Weed Technology

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Planting strategy influences vegetable response to glyphosate and glufosinate applied preplant in plasticulture

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Research Article

Cite this article: Randell-Singleton T, Hand LC, Wright-Smith HE, Vance JC, Culpepper AS (2024) Planting strategy influences vegetable response to glyphosate and glufosinate applied preplant in plasticulture. Weed Technol. **38**(e85), 1–8. doi: 10.1017/wet.2024.85

Received: 3 July 2024
Revised: 3 October 2024
Accepted: 30 October 2024

Nomenclature:
Glufosinate; glyphosate; cucumber; *Cucumis sativus* L. 'Mongoose'; '201'; summer squash; *Cucurbita pepo* L. 'Enterprise'; tomato; *Solanum lycopersicum* L. '7631'

Keywords:
Residual activity; preplant burndown; vegetable production; herbicide wash-off

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Abstract

In Georgia plasticulture vegetable production, a single installation of plastic mulch is used for up to five cropping cycles over an 18-mo period. Preplant applications of glyphosate and glufosinate ensure fields are weed-free before transplanting, but recent data suggest that residual activity of these herbicides may pose a risk to transplanted vegetables. Glyphosate and glufosinate were applied preplant in combination with three different planting configurations, including 1) a new plant hole into new mulch, 2) a preexisting plant hole, 3) or a new plant hole spaced 15 cm from a preexisting plant hole (adjacent). Following herbicide application, overhead irrigation was used to remove residues from the mulch before punching transplanting holes for tomato, cucumber, or squash. Visible injury; widths; biomass; and yield of tomato, cucumber, or squash were not influenced by herbicide in the new mulch or adjacent planting configurations. When glyphosate was applied at 5.0 kg ae ha^{-1} and the new crop was planted into preexisting holes, tomato was injured by 45%, with reduced heights, biomass, and yields; at 2.5 kg ae ha^{-1} injury of 8% and a biomass reduction was observed. Cucumber and squash were injured by 23% to 32% by glyphosate at 5.0 kg ae ha^{-1}, with reductions in growth and early-season yield; lower rates did not influence crop growth or production when the crop was placed into a preexisting plant hole. Glufosinate applied at the same rates did not affect tomato growth or yield when planted into preexisting plant holes. Cucumber, when planted into preexisting plant holes, was injured by 43% to 75% from glufosinate, with reductions in height and biomass, and yield losses of 1.3 to 2.6 kg ai ha^{-1}; similar results from glufosinate were observed in squash. In multi-crop plasticulture production, growers should ensure vegetable transplants are placed a minimum of 15 cm away from soil exposed to these herbicides.

Introduction

Accounting for more than $24 billion annually, specialty crops including fruits, vegetables, nuts, berries, herbs, nursery plants, and ornamentals, comprise 25% of the national economic value for agriculture products (USDA-ERS 2022; USDA-FAS 2022). In 2020, specialty crops were grown across all 50 states, with Georgia contributing more than 33 high-value fresh-market produce crops for domestic consumption (Anonymous 2022; USDA-NASS 2019). Although vegetable crops were grown on fewer than 65 million ha in the United States during 2017, data from the U.S. Department of Agriculture suggest that production area of these high-value crops is increasing, with 11% growth recorded from 2012 to 2017 (USDA-NASS 2015, 2019).

Vegetable production systems are intensive and complex, requiring farmers to maintain optimum pest control and prolonged production cycles to achieve high-quality abundant yields (Culpepper et al. 2009; Sarrantonio 1992). The use of plastic mulch as a component of a system containing drip irrigation, fertigation, and soil fumigation, collectively referred to as plasticulture, ensures that growers can reach a higher return per unit of land and maximize crop quality and quantity (Lamont 1993, 1996). The use of plastic mulch is critical to the success of vegetable production in Georgia, an industry valued at nearly $1.3 billion (Anonymous 2022; Da Silva et al. 2020). Large-bed plastic mulch, a covered raised bed approximately 15 to 20 cm tall and 81 cm wide, is the most used plasticulture production system in Georgia for several cucurbit crops, fruiting vegetables, and cole crops. This system offers numerous benefits, including earlier crop production, resulting in higher yields and market prices (crop earliness), better control of broadleaf and grassy weeds, increased soil moisture retention, and improved water use efficiency. However, implementation and fumigation input costs can be high, prohibiting adoption by some producers (Coolong 2012; Fonsah and Shealey 2019; Hartz 1996;

Hartz and Hochmuth 1996; Lamont 2005; Webster 2005). To help offset the initial expenses of large-bed plastic mulch systems, growers often use a single installation of mulch for three to five cropping cycles, or approximately 18 mo (Da Silva et al. 2020; Fonsah and Shealey 2019). Without reinstalling new mulch and applying the fumigants that are simultaneously applied during the installation of plastic mulch, it becomes challenging to manage weeds that emerge through plant holes and other openings (tears, degradation, stake holes, etc.) in the mulch after the first crop. Fumigants applied through a single line of drip tubing placed beneath the plastic and soil surface can help control weeds emerging in the bed for crop cycles two to five. However, this method of control is expensive and extends only an average of 20 cm across the center of the bed, which can leave emerging weeds on either edge of the bed uncontrolled (Desaeger and Csinos 2005; Yu et al. 2019).

