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Herbicides in plasticulture

Planting Strategy Influences Vegetable Response to Glyphosate and Glufosinate Applied Preplant in Plasticulture

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Abstract

In Georgia plasticulture vegetable production, a single installation of plastic mulch is utilized for up to five cropping cycles over an 18-month period. Preplant applications of glyphosate and glufosinate ensure fields are weed-free before transplanting, but recent data suggest 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 pre-existing plant hole, 3) or a new plant hole spaced 15 cm from a pre-existing plant hole (adjacent). Following herbicide application, overhead irrigation was utilized to remove residues from the mulch before punching transplanting holes for tomato, cucumber, or squash. Visible injury, widths, biomass, 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 pre-existing holes, tomato was injured 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 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 pre-existing plant hole. Glufosinate at the same rates did not affect tomato growth or yield when planted into pre-existing plant holes. Cucumber, when planted into pre-existing plant holes, was injured 43 to 75% from glufosinate, with reductions in height and biomass, and yield losses at 1.3 and 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.

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

Introduction

Accounting for over $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 2022a, 2022b). In 2020, specialty crops were grown across all 50 states, in the U.S., with GA contributing over 33 high-value fresh-market produce crops for domestic consumption (Anonymous 2022; USDA 2019). Although vegetable crops were grown on less than 65 million ha in the U.S. during 2017, data suggests that production area of these high-value crops is increasing, with an 11% growth recorded from 2012 to 2017 (USDA 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, 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 Georgia vegetable production, an industry valued at nearly $1.3 billion (Anonymous 2022; Da Silva et al. 2020). Large bed plastic mulch, a covered raised bed approximately 15-20 cm tall and 81 cm wide, is the most utilized 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), 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; Fonhsah 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 utilize a single installation of mulch for 3-5 cropping cycles, or approximately 18 months (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

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emerging in the bed for crop cycles 2 to 5. However, this method of control is expensive and only extends 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 product development and registration for 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 *Cyperus*, *Amaranthus*, and *Digitaria* weed species (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, low organic matter soils up to 7 days 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 pre-existing 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

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mulch, where final concentrations can be high depending upon the pesticide applied. With many growers using high burndown application rates to control problematic weeds such as nutsedge, 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 pre-existing holes in mulch created by the previous crop, 3) or punching holes into mulch spaced 15 cm away from pre-existing 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 (31.30’18°N, 83.39’03°W, elevation 109 m), 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 27835) was utilized 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, Inc. Greenville, NC 27835) 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, Inc., Ruskin, FL

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33570) was utilized to simultaneously inject metam sodium (Vapam ® HL™, AMVAC ®, Los Angeles, CA 90023) 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 three months 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 Company, St. Louis, MI, 633167) was applied at 1.3, 2.5, and 5.0 kg ae ha^{-1} while glufosinate (Liberty, BASF Cooperation, Research Triangle Park, NC, 27709) was applied at 0.7, 1.3, and 2.6 kg ai ha^{-1} within respective studies. Herbicide treatments were applied to 2 m by 8 m plots using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa, equipped with 11002 Teejet Air Induction nozzles (Teejet Technologies, Wheaton, IL 60187). Within each study, nontreated controls were included for comparison, and all herbicide treatments were replicated four times.

To simulate scenarios where a single installation of plastic mulch is utilized for multiple cropping cycles, the surface of the mulch was manipulated in each study to represent three different planting scenarios. The first planting arrangement treatment 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 hours 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 hours after mulch was completely dry from irrigation and transplants were immediately hand placed into the plant holes.

The second planting arrangement represented a scenario where a crop would be planted into plastic mulch that had been used in a previous cropping cycle, with pre-existing 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 by 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 pre-existing 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 pre-existing plant holes present in the mulch at the time of herbicide application and irrigation (Figure 3); this represents a common scenario where growers plant their second through fifth crop 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 "pre-existing crop holes", with transplants planted by hand into the new plant holes. This planting method would determine if 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 within 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 (Keenco Manufacturing, Inc. 1105 3rd Street NE, Ruskin, FL 33570). The hand-held hole punch allowed for washing the implement 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, USA) 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 days after planting (DAP), wooden stakes and string were placed in the field for plant support, and suckers were hand removed 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 the 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, 3 to 5 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. Above-ground fresh-weight biomass was collected once from each crop when visible injury was at its maximum, by removing the plant material from 4 to 9 plants per plot depending upon crop, leaving 10 plants per plot for further data collection. The above-ground plant material from each plant was collectively weighed to determine per-plot biomass (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 9 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 1991) using a Kerian Speed Sizer fruit grader (Kerian Machines, 1709 Hwy 81 S, P.O. Box 311, Grafton, ND 58237), 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 2016a, 2016b).

