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2,4-D and dicamba removal from the surface of plastic mulch using overhead irrigation: analytical analysis and cucurbit bioassay crop response

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Research Article

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2,4-D; dicamba; annual morningglory; *Ipomea* spp.; cutleaf evening primrose; *Oenothera laciniata* Hill; horseweed; *Conyza canadensis* (L.) Cronq.; wild radish; *Raphanus raphanistrum* L.; cantaloupe; *Cucumis melo* var. *cantalupo* (Ser.); zucchini squash; *Cucurbita pepo* (L.)

Keywords:
herbicide removal from plastic mulch; plasticulture vegetable production; preplant herbicide applications

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Abstract

Glyphosate and paraquat are effective preplant burndown herbicide options for multicrop vegetable production that uses plastic mulch, but problematic weeds such as wild radish, cutleaf evening primrose, annual morningglory, or horseweed may not be adequately controlled with these herbicides alone. The herbicides 2,4-D and dicamba could help control these troublesome weeds prior to planting if they can be removed from plastic mulch and thus avoid crop damage. Treatments included 2,4-D (1,065 and 2,130 g ae ha^{-1}) and dicamba (560 and 1,120 g ae ha^{-1}) applied broadcast over plastic mulch a day before transplanting. Just before transplanting, treatments received either 0.76 cm of water via overhead irrigation or no irrigation. Plastic mulch samples were collected at application and planting to determine herbicide presence using analytical techniques, and cantaloupe and zucchini squash were subsequently transplanted on the plastic beds. Analytical ultra-high performance liquid chromatography revealed that 88% to 99% of the initial herbicide concentration was present at crop planting when irrigation was not implemented. At most, a 1/50 rate of dicamba and a 1/500 rate of 2,4-D was present at planting when overhead irrigation was applied prior to transplanting. Maximum cantaloupe and squash injury from 2,4-D with irrigation was 10% and did not influence plant growth, biomass, or yield. For dicamba with overhead irrigation, cantaloupe injury was 35%, vine lengths were reduced by 24%, and maturity was delayed, whereas squash injury ranged from 9% to 12%, with no influence on growth or yield. Without irrigation to wash herbicides from the mulch prior to planting, 60% to 100% injury of both crops occurred with both herbicides. Zucchini squash was more tolerant to dicamba than cantaloupe. Results demonstrated that 2,4-D can be adequately removed from the surface of plastic mulch with irrigation, whereas a single irrigation event was not sufficient to remove dicamba.

Introduction

Following phase out of the fumigant methyl bromide, pest management in plasticulture vegetable production has undergone significant changes (Culpepper et al. 2009; Eure and Culpepper 2017; Stevens et al. 2016). Fumigant systems in Georgia commonly include a combination of 1,3-dichloropropene, chloropicrin, and metam sodium injected under either low-density polyethylene (LDPE) mulch or totally impermeable film (Culpepper et al. 2008, 2017). This system provides exceptional control of weeds, diseases, and nematodes for the first crop; however, vegetable producers in the Southeast may use a single installation of plastic mulch for up to five crop cycles lasting 18 to 24 mo. The time between the termination of one crop and the planting of another allows weeds to germinate, emerge, and establish in old plant holes or between the plastic mulched beds. To establish a crop that is free of weeds requires additional preplant burndown herbicides that can be applied over plastic mulch without injuring the crop.

Glyphosate and paraquat are two of the most popular herbicides used for preplant burndown over multicrop plastic mulch because of their ability to be removed from the mulch with a single rainfall or irrigation event of 1 cm, thereby minimizing plant-back concerns (Anonymous 2018a; Boyd 2016; Culpepper et al. 2009; Grey et al. 2009). Other herbicides may not be easily removed from plastic mulch. Even herbicides that can be removed may persist in the soil of old plant holes or tears in the mulch; both scenarios pose a serious risk to high-value vegetable crops. Previous research concluded that fomesafen can be removed from plastic mulch with 1 cm of rainfall or overhead irrigation (Culpepper and Smith 2017). However due to soil persistence, sensitive crops such as cole crops [broccoli (*Brassica oleracea* var. *botrytis* L.), cabbage (*Brassica oleracea* var. *oleracea* L.), and cauliflower (*Brassica oleracea* var. *botrytis* L.)], cannot be planted for up to 18 mo after application (Anonymous 2019). In contrast to fomesafen, neither flumioxazin nor halosulfuron are easily or effectively removed from plastic mulch with rainfall or irrigation (Culpepper et al. 2009; Grey et al. 2009). In fact, broccoli, cabbage, and squash were damaged by halosulfuron applications to plastic mulch after 30 d and 19 cm of rainfall had fallen between applications and planting (Randell et al. 2020). Halosulfuron can be removed from mulch eventually, but often not in a realistic time frame for planting sensitive crops such as squash, broccoli, or cabbage (Grey et al. 2018; Randell et al. 2020). Therefore, herbicides that can be used in multicrop plasticulture must effectively control troublesome weeds, mix well with glyphosate or paraquat, and be easily removed from plastic mulch with rainfall or irrigation. Herbicides that meet these parameters and minimize the potential for crop injury could provide significant utility for growers using this system.