The availability of herbicides for use prior to and throughout the growing season of specialty crops is limited (Fennimore and Doohan 2008). Specialty crops are produced on a smaller scale compared to major agronomic crops, offering little opportunity for a return on investment for a new, specialized pesticide product moving through the registration process (Gast 2008). Along with low acreage, there is also a concern of crop sensitivity for these high-value produce crops, which may deter herbicide development and registration for use on these crops (Kunkel et al. 2008). For this reason, many herbicides registered for use on a specialty crop are the result of creative solutions identified for agronomic products. When a weed control need is identified, university scientists often turn to agronomic herbicides to identify a solution.

When considering troublesome weeds that may emerge between successive cropping cycles, preplant applications of glyphosate and glufosinate are beneficial to ensure the next crop is planted into a weed-free field. Glyphosate and glufosinate are nonselective and used to control a broad spectrum of common and troublesome weeds present in vegetable production, including sedges (*Cyperus* spp.), pigweed species (*Amaranthus* spp.), and various species of crabgrass (*Digitaria* spp.) (Anonymous 2017, 2020; Shaner 2014, Van Wychen 2022). Previous research, however, has indicated that significant residual activity from preplant applications of glyphosate and glufosinate can be detrimental to transplanted vegetables placed into sandy soils with low organic matter up to 7 d after application in non-mulched systems (Goodman et al. 2019; Leiva Soto et al. 2017; Smith et al. 2017; Wright-Smith et al. 2023). As plastic mulch–covered beds are used for successive cropping cycles, the mulch begins to lose integrity through natural degradation, impacts from weather events, accidental rips and tears from equipment or human contact, animal tracks, production practices (i.e., plant staking) of various crops, or the preexisting plant holes from previous crops (Kyrikou and Briassoulis 2007).

It is well understood that both glyphosate and glufosinate can effectively be removed from the surface of plastic mulch with overhead irrigation (Culpepper et al. 2009; Eason 2021; Grey et al. 2009). Research conducted by Eason et al. (2021) demonstrated the ability of these products to wash from the mulch and subsequently move into areas of the bed not covered with mulch, where final concentrations can be high depending upon the pesticide applied. With many growers using high burndown application rates of herbicides to control problematic weeds such as nutsedge (*Cyperus* spp.), it is not known how sensitive transplanted vegetables will respond to the potential residual activity of glyphosate or glufosinate when applied over mulched beds, with exposed soil at the time of application, and when herbicides are washed from the mulch. Therefore, the objectives of this experiment were to determine the tolerance of tomato, cucumber, and summer squash to the residual activity of glyphosate and glufosinate applied preplant over plastic mulch, when transplants were placed into three planting scenarios, including: 1) punching a planting hole into new mulch, 2) punching a planting hole into preexisting holes in mulch created by the previous crop, 3) or punching holes into mulch spaced 15 cm away from preexisting holes created by the previous crop (adjacent).

Materials and Methods

Site Selection and Trial Establishment

Two different experiments were each conducted twice during 2019 and 2021 at the University of Georgia Ponder Research Farm in Ty Ty, GA (31.505°N, 83.655°W, 109 m asl), to evaluate vegetable crop response (tomato, cucumber, and squash) to the residual activity of glyphosate and glufosinate applied preplant in vegetable plasticulture systems. This location was selected for all studies because it is in the geographical center of Georgia's plasticulture production region. Soils at the site were a Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) consisting of 85.60% to 89.60% sand, 8% to 12% silt, 2.40% to 4.40% clay, and 0.63% to 0.66% organic matter. The pH ranged from 5.5 to 6.7, and cation exchange capacity was 3.9 to 5.1 across years and fields at the research farm.

Three months prior to experiment initiation, land was prepared conventionally with tillage, and a bedding implement (Hendrix & Dail, Inc., Greenville, NC) was used to simultaneously form raised plant beds (20 cm tall, 81 cm wide) and shank inject a combination of 1,3-D and chloropicrin (Pic-Chlor 60; TriEst Ag Group,. Greenville, NC) into the soil. These fumigants were injected at an application rate of 197 L ha^{-1} to a soil depth of 20 cm, using three evenly spaced shanks (20 cm apart). Immediately following bed formation, a combination bed shaper and plastic mulch layer (Kennco Manufacturing, Ruskin, FL) was used to simultaneously inject meta sodium (Vapam HL; AMVAC, Los Angeles, CA) into the raised bed, place drip tape in the center of the bed directly below the soil surface (2.5 cm), and cover the entire bed with black on black totally impermeable film. The metam sodium was injected into the soil of the raised bed at a rate of 700 L ha^{-1} 10 cm deep, with shanks spaced 10 cm apart. To control of nematodes, fumigants were allowed to dissipate over 3 mo before trial initiation, avoiding any concern of crop injury.

