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Pumpkin Injury and Yield Response to Low Rates of 2,4-D Choline and Dicamba

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Abstract. **The recent release of 2,4-D- and dicamba-tolerant soybean traits has increased the risk of off-target herbicide injury and yield loss for specialty crop growers in the midwestern United States. Most dicotyledonous plants, including many specialty crops like pumpkin (*Cucurbita pepo*), are susceptible to synthetic auxin herbicides; however, the relationship between off-target herbicide rate, visible crop injury, and eventual yield loss is not well documented. The objective of this 2-year field study in 2019 and 2020 was to determine the effect of sublethal herbicide rates of 2,4-D and dicamba on visible injury and crop yield loss in pumpkin when applied at the vegetative and flowering growth stages. Herbicides included 2,4-D choline salt (1066 g ae·ha^{-1} labeled rate) and dicamba diglycolamine salt (560 g ae·ha^{-1} labeled rate) ranging from 1/500 to 1/4 of the labeled rate. Visible injury ratings were recorded every 7 d after application and pumpkins were harvested and weighed when ripe. Injury and yield data were fit to a four-parameter log-logistic regression model to estimate effective doses (ED) required for 5% to 50% visible injury or yield loss. Pumpkin treated with the 1/10 and 1/4 rates of 2,4-D at both growth stages had visible injury (± 1 *SE*) ranging from 8% (± 3%) to 55% (± 3%), but injury did not always result in yield loss. Maximum yield loss from 2,4-D was 32% (± 2%), observed following the 1/4 rate at the vegetative growth stage in 2020 (estimated ED for 20% yield loss was ~1/50). Pumpkin treated at the vegetative growth stage with the 1/10 and 1/4 rates of dicamba resulted in 65% (± 6%) to 82% (± 1%) visible injury and 33% (± 2%) to 86% (± 14%) yield loss (estimated ED for 20% yield loss was ~1/10 in 2019 and ~1/15 in 2020). At the flowering stage, dicamba rates of 1/10 and 1/4 caused visible injury of 31% (± 2%) to 74% (± 5%) and yield loss of 26% (± 10%) to 60% (± 14%) (estimated ED for 20% yield loss was ~1/20 in 2019 and ~1/5 in 2020). Susceptibility of pumpkin to 2,4-D and dicamba suggests herbicide applicators and pumpkin growers should consider strategies that mitigate off-target movement, including using nozzles that increase droplet size, shielded sprayers, thorough tank cleanout, buffer zones, and programs that facilitate communication between applicators and growers.**

New herbicide-tolerant crop traits have been developed recently in response to an increasing number of glyphosate-resistant weeds (Powles 2008). These new traits include tolerance to 2,4-D choline (Dow AgroSciences Indianapolis, IN, USA) and dicamba (Bayer Crop Science, St. Louis, MO, USA) in corn (*Zea mays*), soybean (*Glycine max*), and cotton (*Gossypium* spp.). These new technologies can improve weed management and yield in field crops, particularly when glyphosate-resistant weeds are present (Behrens et al. 2007; Duke 2015). A recent survey suggests that 90% of early adopters of dicamba-tolerant soybean observed improved weed management; however, 51% of respondents also noted dicamba injury in susceptible soybean fields (Werle et al. 2018). Dicamba and 2,4-D are among the herbicides most susceptible to off-target movement and injury resulting from particle drift, volatilization, or tank contamination (Mohseni-Moghadam et al. 2016). Dicamba is a volatile herbicide with potential for off-target injury on sensitive plants, especially when applied under conditions of high temperatures or temperature inversion. Roesler et al. (2020) found that dicamba can drift up to 152 m from the target application area and yield loss in conventional soybean was observed up to 43 m from the application area.

In addition to soybean, many dicotyledonous specialty crops have demonstrated susceptibility to 2,4-D and dicamba. Visible injury from low rate application of 2,4-D dimethylamine salt (1/300 to 1/30 of the labeled rate of 840 g ae·ha^{-1}) ranged from 29% to 66% across five grape (*Vitis vinifera*) cultivars at 42 d after treatment (Mohseni-Moghadam et al. 2016). Peanut (*Arachis hypogaea*) was 0.5 to 2 times more sensitive to yield loss from dicamba compared with 2,4-D; nonetheless, 1/16 to 1/4 rates of 2,4-D amine (1120 g ae·ha^{-1} labeled rate) reduced yield by 11% to 19%, and yield loss often occurred in the absence of visible injury (Leon et al. 2014). Application of 2,4-D at 1/50 rate at the eight-leaf stage reduced broccoli (*Brassica oleraceae* var. *italica*) yield by 50% (Mohseni-Moghadam and Doohan 2015). Horseradish (*Armoracia rusticana*) was injured, and yield loss occurred from 2,4-D rates as low as 1/1000, whereas dicamba rates lower than the labeled rate had no effect on yield (Wiedau et al. 2019). Foliar injury following low rates of dicamba has been documented across eight species of flowering bedding plants (Hatterman-Valenti and Mayland 2005). Dicamba applied at 1/75 the labeled use rate to tomato (*Solanum lycopersicum*) at the early bloom stage caused a 25% yield reduction (Kruger et al. 2012).