Statistical Analysis

To test for treatment by year interactions, data was subjected to an 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 in SAS Enterprise Guide (Version 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 pre-existing hole configuration. When at its maximum 23 DAP, visible injury recorded as plant discoloration increased as 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). 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 utilizing 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.

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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 impacted by increasing preplant glyphosate rate prior to planting tomato within the previous plant hole arrangement. The highest glyphosate rate reduced crop heights 23% while the two highest rates reduced early-season biomass 34% to 65%, when compared to 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, 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, 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%; other rates did not influence early-season yield (Table 1). There were no impacts of glyphosate on tomato yield for the entire season when compared to the control.

Glufosinate. Across all three planting arrangements, differences were not observed when comparing all rates of glufosinate applied before transplanting tomato to the non-treated 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 pre-existing hole arrangement, maximum injury, recorded as chlorosis, stunting, necrosis, or plant death was observed 30 DAP. Combined over locations, cucumber was injured 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 24% and biomass 57% compared to the non-treated control. Both early-season and total cucumber yields were impacted 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 only recorded within the pre-existing hole arrangement. Previous research has documented the high sensitivity of cucumber to the residual activity of glufosinate following applications to sandy, low organic matter soils (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 impacted by glufosinate at the two highest rates, with reductions of 30% to 67%, 44% to 88%, 56% to 87%, and 32% to 61%, respectively, compared to 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 impacted only in pre-existing 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 only statistically influenced by applications of glyphosate 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), where residual glyphosate injured

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transplanted squash, when applied preplant in sandy soils to a bareground production system. In their studies, squash was injured up to 48% following preplant 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 only negatively influenced 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 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, low organic matter soils exposed to these herbicides, as 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 utilizing plasticulture production systems for high-value fresh-market vegetable crops, the same mulch covered raised bed may be utilized for up to 5 successive crops over an 18-month 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 non-selective 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 utilized in sandy, low organic matter soils, up to 7 days 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 pre-existing plant hole, or 3) a new plant hole shifted 15 cm away from a pre-existing plant hole.

Results indicated 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 pre-existing plant hole, then glyphosate or glufosinate can safely be utilized preplant, before planting tomato, cucumber, or squash. Significant crop injury is possible if the vegetable transplant is placed in soil exposed to the herbicide application.

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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 TyTy, GA[a].

Planting arrangement[b]	Application rate	Injury[c,d]		Height[c,d]		Biomass[c,d]		Early yield[c,d]		Total yield[c,d]	
	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
Pre-existing 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 pre-exisitng 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; DAP, days after planting.

[b]Planting arrangement represented three planting scenarios, including: 1) punching a planting hole into new mulch, 2) punching a planting hole into pre-existing 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).

[c]Means followed by the same letter within a column are not significantly different ($P \leq 0.05$).

[d]Tomato injury, height, and fresh-weight biomass measured 23 DAP when injury was at a maximum; early-season yield collected for the first 3 harvests and season-long yield collected over 9 to 10 harvests.

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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 TyTy, GA[a].

Planting arrangement[b]	Application rate	Injury[c,d]		Length[c,d]		Biomass[c,d]		Early yield[c,d]		Total yield[c,d]	
	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
Pre-existing 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 pre-existing 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]Abbreviations: NTC, nontreated control; DAP, days after planting.

[b]Planting arrangement represented three planting scenarios, including: 1) punching a planting hole into new mulch, 2) punching a planting hole into pre-existing 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).

[c]Means followed by the same letter within a column are not significantly different ($P \leq 0.05$).

[d]Cucumber injury, height, and fresh-weight biomass collected 30 DAP when injury was at its maximum; early-season yield recorded for the first 4 harvests and season-long yield collected over 15 harvests.

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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 TyTy, GA[a].

Planting arrangement[b]	Application rate kg ai ha^{-1}	Injury[c,d] %		Length[c,d] % NTC		Biomass[c,d] % NTC		Early yield[c,d] kg ha^{-1}		Total yield[c,d] 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
Pre-existing 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 pre-existing 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]Abbreviations: NTC, nontreated control; DAP, days after planting.

[b]Planting arrangement represented three planting scenarios, including: 1) punching a planting hole into new mulch, 2) punching a planting hole into pre-existing 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).

[c]Means followed by the same letter within a column are not significantly different ($P \leq 0.05$).

[d]Cucumber injury, heights, and fresh-weight biomass collected 22 DAP when maximum injury was observed; early-season yield recorded for the first 4 harvests and season-long yield collected over 15 harvests.

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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 TyTy, GA[a].

Planting arrangement[b]	Application rate	Injury[c,d]		Widths[c,d]		Biomass[c,d]		Early yield[c,d]		Total yield[c,d]	
	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
Pre-existing 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 pre-existing 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]Abbreviations: NTC, nontreated control; DAP, days after planting.

[b]Planting arrangement represented three planting scenarios, including: 1) punching a planting hole into new mulch, 2) punching a planting hole into pre-existing 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).