Studies were separated in space by crop (tomato, cucumber, or summer squash) and preplant herbicide (glyphosate or glufosinate). Within each study, experimental design was a randomized complete block consisting of a 3 by 4 factorial arrangement of treatments with factor one being three planting arrangements and factor two being four herbicide application rates. Glyphosate (Roundup PowerMax II; Monsanto, St. Louis, MO) was applied at 1.3, 2.5, and 5.0 kg ae ha^{-1}; while glufosinate (Liberty; BASF, Research Triangle Park, NC) was applied at 0.7, 1.3, and 2.6 kg ai ha^{-1} within respective studies. Herbicide treatments were applied to 2-m × 8-m plots using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa, equipped with TeeJet 11002 air induction nozzles (Spraying Systems Co., Glendale Heights, IL). Within each study, nontreated controls were included for comparison, and all herbicide treatments were replicated four times.

To simulate scenarios in which a single installation of plastic mulch is used for multiple cropping cycles, the surface of the mulch

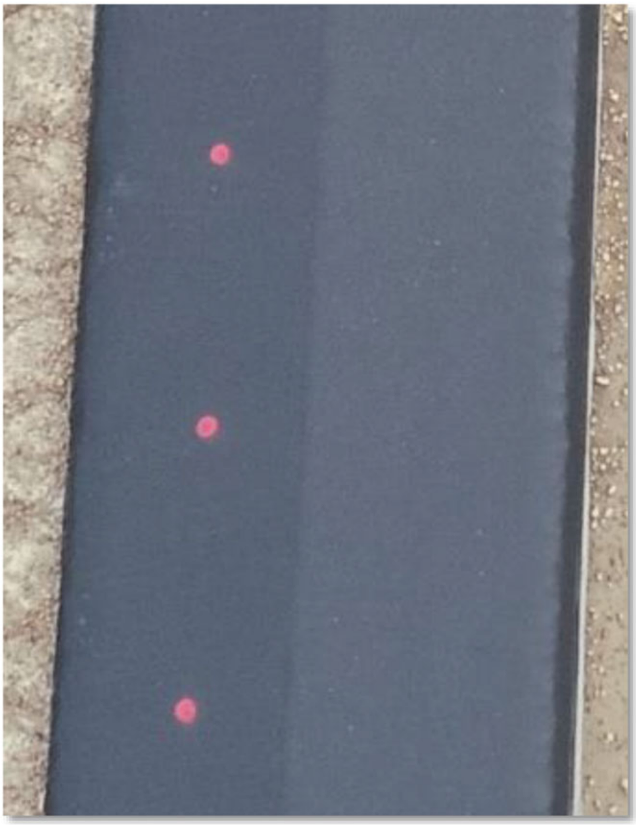

Figure 1. New plant hole. This planting hole configuration represents plant holes punched into newly installed plastic mulch, which would occur for the first crop in a multi-cropping system. To simulate this in the experiment, plastic mulch was laid, and following herbicide applications and overhead irrigation to remove residues from the mulch surface, holes were punched into the red dots, and plants were transplanted.

Figure 2. Previous crop plant hole. This planting hole configuration represents where a crop would be planted into plastic mulch used in a previous cropping cycle, with previous plant holes present in the mulch during herbicide application and irrigation. To simulate this plastic composition, a razor knife was used to remove a small area of plastic (10 cm by 10 cm) to simulate an old plant hole. Herbicides were applied over the mulch, washed with overhead irrigation, and transplants were planted into the exposed soil areas.

was manipulated in each study to represent three different planting scenarios. The first planting arrangement represented plant holes punched into newly installed plastic mulch, which would occur for the first crop planted in a multi-use cropping system (Figure 1). Herbicide treatments were applied over the surface of the mulch, and 48 h later, were followed with approximately 0.63 cm of overhead irrigation to wash the herbicide from the mulch. Plant holes were punched into the plastic 12 to 24 h after mulch was completely dry from irrigation and transplants were immediately hand-placed into the plant holes.

The second planting arrangement represented a scenario in which a crop would be planted into plastic mulch that had been used in a previous cropping cycle, with preexisting plant holes present at the time of herbicide application and irrigation (Figure 2). With this planting strategy, areas of exposed soil are contacted by preplant herbicide applications both from the application itself and from movement in the irrigation water. To simulate this plastic scenario, a razor knife and square-shaped stencil (10 cm × 10 cm) was used to remove a small area of plastic every 30 cm (cucumber and squash) to 46 cm (tomato) down the row on the center surface of the mulch. This simulated the preexisting plant hole remaining from a previous crop. Once the plastic was removed, herbicide treatments were applied over the mulch surface and followed by overhead irrigation to wash the herbicide from the mulch. Plant holes were punched into the exposed area of soil, and transplants were hand-planted into the plant holes.