Pumpkin is an economically important specialty crop in the United States with sales valued at more than $233 million in 2021 (US Department of Agriculture National Agricultural Statistics Service 2022). Many of these pumpkins are grown in the US Midwest near corn and soybean production where 2,4-D- and dicamba-tolerant crops are now widely adopted. Although herbicide susceptibility studies on pumpkin are limited, studies on other species in the cucurbit family suggest pumpkin may be highly susceptible to off-target injury from 2,4-D and dicamba. Hemphill and Montgomery (1981) found that 2,4-D (1040 g ae·ha^{-1} labeled rate) rates between 1/50 and 1/5 in cucumber (*Cucumis sativus*) applied at first bloom stage caused mild epinasty, but yield loss was only observed at rates greater than 1/10. Low rates of 2,4-D (1,120 g ae·ha^{-1} labeled rate) and dicamba (560 g ae·ha^{-1} labeled rate) in watermelon (*Citrullus lanatus*) caused greatest visible injury and yield loss when applications were made before flowering (Culpepper et al. 2018). Visible injury after treatment with the 1/75 rate of 2,4-D at 20 d after planting was 40% compared with 11% visible injury when treated at 60 d after planting. Results were similar for dicamba, where the 1/250 rate reduced yield when applied at 20 d after planting but not 40 or 60 d after planting. Similar results were found in cucumber, where application of 2,4-D and dicamba at the vegetative growth stage caused greatest injury (Hand et al. 2021).

Most reported incidents of off-target herbicide injury in the midwestern United States occur between May and June when corn and soybean growers are applying post-emergence herbicides, including 2,4-D and dicamba (Werle et al. 2018). In the Midwest, pumpkin is typically seeded or transplanted in May or early June and is flowering by late June into July. The objective of this study was to determine the effect of sublethal off-target rates of 2,4-D choline and dicamba on visible injury and crop yield loss in pumpkin when applied at the vegetative and early flowering growth stages.

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Materials and Methods

Experimental design. A total of four field experiments were conducted in 2019 and 2020 for 2,4-D and dicamba. Treatments included herbicide application at two pumpkin growth stages (vegetative vs. flowering) using six sublethal rates of either 2,4-D or dicamba [0, 1/4, 1/10, 1/50, 1/100, and 1/500 of the labeled rate (1066 g ae·ha^{-1} 2,4-D choline salt, 560 g ae·ha^{-1} dicamba diglycolamine salt)]. There were four replicate blocks of all growth stage by rate treatment combinations within separate experiments for 2,4-D and dicamba.

In 2019, 'Orange Smoothie' (F1) (Johnny's Selected Seeds Company; Winslow, ME, USA) pumpkin seeds were planted in flats in the greenhouse on 13 May for seedling plugs. On 31 May, pumpkin seedlings were transplanted to the field located at the UNL Havelock Research Farm in Lincoln, NE, USA (lat. 40.85°N, long. 96.61° W; Aksarben silty clay loam). The previous crop was field corn. Before transplanting, the field was prepared with rotary tillage. Then a single field pass of a bed-shaper/mulch-layer (RB448; Nolt's Produce Supplies, Leola, PA, USA) was used to shape raised beds and lay drip irrigation tape beneath a white-on-black plastic film. Each plot was 12 ft of a single raised-bed row (~4 ft wide); five pumpkins were transplanted in a single row within each plot with 2.4 ft between plants. To minimize off-target herbicide movement among treatments, there was 4.8 ft between plots within rows (equivalent to one skipped plant) and 10 ft between row centers. Plants were fertigated with 45 kg·ha^{-1} N two times during the growing season: once before (14 d after transplanting) and once after herbicide treatment (14 d after herbicide application) using calcium nitrate fertilizer (15N–0P–0K, YaraLiva Tropicote; Yara North America, Tampa, FL, USA). Soil P and K levels were sufficient, and no fertilizer was applied. Plants were irrigated weekly, depending on precipitation, to maintain volumetric soil moisture levels in the top 20 cm at or above 15 cm^3·cm^{-3}.

In 2020, 'Orange Smoothie' pumpkin was direct seeded on 15 May into a field at the UNL East Campus Research Farm (lat. 40.84°N, long. 96.66° W; Zook silty clay loam soil). The previous crop was soybean. The planting method was changed in 2020 to avoid transplant shock observed in 2019 that delayed crop growth and development. Before planting seeds, the experimental area was fertilized with 112 kg·ha^{-1} N as granular urea (46N–0P–0K; PRO-AP, Wawaka, IN, USA) and fertilizer was incorporated with rotary tillage. Soil P and K levels were sufficient, and no fertilizer was applied. Plot setup (raised beds, plastic mulch film, and drip tape), plot dimensions, treatment structure, and management were otherwise identical to the 2019 experiment.