Interest in using 2,4-D and dicamba as preplant herbicides in multicrop plastic systems has increased following the introduction of auxin-tolerant crops and formulation improvements (Anonymous 2018b, 2018c, 2018d; Johnston et al. 2018). With the availability of less volatile formulations and proper stewardship of these weed control formulations, these herbicides could be useful to vegetable growers. Some of the most problematic weeds when planting vegetables in the southeastern United States include wild radish, cutleaf evening primrose, horseweed, and various annual morningglory species. Glyphosate or paraquat alone are reported to provide 80% to 81%, 56% to 60%, 55% to 74%, and 69% to 81% control of these weeds, respectively (Culpepper et al. 2005; Eubank et al. 2008; Wilson and Worsham 1988). When 2,4-D or dicamba were mixed with glyphosate or paraquat, at least 90% control was noted with all four weed species (Culpepper et al. 2005; Eubank et al. 2008; Leon et al. 2016). Although 2,4-D and dicamba would improve preplant weed control in these systems, nontransgenic broadleaf crops are sensitive to these herbicides. Significant injury and yield reductions have been documented in bell pepper, potato, snap bean, squash, and watermelon when low rates of auxinic herbicides were applied to crop foliage (Colquhoun et al. 2014; Culpepper et al. 2018; Dittmar et al. 2016).

Herbicide registrations for use on high-value vegetable crops are rare and often entirely dependent on crop response as opposed to efficacy in weed control (Culpepper et al. 2009; Kuack 2020). Thus, crop response and tolerance must be well understood prior to pursuing registration of any herbicide for use on a vegetable crop. The interaction of 2,4-D or dicamba with plastic mulch as influenced by irrigation prior to planting vegetables has not been studied. Therefore, analytical and bioassay experiments were conducted to quantify 2,4-D and dicamba removal from plastic mulch using a single overhead irrigation event.

Materials and Methods

Site Selection and Trial Establishment

Four studies were conducted at the University of Georgia Ponder Research Farm (31.30°N, 83.39°W) near Ty Ty, Georgia, from the spring of 2018 through the fall of 2019 to determine 1) the influence of overhead irrigation on either 2,4-D or dicamba removal from plastic mulch using analytical techniques; and 2) cantaloupe and zucchini squash response to 2,4-D and dicamba applied preplant broadcast over mulch, and followed by either irrigation or no irrigation prior to transplanting. Soils at the site consisted of a Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with 84% to 90% sand, 8% to 10% silt, 2% to 6% clay, and 0.63% to 0.65% organic matter, and pH 6.2 to 6.6. Soil was prepared conventionally and raised beds (20 cm tall, 81 cm wide) on 183-cm centers were formed in the winter prior to planting to allow fumigant dissipation following standard grower practices. As beds were formed, fumigants (1,3-dichloropropene, chloropicrin, and metam sodium) were applied under the mulch to keep the experimental planting area free of diseases, nematodes, and weeds. The initial bedder (Hendrix & Dail, Inc. Greenville, NC) injected 1,3-dichloropropene and chloropicrin (Pic-Chlor 60; TriEst Ag Group, Inc., Greenville, NC) at a rate of 197 L ha^{-1} 20 cm below the bed top using three evenly spaced injection shanks. This was followed by a combination bed shaper and plastic mulch layer (Kennco Manufacturing, Inc., Ruskin, FL), which injected metam sodium (Vapam® HL™; AMVAC, Los Angeles, CA) 10 cm deep with injection shanks 10 cm apart, at a rate of 700 L ha^{-1}. As metam sodium was injected, drip tape (Rivulus Irrigation Ltd., Gvat, Israel) was laid in the center of the raised bed 2.5 cm below the bed surface, and the entire bed was covered with black-on-white LDPE plastic mulch (Guardian Agricultural Plastics Corporation, Tampa, FL). For the cantaloupe study in 2018 and the fall zucchini squash study in 2019, the white side of the mulch was face-up. For both spring studies in 2019, the black side of the mulch was face-up. This did not have an effect on herbicide removal, but we did this because it is similar to growers' practices. To ensure crop response was not influenced by weed competition from row middles, glyphosate (1.12 kg ae ha^{-1}), flumioxazin (0.14 kg ai ha^{-1}), and *S*-metolachlor (1.1 kg ai ha^{-1}) were applied between plastic-mulched beds approximately 1 wk prior to planting in accordance with university recommendations for the region (Kemble et al. 2019). Row middles were subsequently hand weeded for escapes as needed.

Experimental treatments were an augmented factorial of two herbicides, two application rates, and two preplant irrigation options. A nontreated control was included for comparison. Treatments were arranged in a randomized complete block design with four replications per study site. Herbicides included 2,4-D choline (Embed® Extra; Corteva Agriscience, Indianapolis, IN) at 1,065 and 2,130 g ae ha^{-1}; and dicamba (Xtendimax®; Bayer CropScience, St. Louis, MO) at 560 and 1,120 g ae ha^{-1}. Herbicide rates correspond to a 1× and 2× anticipated field use rate, respectively. Herbicides were applied on April 11, 2018 (cantaloupe), April 10, 2019 (cantaloupe and zucchini squash), and September 22, 2019 (zucchini squash), and allowed to dry for 24 h. Herbicide applications were broadcast directly over plastic mulch using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1}. Different booms were used to apply each herbicide with all dicamba applications using TTI 110015 nozzles (Teejet Technologies, Wheaton, IL); 2,4-D applications used AIXR 11002 nozzles (Teejet Technologies) in 2018 and TTI 110015 nozzles in 2019 due to changes in product labeling. Spray booms were 138 cm long with a nozzle spacing of 46 cm, and booms were held 41 cm above the mulch. At the time of application, air temperature ranged from 12 to 21 C, relative humidity ranged from 75% to 83%, and wind speeds did not exceed 4 km h^{-1}.