The third planting arrangement investigated crop response when transplants were placed into new plant holes, adjacent to preexisting plant holes present in the mulch at the time of herbicide application and irrigation (Figure 3); this represents a common scenario in which growers plant their second through fifth crops in a mulched system. Thus, small square areas of mulch were manually removed from the center surface of the plastic mulch before herbicide treatments and overhead irrigation were implemented. New plant holes were punched down the row, 15 cm adjacent to the so-called preexisting crop holes, with transplants planted by hand into the new plant holes. This planting method would determine whether herbicides potentially concentrating in previous crop holes influence plants placed 15 cm away.

Crop Establishment and Data Collection

Transplant holes were punched into the plastic by hand in each study using a custom-made stainless steel hole punch that created an 8-cm-wide by 10-cm-deep plant hole, identical to the hole created by a standard commercial hole punch wheel (Kennco Manufacturing, Ruskin, FL). The hand-held hole punch allowed the implement to be washed between treatments to prevent plot-to-plot contamination. To investigate crop tolerance to herbicide residues, tomato, cucumber, and squash were established in each study. Tomato (variety '7631'; Seminis, St. Louis, MO) were planted 46 cm apart in a single row just off center of the plant bed, on March 21, 2019, and March 16, 2020. Approximately 21 d after planting (DAP), wooden stakes and string were placed in the field

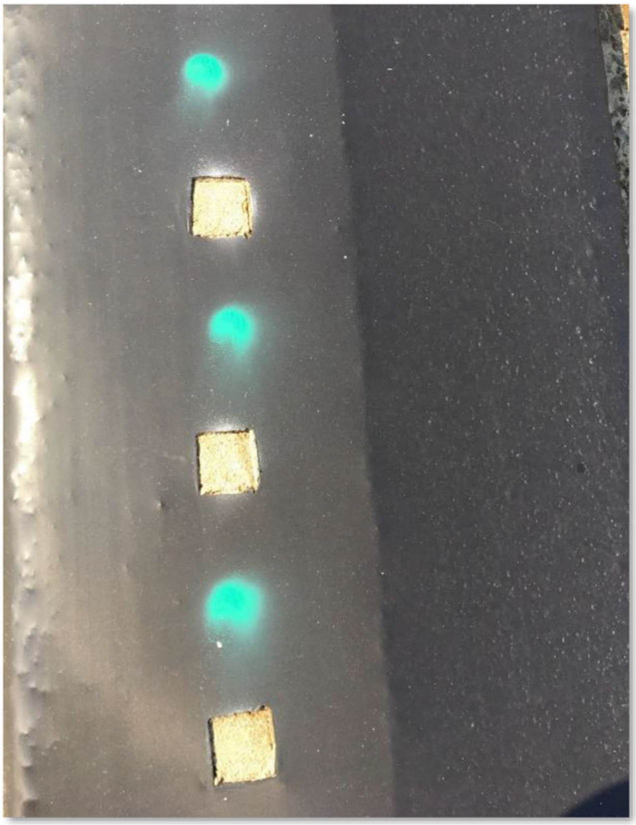

Figure 3. Adjacent to the previous crop plant hole. This planting hole configuration represents where a crop would be planted into plastic mulch used in a previous cropping cycle; instead of planting into pre-existing plant holes, a new hole was punched adjacent to the old hole. To simulate this configuration, small square areas of mulch (10 cm by 10 cm) were manually removed using a razor knife from the surface of the mulch before applying herbicide treatments and overhead irrigation. New plant holes were created by punching a hole through the green dot, and transplants were hand-planted into these holes.

for plant support, and suckers were removed by hand from the tomato plants by a commercial field crew from a local tomato farm. Cucumber (variety 'Mongoose' in 2019 and '201' in 2020) were planted on a 30-cm spacing just off center of the plant bed on March 21, 2019, and March 16, 2020, and straightneck summer squash (variety 'Enterprise') were planted using the same spacing on March 16, 2020, and March 22, 2021. Planted beds were each spaced 3.7 m apart for all crops. Following plant establishment, all irrigation, fertilization, insects, and disease control were performed in accordance with University of Georgia recommendations for the area. Each crop was grown independently of the other to allow implementation of the best production and pest management practices (Kemble et al. 2022).

Crop injury (chlorosis, necrosis, plant stunting) was visibly estimated using a 0% (no crop injury) to 100% (plant death) scale weekly, beginning 4 DAP and continuing until harvest began. This occurred between 30 and 77 DAP, depending on the crop. Treatment impacts on crop growth were quantified by collecting canopy height or width three to five times during the season. Crop heights were measured from the soil line to the top of the growing point for 10 consecutive plants, while widths were collected from across the widest point of the same number of plants. Aboveground fresh-weight biomass was collected once from each crop when visible injury was at its maximum, by removing the plant material from four to nine plants per plot depending upon crop, leaving 10 plants per plot for further data collection. The aboveground plant material from each plant was collectively weighed to determine per-plot biomass in grams per plot (g plot^{-1}).

