but not completely, covered stomatal

openings. In a preliminary experiment, 2% or 3% solutions of ML or WP alone did not cause phytotoxicity (M.R. Warmund, unpublished data). However, a 1% solution of ML or WP was selected for this study, using the manufacturer's labeled rate. Although not examined in the current study, incomplete stomatal coverage or slight breaks in the film layer may have

Table 10. Expt. 2: Percent of aborted flowers at 4 WAT following antitranspirant and herbicide applications on 'Big Beef' and 'Florida 91' tomato plants.^z

	Antitranspirant	Aborted flowers (%) ^y		
		Herbicide		
		Dicamba	2,4-D	None
Cultivar				
Big Beef	Moisture-Loc	20.8 Ba	20.5 Aa	17.0 Aa
	Wilt-Pruf	21.5 Ba	20.2 Aa	15.5 Aa
	None	40.8 Aa	30.1 Aa	7.0 Ab
Florida 91	Moisture-Loc	25.6 Aa	11.5 Bb	16.8 Aab
	Wilt-Pruf	30.0 Aa	16.6 Bb	13.2 Ab
	None	21.9 Aa	26.8 Aa	13.1 Ab
Significant effects				
Cultivar (C)			NS	
Antitranspirant (A)			NS	
Herbicide (H)			***	
C × A			NS	
C × H			NS	
A × H			*	
C × A × H			*	

^zAntitranspirants were applied to tomato plants 24 h before herbicide treatments. The shoot growth of each plant was dipped in a solution of Moisture-Loc or Wilt-Pruf at 100 g·L⁻¹ or Transfilm at 50 g·L⁻¹ for 5 s. Herbicides were applied at 1/200 of the labeled rate (dicamba 0.56 kg ae/ha or 2,4-D 1.06 kg ae/ha). Values represent seven replications of each treatment. WAT = weeks after treatment.

^yPROC GLIMMIX using a link = logit function for binomial distributions was used to analyze floral abortion data as proportion of the total number of reproductive organs. Back-transformed data [% flower abortion = odds/(1 + odds)] are presented. Means for each cultivar and herbicide treatment within a column followed by the same uppercase letters and means within a row followed by the same lowercase letters are not significantly different using Fisher's protected least significant difference test, $P \leq 0.05$.

NS, ***, **, *Indicate nonsignificance and statistical significance at $P \leq 0.001$ or 0.05, respectively.

occurred as plants were transplanted or moved before and after treatment, allowing herbicide absorption.

While ML and WP treatments partially mitigated some of the adverse effects of simulated dicamba and 2,4-D drift, especially on 'FL' plants, they also had some shortcomings. For example, ML is the only product among the three tested that is labeled for use on food crops (canberries and fruit trees) but not tomato. Because of incomplete mitigation of injury symptoms at the rates evaluated in this study, tomato plants exhibiting herbicide injury would most likely be nonsaleable for retailers. Also, fruit harvested from herbicide-injured plants may be considered unacceptable even though it has no detectable herbicide residue or the residue content is below the legal limit established by the Environmental Protection Agency. Furthermore, if tomato plants received multiple drift events, the film barrier on plant surfaces from these antitranspirant products may crack and be less effective with foliar expansion and stem growth. Others have shown that film-forming antitranspirants protected plants from abiotic stress temporarily (Anderson and Kreith, 1978; Englert et al., 1993; Hummel, 1990; Park et al., 2016; Plaut, 2008).

Despite incomplete early protection against herbicide drift on tomato plants, this study provides proof of concept that ML and WP antitranspirants can at least reduce visual symptoms from dicamba and 2,4-D drift injury. Future studies may also show that such film-forming antitranspirants provide partial protection from dicamba or 2,4-D drift injury on woody ornamental vines and shrubs, which may recover from injury with subsequent growth or pruning and become marketable or aesthetically pleasing in the landscape. Also, future studies may be warranted to investigate the use of higher rates of ML or WP and alternative application methods.

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