On the day after application when the plastic was dry from morning dew, to prevent herbicide wash off, custom made metal boxes were placed on top of the plastic mulched beds of plots that did not receive irrigation. Boxes were made of stainless aluminum; weighed approximately 10 kg; and measured 244 cm long, 71 cm wide, and 5 cm tall, tapered to seal against the surface of the plastic-mulched beds without damaging the plastic mulch. Once the covers were in place, overhead irrigation was applied over the plastic mulch at 0.76 cm using a lateral pivot. Upon completion of overhead irrigation, the covers were removed and the mulched beds that received irrigation were allowed time to dry prior to mulch sampling and crop planting. Metal covers remained over mulch less than 3 h.

Analytical Methods

To quantify removal of 2,4-D or dicamba with irrigation, mulch samples were taken approximately 2 h after herbicide application, and again following overhead irrigation but prior to crop planting for a total of two samples per treated plot. Samples of mulch were collected from each plot using a 0.1-m^2 quadrat. A box-cutting knife was used to harvest the mulch along the inside edge of the square. Needle-nose pliers were then used to mechanically fold the LDPE mulch inward without contacting the treated side of the mulch to prevent contamination of the treated surface with any foreign objects. Samples were subsequently stored in plastic bags, frozen upon collection, and stored at −10 C until analysis.

Field plot replicate sample integrity was maintained throughout sample collection, preparation, and chemical analysis. For herbicide analysis, samples were removed from the freezer and allowed to equilibrate to room temperature prior to being placed in a 125-ml volumetric flask sealed with a rubber stopper. Extractions were conducted using 10% methanol with high-performance liquid chromatography (HPLC) water (Fisher Scientific, Hampton, NH). The extraction volumes were 100 ml. Samples were placed on a reciprocating shaker for 2 h at 200 rpm. Upon removal, samples were passed through a 0.2-μM polytetrafloroethylene (PTFE) membrane filter (Fisher Scientific) that was fitted to a Luer-Lok™ syringe (Fisher Scientific), and then passed into a 1.5-ml microcentrifuge tube (Fisher Scientific). Microcentrifuge tubes were sealed, and centrifuged at 12,000 rpm for 5 min. An aliquot was then transferred into HPLC vials (Fisher Scientific). Samples were analyzed with a Waters Acquity Arc ultra-high performance liquid chromatography system, coupled with a Waters 2998 PDA and Waters QDa Mass Spectometry Detector. For analysis, the mobile phase consisted of 1) 1:9 acetonitrile:water, 2) 9:1 acetonitrile:water, and 3) water. A Cortecs C_{18} 4.6 × 50 mm column with 2.7-μm packing (Waters Corporation, Milford, MA) was used with a flow rate of 1.1 ml min^{-1}, an injection volume of 47 μl, and a run time of 5 min per injection. Chromatographic conditions were adapted from those described by Majzik et al. (2006). Standard curves were generated using the formulations applied in experiments and based on the acid equivalent applied.

Crop Establishment and Data Collection

Transplant holes were hand-poked in the plastic mulch using a custom-made hole puncher on April 13, 2018, April 11, 2019, and September 23, 2019. The custom hole puncher, built from stainless aluminum, was used to eliminate plot-to-plot herbicide contamination. After it was used on each plot, the implement was cleaned with a mixture of ammonia and water before beginning on the next plot. The size of the plant hole created by the custom hole puncher was identical to a hole created by a standard transplant hole punch wheel (Kennco Manufacturing, Inc., Ruskin, FL). 'Athena' cantaloupe (10 cm in height) was transplanted April 13, 2018, and April 11, 2019, in single rows with a spacing of 183 cm between beds and 30 cm between plants within a row. 'Spineless Beauty' and 'Payroll' zucchini squash (10 cm in height) were transplanted on April 11, 2019, and September 23, 2019, respectively, using the same spacing as cantaloupe. One day after transplanting, all plots received 0.4 cm of irrigation to water-in the transplants and to simulate a rainfall event in which the herbicide could move onto the foliage of the transplants or wash into the transplant hole. From that point forward, both crops were managed for irrigation, fertility, and control of pests in accordance with university recommendations for the region (Kemble et al. 2019).