Herbicides were applied using a CO_2-pressurized tank sprayer with a two-nozzle boom and nozzles spaced 20 inches apart. The sprayer was calibrated to deliver 140 L·ha^{-1} at 276 kPa through a TeeJet 8001E nozzle (TeeJet Technologies, Spraying Systems Co., Wheaton, IL, USA). Travel speed of the nozzle was based on the walking speed of ~4.8 km/h. The vegetative stage treatment was applied on 20 Jun 2019 (21 d after transplanting; 8 to 10 fully emerged leaves) and 12 Jun 2020 (29 d after direct seeding; 12 to 14 fully emerged leaves) before pumpkin plants had produced any flowers. The flowering stage treatments were applied on 11 Jul 2019 (42 d after transplanting) and 23 Jun 2020 (40 d after direct seeding), when the pumpkin plants were presenting two or more male flowers and had begun vining out. Visible injury ratings were conducted at a 7-d interval until harvest. Visible injury ratings were adapted from Frans et al. (1986) and based on a linear scale of 0 (no injury) to 100 (mortality) relative to the nontreated control (Table 1). The injury symptoms noted were chlorosis, leaf malformation, and epinasty. In 2019, pumpkins were harvested twice; first on 2 Sep and again on 30 Oct. In 2020, pumpkins were harvested three times; 4 and 18 Aug, and 3 Sep. Pumpkin fruit was cut from the vine along with 4 inches of the peduncle (i.e., the handle) and weighed fresh in the field. Stand density was determined before the first herbicide application to account for any plants lost to transplant shock (2019) or poor germination and establishment (2020). Pumpkin yields from each harvest event were pooled for a season total and adjusted for per plot stand density before analysis.

Statistical analysis. Preliminary analysis included analysis of variance to determine the potential for interacting effects of year and herbicide rate on visible injury and yield within each growth stage and herbicide type. The year-by-rate effect was significant ($P < 0.05$) for all responses; therefore, years were analyzed separately.

Due to the nonlinear nature of plant response to low rates of herbicide, a four-parameter log-logistic regression model was used to analyze the relationship between 2,4-D

Table 1. Visible injury rating system adapted from Frans et al. (1986) and used by a single rater every 7 d after pumpkins were treated with 2,4-D or dicamba.

Visible injury rating (%)	Observation
0	No injury evident
5	Very slight, barely noticeable
10	Injury is clearly noticeable
15	Moderate injury, recovery is expected
25	Substantial damage including discoloration, distortion, stunting; some damage appears irreversible
40	Majority of plants damaged; some plants (<40%) dead or dying; substantial necrosis, stunting, and distortion
50	Nearly all plants damaged irreversibly; 40% to 50% dead or dying
70	Severe damage; 50% to 60% dead or dying
80	Very severe damage; 60% to 80% dead or dying
90	Extreme damage; >80% of plants dead or dying and remaining plants are severely damaged
100	100% plant mortality

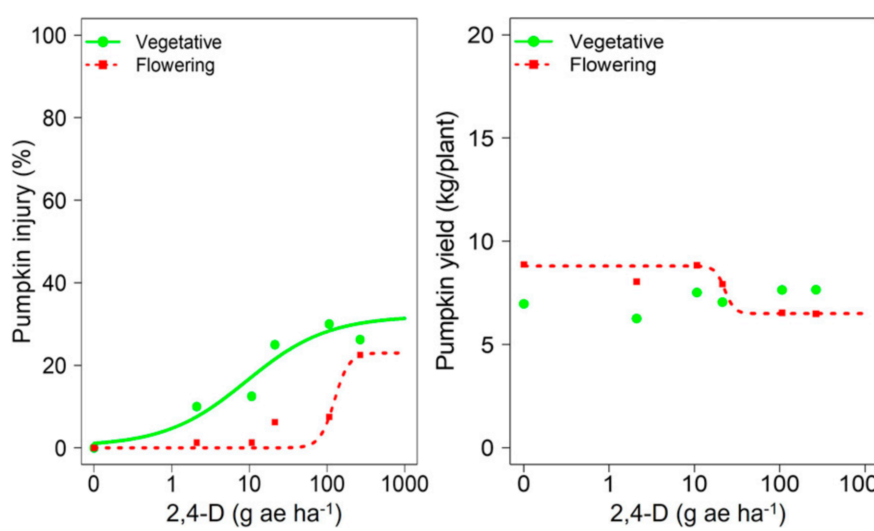

Fig. 1. Four-parameter log-logistic dose response curves in 2019 for pumpkin visible injury (left; 21 d after treatment when symptom severity peaked) and fruit yield (right; 1 kg/plant = 2.205 lbs/plant) following treatment with 2,4-D choline at the vegetative or flowering growth stage. Plotted data points are treatment means across replicate blocks. Herbicide doses on the horizontal axis [0, 1/500, 1/100, 1/50, 1/10, and 1/4 of the 1066 g ae·ha^{-1} (15.22 oz ae/acre) labeled rate for 2,4-D choline] are plotted on a log scale.