From the 10 plants remaining in each crop, yield was collected throughout the growing season, and differentiated into early-season yield (approximately the first 25% of harvests) and total-season yield. Tomato was harvested nine to 10 times each year by removing any mature fruit that had begun to show a trace of red color, a common harvesting practice in fresh market production. Fruit from each plot was separated by size (small, medium, large, or extra-large; USDA-AMS 1991) using a Kerian Speed Sizer fruit grader (Kerian Machines, Grafton, ND), and a number and weight were collected from within each size group, for the individual plot. Cucumber was harvested 15 times, and squash was harvested 21 to 30 times each year, with yield determined by recording the number of marketable mature fruit and its collective weight for each plot (USDA-AMS 2016a, 2016b).

Statistical Analysis

To test for treatment-by-year interactions, data were subjected to ANOVA; no interactions were detected. Therefore, data within crop and herbicide were combined over study years for analysis. To determine whether the combined treatment effects of planting arrangement and application rate impacted crop response, collected data was assessed for normality and analyzed using the GLIMMIX procedure with SAS Enterprise Guide software (v. 8.3, SAS Institute, Cary, NC). Tomato, cucumber (glufosinate study only), and squash injury data were arcsine square root transformed to improve normality and homogeneity of variance prior to analysis. Squash total yield was log transformed in glyphosate studies, and early yield assessments were log transformed in all studies. All data are presented in their back-transformed values.

Treatment main effects and their interactions were included in models as fixed variables, while year and replication (nested within year) were included as random effects. When appropriate, significant means were separated using the Tukey-Kramer least square means test, at an alpha level of 0.05.

Results and Discussion

Tomato

Glyphosate

Combined across locations, tomato injury, heights, early-season biomass, early yield, and total yield were significantly influenced by the interaction between preplant glyphosate rate and planting arrangement. For all variables, however, crop development and production were not influenced by glyphosate when the planting arrangement consisted of new or adjacent hole configurations. In contrast, injury was observed when planting into the preexisting hole configuration. When at its maximum 23 DAP, visible injury recorded as plant discoloration increased as the preplant glyphosate rate increased. In fresh-market vegetable production, crop injury greater than 10% is not tolerated by producers due to strict market and consumer standards for perfectly conformed and imperfection-free fruit (Culpepper et al. 2009). Glyphosate applied preplant at 1.3, 2.5, and 5.0 kg ae ha^{-1} resulted in tomato visible injury of 3%, 8%, and 45%, respectively; this injury exceeded the acceptable threshold (Table 1). Following herbicide applications, overhead irrigation was applied to remove the herbicide residues from the surface of the mulch, as required by the label (Anonymous 2017).

Table 1. Tomato visible injury, height, biomass, early-season yield, and season-long yield following glyphosate applied preplant at four rates within three plasticulture planting arrangements during 2019 and 2020 in Ty Ty, GA.[a,b,c]

Planting arrangement[d]	Application rate	Injury	Height	Biomass	Early yield	Total yield
	kg ae ha^{-1}	%	% NTC	% NTC	kg ha^{-1}	
New plant hole	0	0 c	100 ab	100 a	10,730 a	92,640 a
	1.3	0 c	102 a	102 a	9,590 a	102,500 a
	2.5	0 c	99 ab	93 ab	9,080 a	89,880 a
	5.0	1 c	98 ab	97 a	9,530 a	97,450 a
Preexisting plant hole	0	0 c	100 ab	100 a	7,470 a	96,420 a
	1.3	3 bc	94 ab	89 ab	8,280 a	95,740 a
	2.5	8 b	90 b	66 b	7,220 ab	103,400 a
	5.0	45 a	77 c	35 c	4,310 b	90,130 a
Adjacent to preexisting plant hole	0	0 c	100 ab	100 a	9,450 a	102,060 a
	1.3	0 c	96 ab	98 a	7,480 a	102,840 a
	2.5	0 c	99 ab	99 a	8,600 a	103,610 a
	5.0	0 c	96 ab	94 a	9,390 a	106,410 a

[a]Abbreviations NTC, nontreated control.
[b]Means followed by the same letter within a column are not significantly different ($P \leq 0.05$).
[c]Tomato injury, height, and fresh-weight biomass measured 23 d after planting when injury was at a maximum; early-season yield collected for the first three harvests and season-long yield collected over 9 to 10 harvests.
[d]Planting arrangement represented three planting scenarios, including 1) punching a planting hole into new mulch, 2) punching a planting hole into preexisting holes in mulch created by the previous crop, 3) or punching holes into mulch spaced 15 cm away from existing holes created by the previous crop (adjacent).

A significant amount of water is required to remove the herbicide from the surface of the mulch and raised bed architecture ensures that the water moves down either side of the ridge running along the center of the bed. Previous research using constructed raised beds to quantify herbicide-water movement into plant holes has identified that a complex relationship exists between plasticulture, herbicides, and the amount of product potentially ending up in plant holes during overhead irrigation events. Although water was uniformly applied over the plant bed in research conducted by Eason et al. (2021), collection jars under plant holes indicated that herbicide concentrations greater than field applied rates may wash into plant holes, and for products with residual activity, this could lead to increased crop injury. Furthermore, previous research has confirmed the potential for residual activity from glyphosate to sensitive vegetable transplants when planted into sandy soils with low organic matter (Goodman et al. 2019; Wright-Smith et al. 2023).