Estimates of visual crop injury (chlorosis, epinasty, stunting, leaf deformations) was rated on a scale of 0% to 100% (0% being no injury, 100% being crop death) every 7 d beginning 1 wk after planting up to 5 wk after planting. Reductions in cantaloupe growth were quantified by measuring the length of the longest vine; zucchini squash growth was quantified by measuring across the diameter of the plant. Eight plants per plot were measured weekly up to 3 wk after planting. Early-season fresh weight biomass was measured by removing plants at the ground level and recording their collective weight. For cantaloupe, biomass was taken by harvesting every other plant leaving eight plants per plot spaced 60 cm apart for harvest and for squash, biomass was taken from plants on each end of the plot leaving the eight center plants per plot spaced 30 cm apart for harvest (Coolong and Kelley 2014; Coolong and Boyhan 2017). Cantaloupes were harvested 9 to 13 times, with number of fruit and weight per plot recorded for each harvest. Harvests were then split into early harvests (1 to 4) and total harvests (1 to 13) to determine the impacts of crop damage on earliness of harvest as well as total harvest for the season. Zucchini squashes were harvested up to 31 times, with number of fruit and weight per plot recorded for each harvest. Zucchini squash harvests were then split into early harvests (1 to 8), and total harvests (1 to 31) to determine the impacts of crop damage on earliness of harvest as well as harvest throughout the season.

Statistical Analysis

Analytical and bioassay data were subjected to an ANOVA to test for experimental run by treatment interactions. No significant interactions were present; therefore, all data are pooled over experimental run. Analytical data were compared using the GLIMMIX procedure in SAS software (version 9.4; SAS Institute Inc., Cary, NC) to determine whether the combined treatment effects of herbicide, rate applied, and preplant irrigation affected herbicide concentration present on the plastic mulch at planting. Concentrations were log transformed to improve normality and homogeneity of variance prior to analysis; however, all data are presented in their nontransformed values. Replications and location were included in the model as random factors. Concentration means were compared and adjusted using the Shaffer-simulated method ($\alpha = 0.05$).

Bioassay data were compared using the GLIMMIX procedure in SAS to determine whether the combined treatment effects of herbicide, rate, and preplant irrigation option influenced cantaloupe and zucchini squash growth, development, and yield. Replications and location were included in the model as random factors. All data for cantaloupe were normally distributed. Zucchini squash injury, fruit number, and weight were arcsine square root, square root, and log transformed, respectively, to improve normality and homogeneity of variance; however, all data are presented in their back-transformed values. All P-values for tests of differences between least-squares means were compared and adjusted using the Shaffer-simulated method ($\alpha = 0.05$).

Table 1. Herbicide concentration remaining on plastic mulch at planting as influenced by herbicide option, rate applied, and preplant overhead irrigation option.[a]

Herbicide	Original concentration[b]	No irrigation	Irrigation
		Concentration at planting[c,d]	
	ppm m^{-2}		
2,4-D	1,059	932 ab	2 d
	2,118	1,925 a	3 d
Dicamba	535	530 b	7 c
	1,070	1,059 ab	11 c

[a]Herbicide concentrations are combined over four experimental runs.
[b]Original concentrations are concentrations that were present on plastic mulch 2 h after application.
[c]Concentrations present at planting were evaluated following a 1-d interval and implementation of the overhead irrigation treatment. Irrigated treatments received 0.76 cm, while treatments without irrigation were covered to prevent herbicide wash off.
[d]Means followed by the same letter with respect to herbicide concentration present on plastic at planting do not differ significantly ($P \leq 0.05$).

Table 2. Cantaloupe injury and vine length response as influenced by herbicide option, rate applied, and preplant overhead irrigation option.

Irrigation option[a]	Herbicide	Injury[b] 1× rate[c]	Injury[b] 2× rate[c]	Vine lengths[b] 1× rate[c]	Vine lengths[b] 2× rate[c]
		%		cm	
Irrigation	2,4-D	4 e	5 e	55 a	50 ab
	Dicamba	18 d	35 c	48 ab	39 b
No irrigation	2,4-D	75 b	85 b	18 c	13 cd
	Dicamba	99 a	100 a	1 d	0 d
	NTC[d,e]	0		51 a	

[a]Treatments requiring overhead irrigation received 0.76 cm, while nonirrigated treatments were covered to prevent herbicide wash off.
[b]Means followed by the same letter with respect to the response variable do not differ significantly ($P \leq 0.05$). Data are pooled over 2018 and 2019.
[c]Rates applied were 1,065 (1×) and 2,130 (2×) g ae ha^{-1} for 2,4-D and 560 (1×) and 1,120 (2×) g ae ha^{-1} for dicamba.
[d]Abbreviation: NTC, nontreated control.
[e]NTC plots were maintained weed free to ensure growth was not impacted by weed competition.

Results and Discussion

2,4-D and Dicamba Concentrations Present On the Mulch at Crop Planting

Dicamba application rates of 560 and 1,120 g ae ha^{-1} are equivalent to 535 and 1,070 ppm m^{-2}, respectively, whereas 2,4-D applied at 1,065 and 2,130 g ae ha^{-1} is equivalent to 1,059 and 2,118 ppm m^{-2}, respectively. When irrigation was not implemented, dicamba was present at 99% of the applied concentration at planting, whereas 2,4-D was present at 88% to 91% of the initial concentration (Table 1). Overhead irrigation significantly reduced concentrations of both herbicides to less than 12% of the original concentration. Dicamba concentrations, even when applying half the concentration compared to 2,4-D, remained on the mulch at more than 3.5 times than observed with 2,4-D. Concentrations retained on the mulch were 1/50 to 1/100 the 1× rate of dicamba and 1/500 to 1/625 the 1× rate of 2,4-D. Previous studies have noted a high level of injury and yield loss from dicamba at much lower rates than those observed on the mulch in this study when applied to the foliage of squash and cantaloupe (Culpepper and Vance 2019; Dittmar et al. 2016; Hand et al. 2019). Injury from 2,4-D has not been noted from rates lower than 1/300× for either cantaloupe or squash (Culpepper and Vance 2019).