and dicamba rates and visible injury and yield (Knezevic et al. 2007). The date of maximum observed visible injury (either 14 or 21 DAT) was used for dose response analyses. The four-parameter model used was

$$Y = c + \{d - c/1 + \exp[b\ (\log x - \log e)]\},$$

where c is the lower limit, d is the upper limit, b is the slope and e is the ED 50 (dose required for 50% response) (Knezevic et al. 2007; Seefeldt et al. 1995). Injury ratings within time intervals and pumpkin growth stage treatments were averaged across the four replicate blocks and fit to the dose-response model across the six tested herbicide doses. Analysis was conducted using the *drc* package in R version 3.4.1 (R Core Team 2019).

Goodness-of-fit parameters for nonlinear functions (Spiess and Neumeyer 2010), including root mean square error (RMSE) and model efficiency (ME), were calculated to evaluate the model-fit using the following equations:

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2\right]^{1/2}$$

$$\mathrm{ME} = 1 - \left[\sum_{i=1}^{n}(O_i - P_i)^2 \Big/ \sum_{i=1}^{n}(O_i - \bar{O}_i)^2\right],$$

where P_i is the predicted value, O_i is the observed value, $\bar{O}_i$ is the mean observed value, and n is the total number of observations. Generally, a smaller RMSE value indicates better model fit, and an ME value closer to 1 indicates more accurate predictions.

Results and Discussion

Pumpkin injury and yield reduction from 2,4-D. In 2019, pumpkins treated with 2,4-D at the vegetative stage showed injury symptoms including leaf and stem curling and epinasty as early as 1 d after treatment (DAT) on the two highest rates of 1/4 and 1/10. Injury symptoms peaked at 21 DAT and the three highest rates of 1/50, 1/10, and 1/4 showed injury (± 1 *SE*) ranging from 25% (± 8%) to 30% (± 2%) (Fig. 1). At 21 DAT at the vegetative stage, the effective herbicide dose required to cause 5% injury (ED5) was 0.3 ± 0.2 g ae·ha^{-1} (∼1/3300 rate) and the effective herbicide dose required to cause 50% injury (ED50) was 9.2 ± 5.2 g ae·ha^{-1} (∼1/120 rate; Table 2). In 2020, at the vegetative stage, the two highest rates also showed symptoms as early as 1 DAT. However, injury symptoms peaked earlier at 14 DAT and the two highest rates showed injury from 46% (± 4%) to 55% (± 3%) (Fig. 2). At 14 DAT at the vegetative stage, the ED5 was 10.7 ± 2.6 g ae·ha^{-1} (∼1/100 rate) and the ED50 was 48.4 ± 8.6 g ae·ha^{-1} (∼1/20 rate).

At the flowering stage in 2019, the 1/10 rate caused 8% (± 3%) injury and 1/4 rate caused 23% (± 3%) injury by 21 DAT (Fig. 1). The ED5 for visible injury was 71.0 ± 8.9 g ae·ha^{-1} (∼1/15 rate) and the ED50 was 133.7 ± 16.8 g ae·ha^{-1} (∼1/8 rate; Table 2). In 2020, visible injury at 14 DAT during the flowering stage was more severe. The 1/10 rate caused 19% (± 5%) injury and the 1/4 rate caused 38% (± 4%) injury. The ED5 for visible injury was 2.4 ± 1.4 g ae·ha^{-1} (∼1/430 rate), and the ED50 was 51.3 ± 29.0 g ae·ha^{-1} (∼1/20 rate).

Table 2. Model estimated effective doses (ED; g ae·ha^{-1}) in 2019 for 5%, 10%, 20%, and 50% visible injury (21 d after treatment) and yield loss to pumpkin after treatment with 2,4-D choline at the vegetative or flowering growth stage. Standard errors of ED estimates are included in parentheses. The root mean square error (RMSE) and model efficiency (ME) are goodness-of-fit parameters for the four-parameter log-logistic dose response model. Missing estimates (–) indicate a lack of model convergence due to a lack of dose response trend. The labeled rate (dose) for 2,4-D is 1066 g·ha^{-1} (15.22 oz/acre).