Converted to a percentage of the nontreated control to account for differences in observation interval, crop growth was quantified through assessments of plant height and early-season biomass. Following a similar trend as visible injury, growth was negatively affected by increasing preplant glyphosate rate prior to planting tomato within the previous plant hole arrangement. The highest glyphosate rate reduced crop heights by 23%, whereas the two highest rates reduced early-season biomass by 34% to 65%, compared with the nontreated control (Table 1). Tomato growth was not influenced when glyphosate was applied at the lowest rate of 1.3 kg ae ha^{-1}.

Early-season yield, which is representative of the first 25% of harvests during the season, is often the most valuable fruit harvested from a crop. The ability to begin harvesting a crop earlier in the season and get the product to the market quickly when consumer demands are high, often comes with a price premium and is desirable to producers. Therefore, any action that may delay earliness in crop maturity and the beginning of harvest, is not tolerated by vegetable producers. Early-season tomato yield, which is representative of the first three harvests of the season, was consistent with injury and crop growth observations. Glyphosate applied at 5.0 kg ae ha^{-1} within the previous planting hole arrangement reduced early-season yield 42%, but other rates did not influence early-season yield (Table 1). There were no effects of glyphosate on tomato yield for the entire season when compared with control plants.

Glufosinate

Across all three planting arrangements, differences were not observed when comparing all rates of glufosinate applied before transplanting tomato to the nontreated control, regarding crop injury, plant height, biomass, early-season yield, and total yield (data not shown).

Cucumber

Glyphosate

Similar to tomato, visible injury, shoot lengths, biomass, early yield, and total yield were influenced by the interaction between preplant glyphosate rate and planting hole arrangement. Also similar to tomato, none of the variables used to measure crop development were influenced by glyphosate when the planting arrangement specifically consisted of new or adjacent planting configurations.

In the preexisting hole arrangement, maximum injury, recorded as chlorosis, stunting, necrosis, or plant death was observed 30 DAP. Combined over locations, cucumber was injured by 4%, 6%, and 23% from glyphosate applied at 1.3, 2.5, and 5.0 kg ae ha^{-1}, respectively (Table 2). Assessments of crop growth and yield followed similar trends, with glyphosate applied preplant at 5.0 kg ae ha^{-1} reducing cucumber vine lengths by 24% and biomass by 57% compared with the nontreated control. Both early-season and total cucumber yields were affected by glyphosate applied at the highest rate, with yields reduced by 47% and 21%, respectively.

Glufosinate

Like glyphosate, cucumber response to glufosinate was influenced by the interaction between preplant rate and planting hole arrangement, with differences recorded only within the preexisting hole arrangement. Previous research has documented the high sensitivity of cucumber to the residual activity of glufosinate following applications to sandy soils with low organic matter (Leiva Soto et al. 2017; Randell et al. 2022). Maximum cucumber injury was observed 22 DAP in our research within the previous planting hole configuration, with 10%, 43%, and 75% injury observed following applications at 0.7, 1.3, and 2.6 kg ai ha^{-1}, respectively (Table 3). Cucumber vine length, biomass, early yield, and total yield were significantly affected by glufosinate at the two

Table 2. Cucumber visible injury, height, biomass, early-season yield, and season-long yield following glyphosate applied preplant at four rates within three plasticulture planting arrangements during 2019 and 2020 in Ty Ty, GA.[a,b,c]

Planting arrangement[d]	Application rate	Injury	Length	Biomass	Early yield	Total yield
	kg ae ha^{-1}	%	% NTC	% NTC	kg ha^{-1}	kg ha^{-1}
New plant hole	0	0 c	100 ab	100 ab	3,540 ab	59,950 ab
	1.3	0 c	112 a	155 a	4,010 a	67,610 ab
	2.5	0 c	117 a	150 a	4,730 a	68,540 ab
	5.0	0 c	117 a	150 a	4,240 a	71,720 a
Preexisting plant hole	0	0 c	100 ab	100 ab	4,450 a	72,550 a
	1.3	4 b	98 ab	101 ab	4,580 a	66,200 ab
	2.5	6 b	101 ab	101 ab	4,190 a	69,160 ab
	5.0	23 a	76 b	43 b	2,340 b	57,040 b
Adjacent to preexisting plant hole	0	0 c	100 ab	100 ab	4,090 a	63,700 ab
	1.3	0 c	116 a	117 a	4,410 a	70,020 a
	2.5	0 c	106 ab	120 a	4,200 a	67,800 ab
	5.0	0 c	105 ab	117 a	4,570 a	65,250 ab

[a]Abbreviation: NTC, nontreated control.
[b]Means followed by the same letter within a column are not significantly different ($P \leq 0.05$).
[c]Cucumber injury, height, and fresh-weight biomass collected 30 d after planting when injury was at its maximum; early-season yield recorded for the first four harvests and season-long yield collected over 15 harvests.
[d]Planting arrangement represented three planting scenarios, including 1) punching a planting hole into new mulch, 2) punching a planting hole into preexisting holes in mulch created by the previous crop, 3) or punching holes into mulch spaced 15 cm away from existing holes created by the previous crop (adjacent).