Cantaloupe Experiment

Visual injury estimates were maximum at 22 to 29 d after planting (DAP). Cantaloupe injury was significantly affected by the interaction of herbicide, rate, and irrigation option ($P < 0.0001$). When overhead irrigation was received prior to transplanting, 2,4-D treatments caused ≤5% injury, regardless of rate (Table 2). Dicamba applied at a 1× and 2× rate and subsequently treated with overhead irrigation resulted in 18% and 35% injury, respectively. Dicamba treatments that received overhead irrigation prior to planting recovered as the season progressed, with 10% to 15% injury noted approximately at 40 DAP (data not shown). When overhead irrigation was not implemented damage was severe regardless of herbicide or rate applied; however, cantaloupe damage was 15% to 24% less with 2,4-D as compared to dicamba used at comparable rates.

Cantaloupe vine lengths were also influenced by the interaction of herbicide, rate, and irrigation option when collected 27 to 28 DAP ($P < 0.0001$). Similar vine lengths were observed between the control, both rates of 2,4-D, and the low rate of dicamba as long as irrigation occurred after application and before planting (Table 2). The 2× rate of dicamba, even with overhead irrigation, resulted in plant vine lengths that were reduced 24% compared to the control. Without overhead irrigation, 2,4-D or dicamba reduced vine lengths by 65% to 100%. Fresh weight biomass measured 20 to 25 DAP was influenced by the interaction of herbicide and overhead irrigation option prior to planting ($P < 0.0001$). Averaged over herbicide rate, when 2,4-D was applied and washed from the mulch, fresh weight biomass was similar to that of the control (Table 3). In contrast, even when dicamba was washed from the mulch, a reduction in fresh weight biomass of 19% was observed. When neither herbicide was removed from the mulch with overhead irrigation, fresh weight biomass reductions of 91% to 99% resulted.

Table 3. Cantaloupe fresh weight biomass and early harvest fruit weight as influenced by overhead irrigation prior to planting and herbicide applied.[a]

Irrigation option[b]	Herbicide	Biomass[c]	Early fruit weight[c]
		g $plant^{-1}$	kg ha^{-1}
Irrigation	2,4-D	52 a	10,930 a
	Dicamba	43 b	7,800 b
No irrigation	2,4-D	5 c	0 c
	Dicamba	1 c	0 c
	NTC[d,e]	53 a	11,520 a

[a]Data are averaged over year and herbicide rate applied. Early harvests were the first four harvests for cantaloupe experiments.
[b]Treatments requiring overhead irrigation received 0.76 cm, while nonirrigated treatments were covered to prevent herbicide wash off.
[c]Means followed by the same letter with respect to the response variable do not differ significantly ($P \leq 0.05$).
[d]Abbreviation: NTC, nontreated control.
[e]NTC plots were maintained weed free to ensure growth was not impacted by weed competition.

Maturity or earliness of harvest is of paramount importance in vegetable production because of its impact on fruit value. Injury from an herbicide application causing a delay in maturity could directly affect profitability. Therefore, to quantify potential delays in maturity, the first four cantaloupe harvests were analyzed. Early-

Table 4. Cantaloupe yield over the entire season as influenced by herbicide option, rate applied, and preplant overhead irrigation option.

Irrigation option[a]	Herbicide	Fruit number[b] 1× rate[c]	Fruit number[b] 2× rate[c]	Fruit weight[b] 1× rate[c]	Fruit weight[b] 2× rate[c]
		no. ha^{-1}		kg ha^{-1}	
Irrigation	2,4-D	23,956 ab	24,517 ab	55,545 a	57,282 a
	Dicamba	25,357 a	24,517 ab	66,419 a	53,256 a
No Irrigation	2,4-D	19,994 b	10,647 c	53,521 a	26,855 b
	Dicamba	0 d	0 d	0 c	0 c
	NTC[d,e]	24,417 ab		56,677 a	

[a]Treatments requiring overhead irrigation received 0.76 cm, while nonirrigated treatments were covered to prevent herbicide wash off.
[b]Means followed by the same letter with respect to the response variable do not differ significantly ($P \leq 0.05$). Data pooled over 2018 and 2019. Cantaloupe were harvested a total of 9 to 13 times.
[c]Rates applied were 1,065 (1×) and 2,130 (2×) g ae ha^{-1} for 2,4-D and 560 (1×) and 1,120 (2×) g ae ha^{-1} for dicamba.
[d]Abbreviation: NTC, nontreated control.
[e]NTC plots were maintained weed free to ensure growth was not impacted by weed competition.