[c]Means followed by the same letter within a column are not significantly different ($P \leq 0.05$).

[d]Squash injury, height, and fresh-weight biomass collected 16 DAP 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.

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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 TyTy, GA[a].

Planting arrangement[b]	Application rate kg ai ha^{-1}	Injury[c,d] %		Widths[c,d] % NTC		Biomass[c,d] % NTC		Early yield[c,d] kg ha^{-1}		Total yield[c,d] 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
Pre-existing 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 pre-existing 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]Abbreviations: NTC, nontreated control; DAP, days after planting.

[b]Planting arrangement represented three planting scenarios, including: 1) punching a planting hole into new mulch, 2) punching a planting hole into pre-existing 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).

[c]Means followed by the same letter within a column are not significantly different ($P \leq 0.05$).

[d]Squash injury, height, and fresh-weight biomass reported 16 DAP 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.

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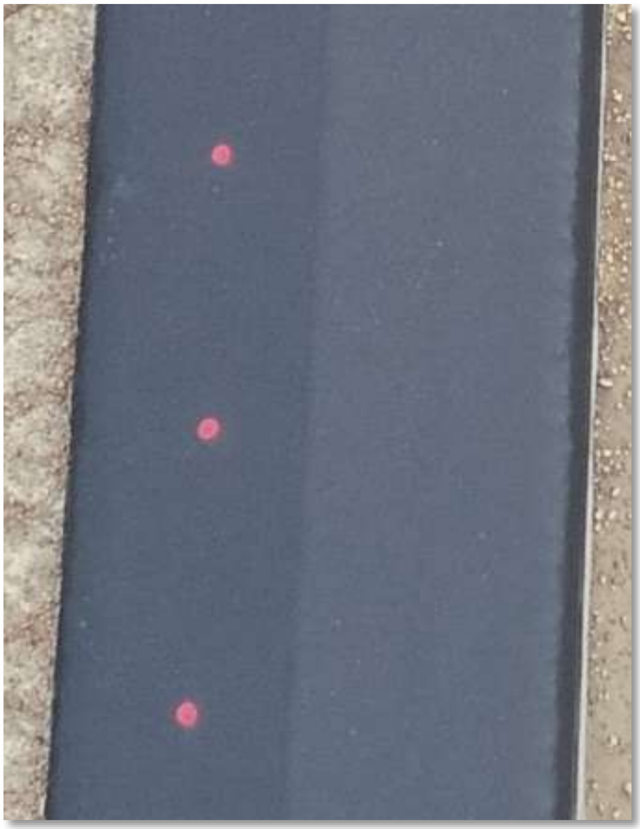

Figure 1. New plant hole. This planting hole configuration represents plant holes punched into newly installed plastic mulch, which would occur for the first crop in a multi-cropping system. To simulate this in the experiment, plastic mulch was laid, and following herbicide applications and overhead 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.

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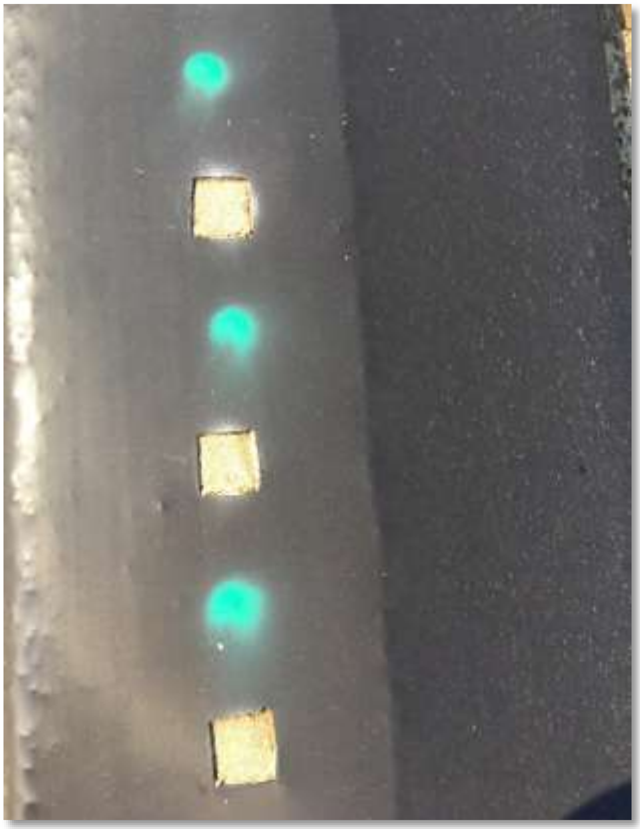

Figure 3. Adjacent to the previous crop plant hole. This planting hole configuration represents where a crop would be planted into plastic mulch used in a previous cropping cycle; instead of planting into pre-existing plant holes, a new hole was punched adjacent to the old hole. To simulate this configuration, 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.

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