Table 3. Cucumber visible injury, height, biomass, early-season yield, and season-long yield following glufosinate applied preplant at four rates within three plasticulture planting arrangements during 2019 and 2020 in Ty Ty, GA.[a,b,c]

Planting arrangement[d]	Application rate	Injury	Length	Biomass	Early yield	Total yield
	kg ai ha^{-1}	%	% NTC	% NTC	kg ha^{-1}	kg ha^{-1}
New plant hole	0	0 c	100 a	100 ab	3,940 ab	61,270 ab
	0.7	0 c	104 a	108 a	4,690 a	67,730 ab
	1.3	1 c	105 a	115 a	5,040 a	66,650 ab
	2.6	6 c	101 a	96 ab	4,390 ab	65,400 ab
Preexisting plant hole	0	0 c	100 a	100 ab	5,460 a	80,320 a
	0.7	10 c	95 a	82 ab	4,900 a	73,110 ab
	1.3	43 b	70 b	56 bc	2,430 b	54,930 b
	2.6	75 a	33 c	12 c	710 c	31,680 c
Adjacent to preexisting plant hole	0	0 c	100 a	100 ab	4,900 a	70,660 ab
	0.7	1 c	97 a	97 ab	4,120 ab	68,180 ab
	1.3	1 c	99 a	97 ab	3,750 ab	79,730 a
	2.6	1 c	101 a	108 a	4,330 ab	71,320 ab

[a]Abbreviation: NTC, nontreated control.
[b]Means followed by the same letter within a column are not significantly different ($P \leq 0.05$).
[c]Cucumber injury, heights, and fresh-weight biomass collected 22 d after planting when maximum injury was observed; early-season yield recorded for the first four harvests and season-long yield collected over 15 harvests.
[d]Planting arrangement represented three planting scenarios, including 1) punching a planting hole into new mulch, 2) punching a planting hole into preexisting holes in mulch created by the previous crop, 3) or punching holes into mulch spaced 15 cm away from existing holes created by the previous crop (adjacent).

highest rates, with reductions of 30% to 67%, 44% to 88%, 56% to 87%, and 32% to 61%, respectively, compared with the control (Table 3).

Squash

Similar to tomato and cucumber, squash response to preplant herbicides was influenced by the interaction between application rate and planting arrangement. For both glyphosate and glufosinate, squash injury, crop growth, early yield, and total yield were affected only in the preexisting hole planting arrangement.

Glyphosate

Maximum visible injury recorded 16 DAP, was 7%, 6%, and 32%, with glyphosate applied at 1.3, 2.5, and 5.0 kg ae ha^{-1}, respectively (Table 4). Crop width, biomass, early yield, and total yield were statistically influenced by applications of glyphosate only at the highest rate, with reductions of 19%, 19%, 28%, and 9% observed, respectively (Table 4). These results follow trends observed by Goodman et al. (2019), who noted that residual glyphosate injured transplanted squash when applied preplant in sandy soils to a bareground production system. In their studies, squash was injured up to 48% following a preplant application of glyphosate at 3.8 kg ae ha^{-1}, indicating that transplanted squash can be highly sensitive to glyphosate residues in soil.

Glufosinate

Maximum squash injury from glufosinate was also recorded 16 DAP with chlorosis, stunting, and necrosis being observed. Glufosinate applications of 1.3 and 2.6 kg ai ha^{-1} caused injury of 34% and 86%, respectively (Table 5). At the same rates, biomass was reduced 34% to 61%. Squash widths, early yield, and total yield were negatively influenced only at the highest application rate, with reductions of 48%, 51%, and 25%, respectively.

In conclusion, glyphosate and glufosinate can be applied safely over raised bed mulch systems as long as the herbicide is removed

https://doi.org/10.1017/wet.2024.85 Published online by Cambridge University Press

Table 4. Squash visible injury, height, biomass, early-season yield, and season-long yield following glyphosate applied preplant at four rates within three plasticulture planting arrangements during 2020 and 2021 in Ty Ty, GA.[a,b,c]

Planting arrangement[d]	Application rate	Injury	Widths	Biomass	Early yield	Total yield
	kg ae ha^{-1}	%	% NTC	% NTC	kg ha^{-1}	kg ha^{-1}
New plant hole	0	0 c	100 a	100 a	14,330 a	81,150 ab
	1.3	0 c	97 a	97 a	13,110 a	77,100 ab
	2.5	1 bc	93 a	93 a	13,480 a	76,230 ab
	5.0	0 c	94 a	94 a	13,430 a	80,300 ab
Preexisting plant hole	0	0 c	100 a	100 a	14,000 a	79,830 ab
	1.3	7 b	96 a	96 a	12,570 ab	76,530 ab
	2.5	6 b	95 a	95 a	13,000 a	77,800 ab
	5.0	32 a	81 b	81 b	10,080 b	71,910 b
Adjacent to preexisting plant hole	0	0 c	100 a	100 a	14,190 a	84,740 a
	1.3	0 c	101 a	101 a	12,830 ab	76,650 ab
	2.5	0 c	98 a	98 a	13,060 a	78,310 ab
	5.0	0 c	100 a	100 a	13,300 a	79,840 ab