	Visual injury		Yield	
	Vegetative	Flowering	Vegetative	Flowering
	(g ae·ha^{-1})			
ED5	0.3 (0.2)	71.0 (8.9)	—	16.1 (5.3)
ED10	0.7 (0.4)	83.3 (10.5)	—	17.7 (5.8)
ED20	1.7 (1.0)	99.2 (12.5)	—	19.7 (6.5)
ED50	9.2 (5.2)	133.7 (16.8)	—	23.5 (7.7)
RMSE	8.73	4.32	—	1.98
ME	0.76	0.94	—	0.61

In 2019, no significant reduction in yield was observed when pumpkin were treated with 2,4-D at the vegetative stage (Fig. 1). Model efficiency (ME) was poor (0.51) and standard errors of ED estimates were high indicating poor model fit and a lack dose response. This observation in 2019 may be related to a rainfall event 4 h after application, which could have reduced plant uptake and translocation of 2,4-D [though the product is advertised as rainfast beginning 4 h after application (Corteva AgriScience 2023)]. In 2020, yield was reduced by 31% (± 10%) to 32% (± 2%) at the two highest rates of 1/10 and 1/4 applied at the vegetative stage (Fig. 2). The ED5 for yield was 17.1 ± 3.3 g ae·ha^{-1} (∼1/60 rate) and the ED50 was 24.5 ± 4.8 g ae·ha^{-1} (∼1/40 rate; Table 3). In 2019, the two highest rates (1/10 and 1/4) of 2,4-D applied at the flowering stage caused yield reductions of 26% (± 8%) to 27% (± 15%) (Fig. 1); the ED5 for yield was 16.1 ± 5.3 g ae·ha^{-1} (∼1/70 rate) and the ED50 was 23.5 ± 7.7 g ae·ha^{-1} (∼1/50 rate; Table 2). However, in 2020, there was no significant yield loss across 2,4-D application rates at the flowering stage and the dose response model did not converge (Fig. 2).

Overall, pumpkins treated at the vegetative stage were more susceptible to 2,4-D visible injury compared with the flowering stage, especially at the two highest rates. This finding is consistent with studies in other cucurbit crops including watermelon (Culpepper et al. 2018), cucumber (Gilreath et al. 2001), and cantaloupe (*Cucumis melo* var. *cantalupo*) (Hand et al. 2021) where plants were most susceptible to injury at early vegetative stages of growth. However, visible injury from 2,4-D did not consistently translate to pumpkin yield loss. In 2019, for example, visible injury of up to 30% by 21 DAT at the

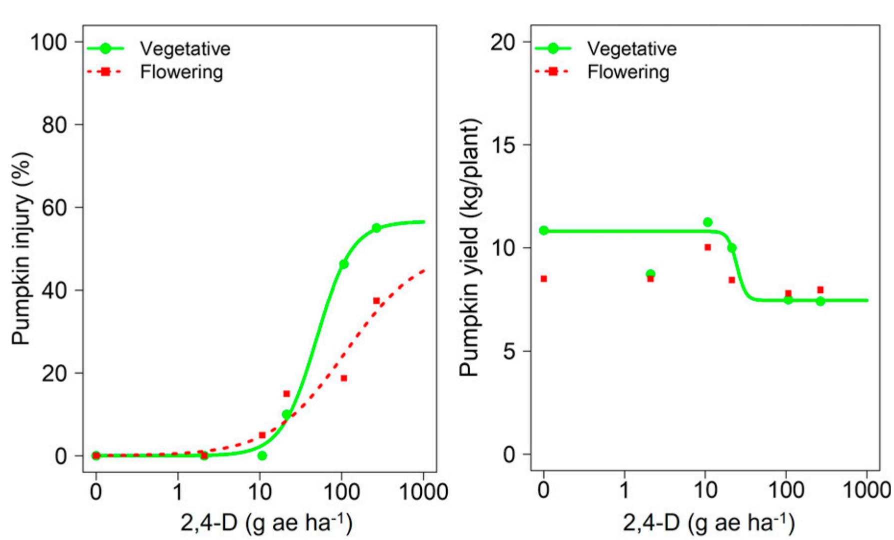

Fig. 2. Four-parameter log-logistic dose response curves in 2020 for pumpkin visible injury (left; 14 d after treatment when symptom severity peaked) and fruit yield (right; 1 kg/plant = 2.205 lbs/plant) following treatment with 2,4-D choline at the vegetative or flowering growth stage. Plotted data points are treatment means across replicate blocks. Herbicide doses on the horizontal axis [0, 1/500, 1/100, 1/50, 1/10, and 1/4 of the 1066 g ae·ha^{-1} (15.22 oz ae/acre) labeled rate for 2,4-D choline] are plotted on a log scale.

Table 3. Model estimated effective doses (ED; g ae·ha^{-1}) in 2020 for 5%, 10%, 20%, and 50% visible injury (14 d after treatment) and yield loss to pumpkin after treatment with 2,4-D choline at the vegetative or flowering growth stage. Standard errors of ED estimates are included in parentheses. The root mean square error (RMSE) and model efficiency (ME) are goodness-of-fit parameters for the four-parameter log-logistic dose response model. Missing estimates (—) indicate a lack of model convergence due to a lack of dose response trend. The labeled rate (dose) for 2,4-D is 1066 g·ha^{-1} (15.22 oz/acre).