season fruit counts were influenced only by the overhead irrigation option ($P < 0.0001$). Averaged over herbicide and rate applied, early-season fruit count (5,746 fruit ha^{-1}) was similar to that of the nontreated control (6,421 fruit ha^{-1}) when irrigation was implemented (data not shown). When herbicides weren't washed from the mulch, early-season fruit counts were reduced 100%. Although early-season fruit counts were influenced only by the preplant irrigation option, early-season fruit weight was influenced by the interaction of herbicide and preplant overhead irrigation option ($P < 0.0001$). Similar to previous results, when 2,4-D was washed from the mulch, early-season fruit weights were not influenced (Table 3). However, when dicamba was washed from the mulch, early-season fruit weight was reduced by 32% compared to the control. Herbicides that were not washed from the mulch eliminated early-season fruit.

Total cantaloupe yield (in fruit counts and weight) was affected by the interaction of herbicide, rate, and preplant irrigation option when harvested 9 to 13 times ($P < 0.0001$). Cantaloupe yielded 24,417 fruit ha^{-1} weighing 56,677 kg ha^{-1} in the control (Table 4). Fruit counts and weights were not influenced by either 2,4-D or dicamba as long as overhead irrigation was included. Although early-season injury from dicamba with irrigation was observed, the crop was able to recover without season-long yield loss. The ability of crops to recover from low-dose auxin injury early in the season has been observed. For example, in cotton, exposure of auxin susceptible two-leaf cotton to low-doses of 2,4-D or dicamba resulted in significant injury in the first 2 wk following exposure (50% to 57%), but effects on yield were minimal (Everitt and Keeling 2009). Similar observations were noted in nontolerant soybean (Solomon and Bradley 2014). When overhead irrigation was not implemented prior to planting and injury was more severe, the 1× rate of 2,4-D did not significantly reduce fruit weight, but fruit count was reduced by 18%. The 2× rate of 2,4-D reduced counts and weights by 53% to 56%. This demonstrates a lack of a 2× safety factor in the absence of preplant overhead irrigation, which is generally required for herbicide registrations (Monaco et al. 2002). Impact was more severe with dicamba, as no fruit was harvested.

Zucchini Squash Experiments

Visual injury estimates for zucchini squash were at their maximum 14 to 21 DAP, and was significantly affected by the interaction of herbicide, rate, and irrigation option ($P < 0.0001$). With overhead irrigation included prior to planting, injury was similar with both rates of dicamba and 2,4-D, ranging from 6% to 12% (Table 5). Previous research has noted zucchini squash to be more tolerant

Table 5. Zucchini squash injury and widths as influenced by herbicide, rate applied, and preplant overhead irrigation option.[a]

Irrigation option[b]	Herbicide	Injury[c] 1× rate[d]	Injury[c] 2× rate[d]	Widths[c] 1× rate[d]	Widths[c] 2× rate[d]
		%		cm	
Irrigation	2,4-D	6 d	10 d	99 a	98 a
	Dicamba	9 d	12 d	103 a	97 a
No irrigation	2,4-D	60 c	68 b	71 b	60 b
	Dicamba	90 a	92 a	21 c	11 c
	NTC[e,f]	0		98 a	

[a]All data are combined across spring and fall of 2019.
[b]Treatments requiring overhead irrigation received 0.76 cm, while nonirrigated treatments were covered to prevent herbicide wash off.
[c]Means followed by the same letter with respect to the response variable do not differ significantly ($P \leq 0.05$).
[d]Rates applied were 1,065 (1×) and 2,130 (2×) g ae ha^{-1} for 2,4-D and 560 (1×) and 1,120 (2×) g ae ha^{-1} for dicamba.
[e]Abbreviation: NTC, nontreated control.
[f]NTC plots were maintained weed free to ensure growth was not impacted by weed competition.

of herbicides compared to yellow squash cultivars, which may have influenced the low levels of injury observed with dicamba in zucchini squash (Webster et al. 2003). When no overhead irrigation was implemented, preplant applications of 2,4-D injured zucchini squash by 60% at the 1× rate and by 68% at the 2× rate, which was less than the 90% to 92% noted with dicamba.

Zucchini squash plant widths, measured 21 to 27 DAP, were significantly affected by the interaction between herbicide, rate, and irrigation option ($P < 0.0001$). Zucchini squash averaged 98 cm in width among control plants (Table 5). Regardless of herbicide, when overhead irrigation was applied prior to planting, squash widths were similar to those of the control plants (97–103 cm). When irrigation was not included, 2,4-D use resulted in reduced widths by 28% to 39%, whereas dicamba was more damaging and widths were reduced by 79% to 89%. Fresh weight biomass, collected 15 to 20 DAP, was influenced only by irrigation ($P < 0.0001$; data not shown). The average fresh weight biomass of squash was 128 g plant^{-1} and was not influenced by either herbicide if irrigation was included. Without irrigation, 2,4-D and dicamba use resulted in 75% and 86% reduced biomass, respectively.

To quantify potential delays in maturity for zucchini squash, the first eight harvests were analyzed. Earliness was not influenced by herbicide or rate when the mulch was washed prior to transplanting for fruit number or fruit weight (data not shown).