[a]Abbreviation: NTC, nontreated control.
[b]Means followed by the same letter within a column are not significantly different ($P \leq 0.05$).
[c]Squash injury, height, and fresh-weight biomass collected 16 d after planting when injury was at a maximum; early-season yield recorded for the first 6 to 8 harvests and season-long yield collected over 21 to 30 harvests.
[d]Planting arrangement represented three planting scenarios, including 1) punching a planting hole into new mulch, 2) punching a planting hole into preexisting holes in mulch created by the previous crop, 3) or punching holes into mulch spaced 15 cm away from existing holes created by the previous crop (adjacent).

Table 5. Squash visible injury, height, biomass, early-season yield, and season-long yield following glufosinate applied preplant at four rates applied within three plasticulture planting arrangements during 2020 and 2121 in Ty Ty, GA.[a,b,c]

Planting arrangement[d]	Application rate	Injury	Widths	Biomass	Early yield	Total yield
	kg ai ha^{-1}	%	% NTC	% NTC	kg ha^{-1}	kg ha^{-1}
New plant hole	0	0 c	100 a	100 a	8,500 a	50,440 a
	0.7	0 c	99 a	101 a	7,920 a	52,250 a
	1.3	0 c	94 a	106 a	7,950 a	51,960 a
	2.6	2 c	93 a	92 a	7,990 a	51,360 a
Preexisting plant hole	0	0 c	100 a	100 a	7,950 a	49,980 a
	0.7	4 c	91 a	92 ab	8,290 a	52,520 a
	1.3	34 b	82 a	66 b	6,310 ab	46,970 ab
	2.6	86 a	52 b	39 c	3,880 b	37,470 b
Adjacent to preexisting plant hole	0	0 c	100 a	100 a	8,560 a	52,150 a
	0.7	0 c	100 a	106 a	7,970 a	48,500 a
	1.3	1 c	96 a	100 a	8,630 a	51,560 a
	2.6	0 c	98 a	102 a	8,070 a	50,690 a

[a]Abbreviation: NTC, nontreated control.
[b]Means followed by the same letter within a column are not significantly different ($P \leq 0.05$).
[c]Squash injury, height, and fresh-weight biomass reported 16 d after planting when injury was at a maximum; early-season yield recorded for the first 6 to 8 harvests and season-long yield collected over 21 to 30 harvests.
[d]Planting arrangement represented three planting scenarios, including 1) punching a planting hole into new mulch, 2) punching a planting hole into preexisting holes in mulch created by the previous crop, 3) or punching holes into mulch spaced 15 cm away from existing holes created by the previous crop (adjacent).

from the mulch with irrigation, and respective transplants are placed at least 15 cm away from soil exposed to these herbicides. Growers should avoid placing transplants into sandy soils with low organic matter exposed to these herbicides, because herbicide concentrations in the soil are unknown following a preplant application, and are influenced by topography, bed formation, and overhead irrigation/rainfall volumes.

Practical Implications

For growers who use plasticulture production systems for high-value fresh-market vegetable crops, the same mulch-covered raised bed may be used for up to five successive crops over an 18-mo period. Without preparing the land, reinstalling the mulch, and applying fumigants, managing weeds that emerge between consecutive crops is challenging, especially considering the high sensitivity of vegetables to herbicide residues. Burndown applications of nonselective herbicides prior to planting the next crop is beneficial to control these problematic weeds, ensuring that the new crop is planted into a weed-free field. Previous research, however, has indicated that residual activity from glyphosate and glufosinate can lead to significant vegetable crop injury when they are applied to sandy soils with low organic matter, up to 7 d after application in a bareground production system.

Herbicide products applied preplant burndown and washed from the mulch can move into areas of the bed not covered by the plastic (i.e., old plant holes, tears, etc.), potentially resulting in higher herbicide concentrations in the bed. Therefore, the objectives of this experiment were to understand the residual activity of preplant glyphosate and glufosinate on tomato, cucumber, and squash when planted into three different plasticulture scenarios: 1) a new plant hole; 2) a preexisting plant hole; or 3) a new plant hole shifted 15 cm away from a preexisting plant hole.

Results from our study indicate that if the herbicide is washed from the mulch with rainfall or overhead irrigation, and transplants are either placed in a new plant hole or shifted 15 cm away from a preexisting plant hole, then glyphosate or glufosinate can safely be applied preplant, before tomato, cucumber, or squash is planted. Significant crop injury is possible if the vegetable transplant is placed in soil exposed to the herbicide application.

Acknowledgments. We thank Tim Richards for his technical assistance with this research.

Funding. This research was funded by the Georgia Commodity Commission for Vegetables.

Competing Interests. The authors declare they have no competing interests.

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