	Visual injury		Yield	
	Vegetative	Flowering	Vegetative	Flowering
	(g ae·ha^{-1})			
ED5	10.7 (2.6)	5.5 (2.4)	17.1 (3.3)	—
ED10	15.7 (3.1)	11.9 (5.1)	18.7 (3.7)	—
ED20	23.8 (3.9)	27.8 (12.0)	20.7 (4.1)	—
ED50	48.4 (8.6)	117.6 (50.7)	24.5 (4.8)	—
RMSE	4.31	11.49	1.83	—
ME	0.98	0.85	0.67	—

vegetative stage did not result in any yield loss. In some cases, 2,4-D injury may delay but not reduce yield; Mohseni-Moghadam and Doohan (2015) reported delayed pepper (*Capsicum annuum*) fruit maturation due to simulated drift of 2,4-D and dicamba. Rapid metabolism of 2,4-D has been demonstrated in cucumber (Schroeder 1998), which may help explain instances where visible injury did not cause yield loss in this study. However, high rates of 2,4-D (1/4 and 1/10) at both vegetative and flowering growth stages in our study typically reduced pumpkin yield. Even when plants visibly recover from injury, Colquhoun et al. (2014) found that fruiting vegetable crops can still experience delayed flowering and yield loss.

Pumpkin injury and yield reduction from dicamba. In 2019, dicamba injury on pumpkins at the vegetative growth stage was most severe at the highest application rate (1/4) and typical symptoms included leaf and stem curling with stunted growth (Fig. 3). In 2020, injury was most severe at the two highest rates (1/4 and 1/10) (Fig. 4). In both years, visible injury peaked at 21 DAT when applied at the vegetative growth stage. The highest rate (1/4) in 2019 caused 65% (± 6%) visible injury (Fig. 3) and rates of 1/10 and 1/4 caused 70% (± 0%) and 82% (± 1%) injury in 2020, respectively (Fig. 4). In 2019, the ED5 for visible injury at the vegetative stage 21 DAT was 97.6 ± 9.9 g ae·ha^{-1} (∼1/6 rate) and the ED50 was 98.7 ± 10.0 g ae·ha^{-1} (∼1/6 rate; Table 4). In 2020, the ED5 for visible injury at the vegetative stage 21 DAT was 13.8 ± 3.3 g ae·ha^{-1} (∼1/40 rate) and the ED50 was 33.1 ± 3.2 g ae·ha^{-1} (∼1/15 rate; Table 5).

Dicamba injury after application at the flowering stage was similar to the vegetative stage and symptoms again peaked at 21 DAT. In both years, the two highest rates (1/4 and 1/10) caused significant injury. In 2019, rates of 1/10 and 1/4 caused 31% (± 2%) and 51% (± 1%) injury, respectively (Fig. 3). The ED5 for visible injury at the flowering stage 21 DAT was 21.2 ± 4.7 g ae·ha^{-1} (∼1/25 rate) and the ED50 was 50.4 ± 1.9 g ae·ha^{-1} (∼1/10 rate; Table 4). Injury in 2020 was more severe, and rates of 1/10 and 1/4 caused 49% (± 8%) and 74% (± 5%) injury, respectively (Fig. 4). The ED5 for visible injury at the flowering stage 21 DAT was 35.3 ± 2.3 g ae·ha^{-1} (∼1/15 rate) and the ED50 was 53.1 ± 3.4 g ae·ha^{-1} (∼1/10 rate; Table 5).

Pumpkin yield in 2019 was reduced by 33% (± 2%) after the 1/4 application rate during the vegetative stage. In 2020, yield was reduced at both the 1/10 and 1/4 application rates at the vegetative stage and yield loss ranged from 38% (± 16%) to 86% (± 14%). In 2019, the ED5 for yield after treatment at the vegetative stage was 33.2 ± 10.3 g ae·ha^{-1} (∼1/15 rate) and the ED50 was 75.7 ± 23.5 g ae·ha^{-1} (∼1/7 rate; Table 4). In 2020, the ED5 for yield after treatment at the vegetative stage was 21.7 ± 6.1 g ae·ha^{-1} (∼1/25 rate) and the ED50 was 68.5 ± 19.2 g ae·ha^{-1} (∼1/8 rate; Table 5).

When applied at the flowering stage in 2019, dicamba rates of 1/10 and 1/4 reduced yield by 26% (± 10%) and 41% (± 3%), respectively (Fig. 3). However, yield differences in 2020 were only evident at the 1/4 rate and reached 60% (± 14%) (Fig. 4). The ED5 and ED50 estimates for yield after treatment with dicamba in 2019 at the flowering stage were 19.5 ± 5.8 g ae·ha^{-1} (∼1/30 rate) and 47.0 ± 14.0 g ae·ha^{-1} (∼1/10 rate), respectively (Table 4). In 2020, the dose response model fit was poor (ME = 0.58) and ED estimates were unreliable because yield was highly variable and reductions were only evident at the 1/4 rate (Table 5). Overall, plants in 2020 were healthier due to better establishment (direct seeding instead of transplanting) and an improved nutrition program (increased N fertilizer pre-plant), which may explain differences in results between years.