Table 6. Zucchini squash yield over the entire season as influenced by herbicide, rate applied, and preplant overhead irrigation option.[a]

Irrigation option[b]	Herbicide	Total fruit number[c] 1× rate[d]	Total fruit number[c] 2× rate[d]	Total fruit weight[c] 1× rate[d]	Total fruit weight[c] 2× rate[d]
		——no. ha^{-1}——		——kg ha^{-1}——	
Irrigation	2,4-D	248,086 a	249,593 a	70,516 ab	69,546 ab
	Dicamba	262,849 a	271,894 a	70,308 ab	75,106 a
No irrigation	2,4-D	167,807 b	143,417 b	52,713 bc	50,822 c
	Dicamba	43,856 c	11,100 d	22,928 d	7,523 d
	NTC[e,f]	261,888 a		73,627 a	

[a]Yield data are combined across spring and fall of 2019. Zucchini squash were harvested 18 to 31 times.
[b]Treatments that received overhead irrigation received 0.76 cm, while nonirrigated treatments were covered to prevent herbicide wash off.
[c]Means followed by the same letter with respect to the response variable do not differ significantly ($P \leq 0.05$).
[d]Rates applied were 1,065 (1×) and 2,130 (2×) g ae ha^{-1} for 2,4-D and 560 (1×) and 1,120 (2×) g ae ha^{-1} for dicamba.
[e]Abbreviation: NTC, nontreated control.
[f]NTC plots were maintained weed free to ensure growth was not impacted by weed competition.

However, without irrigation, a reduction in harvested fruit count and weight ranged from of 60% to 65% for both rates of 2,4-D, while the impact from dicamba was generally higher, ranging from 61% to 93%. To obtain total yield, squash was harvested 18 to 31 times, 6 d/wk with both fruit number and respective weights being significantly affected by the interaction between herbicide, rate, and irrigation option ($P < 0.0001$). On average, zucchini squash yielded 261,888 fruit ha^{-1} weighing 73,627 kg ha^{-1} over the entire season when auxin herbicides were not applied (Table 6). Similar to early-season yield, neither 2,4-D nor dicamba influenced yield as long as irrigation was implemented after herbicide application and before transplanting. Without irrigation, fruit counts and weights were reduced by 36% to 45% and by 28% to 31%, respectively, by both rates of 2,4-D. Greater yield loss was noted with dicamba as fruit counts and fruit weights were reduced by 83% to 96% at the 1× rate and by 69% to 96% at the 2× rate.

Conclusions

Preplant applications of 2,4-D and dicamba could provide vegetable growers an additional mechanism of action to control problematic weeds prior to crop planting. Analytical and bioassay experiments demonstrated that a single irrigation event of 0.76 cm could successfully remove 2,4-D from plastic mulch. Furthermore, doubling the rate of 2,4-D did not result in adverse effects on visual injury, crop growth, or yield in either crop, demonstrating adequate crop safety. In contrast, irrigation was not as effective in removing dicamba from the plastic mulch, with significant injury, growth reduction, and early-season yield loss detected when these herbicides were used on cantaloupe. Without irrigation to wash herbicides from the mulch prior to planting, damage was so severe that both crops would have been abandoned. Squash was more tolerant and resilient compared to cantaloupe.

Although 2,4-D demonstrates great potential applied preplant in a vegetable plasticulture system where irrigation can be implemented to remove it from the mulch, further research is needed to evaluate its use in multicrop plasticulture production systems. These experiments specifically focused on the relationship of herbicides and mulch void of holes or tears in the mulch. In many cases, if labeled, 2,4-D would be applied over plastic mulch that contained old plant holes or tears that would allow the herbicide to contact the soil and potentially result in residual activity that could damage the crop. Thus, understanding the distance to place new transplants relative to old holes or tears containing 2,4-D and the amount of time needed between application and planting will be paramount for success. Future research should evaluate potential use patterns for 2,4-D in this system and tolerance of other crops grown in plasticulture.

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References

Anonymous (2018a) Roundup Powermax® II Herbicide product label. Bayer CropScience Publication No. 101816. St. Louis, MO: Bayer CropScience. 22 p
Anonymous (2018b) Engenia® herbicide product label. BASF Publication No. NVA 2018-04-385-0080. Research Triangle Park, NC: BASF. 29 p
Anonymous (2018c) Enlist™ Duo with Colex D Technology herbicide product label. Corteva Agrisciences Publication No. D02-407-003. Indianapolis, IN: Dow Agrosciences. 7 p
Anonymous (2018d) Xtendimax® with VaporGrip Technology product label. Monsanto Publication No. 181101. St. Louis, MO: Monsanto Company. 20 p
Anonymous (2019) Reflex® Herbicide product label. Syngenta Crop Protection Publication No. 993A-L1S 0619. Greensboro, NC; Syngenta Crop Protection, LLC. 51 p
Boyd NS (2016) Pre- and postemergence herbicides for row middle weed control in vegetable plasticulture production systems. Weed Technol 30:949–957
Colquhoun JB, Heider DJ, Rittmeyer RA (2014) Relationship between visual injury from synthetic auxin and glyphosate herbicide and snap bean and potato yield. Weed Technol 28:671–678
Coolong T, Kelley WT (2014) Commercial squash production. Bulletin 527. Athens, GA: University of Georgia
Coolong T, Boyhan GE (2017) Cantaloupe and specialty melons. Bulletin 1179. Athens, GA: University of Georgia
Culpepper AS, Carlson DS, York AC (2005) Pre-plant control of cutleaf eveningprimrose and wild radish in conservation tillage cotton. Cotton Sci 9:223–228
Culpepper AS, Sosnoskie L, Rucker K, Tankersley B, Webster T, Upchurch W (2008) DMDS or the 3-way: Which is more effective in Georgia? Pages 7-1 through 7-4 in Proceedings of the Annual International Research Conference on Methyl Bromide Alternative and Emissions Reductions. Corvallis, OR: U.S. Environmental Protection Agency
Culpepper AS, Grey TL, Webster TM (2009) Vegetable response to herbicides applied to low-density polyethylene mulch prior to transplant. Weed Technol 23:444–449
Culpepper AS, Vance JC, Dutta B (2017) 2017 vegetable fumigant systems for plasticulture for Georgia. Bulletin 1068. Athens, GA: The University of Georgia