Wasacz et al. (2022) noted cucurbits, including pumpkin, were generally less sensitive to dicamba compared with other specialty crops, particularly those in the Fabaceae and Solanaceae families. However, injury and leaf deformation were visible on cucurbits at the 1/250 rate 4 weeks after treatment with dicamba (Wasacz et al. 2022). Crop injury, reduced quality, and yield loss have also been detected in sweetpotato after dicamba application rates of 1/80 and 1/250 (Batts et al. 2021). Our results indicate greater tolerance in the tested pumpkin 'Orange Smoothie'; an estimated rate of 1/6 (2019) or 1/40 (2020) dicamba was required before even 5% visible injury was detected at 21 DAT (Tables 4 and 5). However, even if pumpkin is more tolerant to dicamba and recovers from herbicide injury symptoms, previous research suggests it is possible that the plant is still accumulating the herbicide in fruit tissue. Culpepper et al. (2018) detected dicamba in fruit tissue when rates of 1/75 and 1/250 were applied at 40 or 60 d after planting.

It is important that pesticide applicators take extra precautions to prevent off-target movement of 2,4-D and dicamba. Proper nozzle selection, particularly nozzles that create larger droplets that are less susceptible to movement by wind, is an important first step in mitigating off-target injury (Creech et al. 2015). An additional precaution, although not

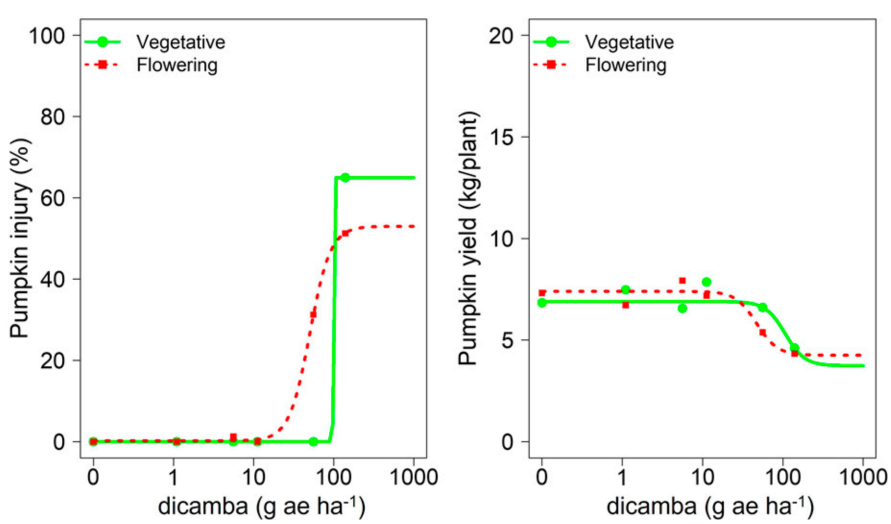

Fig. 3. Four-parameter log-logistic dose response curves in 2019 for pumpkin visible injury (left; 21 d after treatment when symptom severity peaked) and fruit yield (right; 1 kg/plant = 2.205 lbs/plant) following treatment with dicamba at the vegetative or flowering growth stage. Plotted data points are treatment means across replicate blocks. Herbicide doses on the horizontal axis [0, 1/500, 1/100, 1/50, 1/10, and 1/4 of the 560 g ae·ha^{-1} (7.99 oz ae/acre) labeled rate for dicamba] are plotted on a log scale.

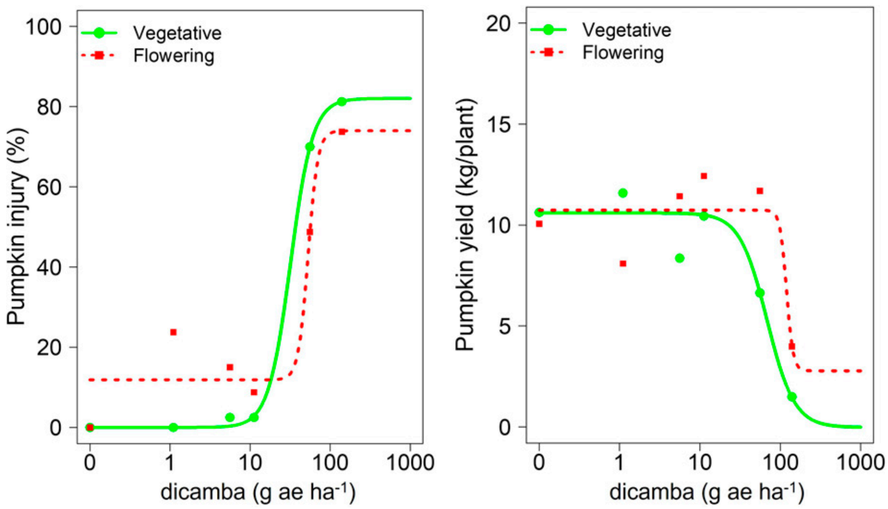

Fig. 4. Four-parameter log-logistic dose response curves in 2020 for pumpkin visible injury (left; 21 d after treatment when symptom severity peaked) and fruit yield (right; 1 kg/plant = 2.205 lbs/plant) following treatment with dicamba at the vegetative or flowering growth stage. Plotted data points are treatment means across replicate blocks. Herbicide doses on the horizontal axis [0, 1/500, 1/100, 1/50, 1/10, and 1/4 of the 560 g ae·ha^{-1} (7.99 oz ae/acre) labeled rate for dicamba] are plotted on a log scale.

Table 4. Model estimated effective doses (ED; g ae·ha^{-1}) in 2019 for 5%, 10%, 20%, and 50% effect on visible injury (21 d after treatment) and yield loss in pumpkin after treatment with dicamba at the vegetative or flowering growth stage. Standard errors of ED estimates are included in parentheses. The root mean square error (RMSE) and model efficiency (ME) are goodness-of-fit parameters for the four-parameter log-logistic dose response model. The labeled rate (dose) for dicamba is 560 g·ha^{-1} (7.99 oz/acre).

	Visual injury		Yield	
	Vegetative	Flowering	Vegetative	Flowering
	(g ae·ha^{-1})			
ED5	97.6 (9.9)	21.2 (4.7)	33.2 (10.3)	19.5 (5.8)
ED10	97.9 (9.9)	26.4 (4.6)	40.9 (12.7)	24.4 (7.2)
ED20	98.2 (10.0)	33.5 (4.1)	51.4 (15.9)	31.0 (9.2)
ED50	98.7 (10.0)	50.4 (1.9)	75.7 (23.5)	47.0 (14.0)
RMSE	4.56	2.16	1.03	1.06
ME	0.98	1.0	0.76	0.75

yet widely adopted, is the use of shielded sprayers, which can reduce drift by up to 59% (Ozkan et al. 1997). Most important, pesticide applicators should continue to follow the label for 2,4-D and dicamba to avoid weather (e.g., high wind speeds and temperature inversions) and management (e.g., high boom speed and height) conditions that might increase the potential for off-target drift. Applicators should also consider steps to minimize residual tank contamination (e.g., double washing with water) after using 2,4-D and dicamba in and around pumpkin and other specialty crops (Roesler et al. 2020). For additional protection, pumpkin growers may consider the use of buffer zones or windbreaks to mitigate the worst effects of off-target herbicide movement from neighboring corn and soybean fields (Brown et al. 2004). Importantly, pumpkin growers and other specialty crop farmers, should be encouraged to register their farms with DriftWatch™ (FieldWatch, Inc., West Lafeyette, IN, USA) or through their local or state department of agriculture to increase awareness and communication among commercial pesticide applicators in field crops and specialty crop growers.

Future research efforts should be directed toward improving knowledge about the relationship between plant tissue residue analyses after off-target injury events and potential yield loss in specialty crops. After a suspected off-target herbicide injury event, growers are encouraged to send a tissue sample to a commercial laboratory for testing to confirm the presence of herbicide residues. These tests are helpful for confirming categorical presence or absence of suspected chemicals, but less is known about whether these tests can be reliably used to inform possible off-target injury rates. Andersen et al. (2004) reported correlations between soybean foliar residue concentrations and application rates of dicamba and 2,4-D for up to 24 and 12 d after treatment, respectively. However, the nature of this relationship will be affected by crop species, herbicide formulation, and weather (Hand et al. 2021), which will require further research. Establishing a relationship between residual herbicide concentrations and initial off-target rates will help growers make better use of dose response data from this study and others to make important economic decisions after off-target herbicide injury events.

Table 5. Model estimated effective doses (ED; g ae·ha^{-1}) in 2020 for 5%, 10%, 20%, and 50% effect on visible injury (21 d after treatment) and yield loss in pumpkin after treatment with dicamba at the vegetative or flowering growth stage. Standard errors of ED estimates are included in parentheses. The root mean square error (RMSE) and model efficiency (ME) are goodness-of-fit parameters for the four-parameter log-logistic dose response model. The labeled rate (dose) for dicamba is 560 g·ha^{-1} (7.99 oz/acre).

	Visual injury		Yield	
	Vegetative	Flowering	Vegetative	Flowering
	(g ae·ha^{-1})			
ED5	13.8 (3.3)	35.3 (2.3)	21.7 (6.1)	91.7 (552.1)
ED10	17.3 (3.5)	39.2 (2.5)	29.1 (8.2)	98.1 (626.1)
ED20	22.0 (3.5)	43.8 (2.8)	39.9 (11.2)	105.6 (720.0)
ED50	33.1 (3.2)	53.1 (3.4)	68.5 (19.2)	119.7 (916.2)
RMSE	2.76	13.04	2.41	4.12
ME	1.0	0.92	0.86	0.58

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