Culpepper AS, Smith JC (2017) UGA weed control programs for watermelon in 2017. Circular 1080. Athens, GA: University of Georgia

Culpepper AS, Sosnoskie LM, Shugart J, Leifheit N, Curry M, Gray T (2018) Effects of low-dose applications of 2,4-D and dicamba on watermelon. Weed Technol 32:267–272

Culpepper AS, Vance JC (2019) Palmer amaranth control in Georgia cotton during 2019. UGA Circular No. 952. Athens, GA: University of Georgia

Dittmar PJ, Ferrell JA, Fernandez JV, Smith H (2016) Effect of glyphosate and dicamba drift timing and rates in bell pepper and yellow squash. Weed Technol 30:217–223

Everitt JD, Keeling JW (2009) Cotton growth and yield response to simulated 2,4-D and dicamba drift. Weed Technol 23:503–506

Eubank TW, Poston DH, Nandula VK, Koger CH, Shaw DR, Reynolds DB (2008) Glyphosate-resistant horseweed control using glyphosate-, paraquat-, and glufosinate-based herbicide programs. Weed Technol 22:16–21

Eure PM, Culpepper AS (2017) Bell pepper and weed response to dimethyl disulfide plus chloropicrin and herbicide systems. Weed Technol 31:694–700

Grey TL, Vencill WK, Webster TM, Culpepper AS (2009) Herbicide dissipation from low density polyethylene mulch. Weed Sci 57:351–356

Grey TL, Culpepper AS, Li X, Vencill WK (2018) Halosulfuron-methyl degradation from the surface of low-density polyethylene mulch using analytical and bioassay techniques. Weed Sci 66:15–24

Hand LC, Culpepper AS, Gray T, Shugart J (2019) Effects of low-dose applications of 2,4-D and dicamba on cucumber and cantaloupe. Proc South Weed Sci Soc 72:235

Johnston CR, Eure PM, Grey TL, Culpepper AS, Vencill WK (2018) Time of application influences translocation of auxinic herbicides in Palmer amaranth. Weed Sci 66:4–14

Kemble JM, Meadows IM, Jennings KM, Walgenback JF, eds (2019) 2019 Vegetable Crop handbook. Auburn, AL: Southeastern Vegetable Extension Workers. 356 p

Kuack D (2020) Herbicide label expansion could provide cucumber and squash growers extended weed control. https://www.ir4project.org/fc/clomazone-cucumber-squash-2020/ Accessed: August 14, 2020

Leon RG, Ferrell JA, Sellers BA (2016) Seed production and control of sicklepod (*Senna obtusifolia*) and pitted morningglory (*Ipomoea lacunosa*) with 2,4-D, dicamba, and glyphosate combinations. Weed Technol 30:76–84

Majzik ES, Toth F, Benke L, Kiss Z (2006) SPE-LC-MS-MS Determination of Phenoxy Acid Herbicides in Surface and Ground Water. Chromatographia 63:S105–S109

Monaco TJ, Weller SC, Ashton FM (2002) Weed Science: Principals and Practices. New York: John Wiley & Sons, Inc.

Randell TM, Vance JC, Culpepper AS (2020) Broccoli, cabbage, squash and watermelon response to halosulfuron preplant over plastic mulch. Weed Technol 4:202–207

Solomon CB, Bradley KW (2014) Influence of application timings and sublethal rates of synthetic auxin herbicides on soybean. Weed Technol 28:454–464

Stevens MC, Freeman JH, Dittmar PJ (2016) Impact of totally impermeable film on the efficacy of 1,3-dicloropropene and chloropicrin mixtures for the control of nutsedge. Weed Technol 30:910–918

Webster TM, Culpepper AS, Johnson WC III (2003) Response of squash and cucumber cultivars to halosulfuron. Weed Technol 17:173–176

Wilson JS, Worsham AD (1988) Combinations of nonselective herbicides for difficult to control weeds in no-till corn, *Zea mays*, and soybeans, *Glycine max*. Weed Sci 36:648–652.