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Transplant broccoli and collard response to the residual activity of glyphosate applied preplant

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Research Article

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Abstract

Cole crops including broccoli and collard contribute more than $119 million to Georgia's farm gate value yearly. To ensure maximum profitability, these crops must be planted into weed-free fields. Glyphosate is a tool often used to help achieve this goal because of its broad-spectrum activity on weeds coupled with the knowledge that it poses no threat to the succeeding crop when used as directed. However, recent research suggests that with certain soil textures and production systems, the residual soil activity of glyphosate may damage some crops. Therefore, field experiments were conducted in fall 2019 and 2020 to evaluate transplanted broccoli and collard response to glyphosate applied preplant onto bare soil and what practical mitigation measures could be implemented to reduce crop injury. Herbicide treatments consisted oGf 0, 2.5, or 5 kg ae ha^{-1} glyphosate applied preplant followed by 1) no mitigation measure, 2) tillage, 3) irrigation, or 4) tillage and irrigation prior to transplanting broccoli and collard by hand. When no mitigation was implemented, the residual activity of glyphosate at 2.5 and 5.0 kg ae ha^{-1} resulted in 43% to 71% and 79% to 93% injury to broccoli and collard transplants, respectively. This resulted in a 35% to 50% reduction in broccoli marketable head weights and 63% to 71% reduction in collard leaf weights. Irrigation reduced visible damage by 28% to 48%, whereas tillage reduced injury by 43% to 76%, for both crops. Irrigation alleviated yield losses for broccoli but only tillage eliminated yield loss for both crops. Care must be taken when transplanting broccoli and collard into a field recently treated with glyphosate at rates ≥2.5 kg ae ha^{-1}. Its residual activity can damage transplants with injury levels influenced by glyphosate rate, and tillage or irrigation after application and prior to planting.

Introduction

Vegetable production in Georgia contributes $1.2 billion to the farm gate value (Stubbs 2020). Cole crops and leafy greens contribute more than $119 million annually to the Georgia farm gate value and are grown on 37,160 ha (Stubbs 2020). Georgia ranks first in collard production and fourteenth in broccoli production in the United States (USDA-NASS 2022a, 2022b). As production of these crops has increased across the Southeast, the method of planting has shifted from being seeded to mostly transplanted; approximately 80% of broccoli and 70% of collard plants are currently transplanted (Coolong et al. 2016, 2017). The shift toward transplanting is due to significantly reduced germination associated with high fall soil temperatures (Coolong et al. 2016). Transplanting also improves uniformity and shortens the production season thus facilitating a greater potential for higher market prices (Orzolek 1991).

In addition to transplanting, beginning the season with a weed-free field is crucial for profitability. Deemed the *critical weed-free period*, beginning at planting and continuing for several weeks, this period is when young plants are most susceptible to competition and interference from weeds, resulting in lower yield (Zimdahl 2018). Shadbolt and Holm (1956) reported that even a low density of weeds, 15% of a normal stand, was sufficient to reduce yield in carrot, onion, and beet crops by 30%, 25%, and 22%, respectively, when weeds were allowed to grow alongside the crop for 4 wk after planting. They also determined that managing weeds from planting through 4 wk after planting was sufficient to mitigate yield losses from weed competition. Additionally, a study conducted on cabbage and tomato transplants found the critical weed-free period to be from planting through 3 to 5 wk after planting, respectively (Weaver 1984). By planting into weed-free fields, vegetable crops can establish and grow competitively. However, when weeds are present at planting, it is more difficult to manage these weeds in-crop, often resulting in reduced yields and quality.

Tillage, glyphosate, and paraquat are effective tools available to help eliminate weeds prior to planting cole crops in Georgia (Coolong et al. 2017; Culpepper and Randell 2022). Of these options, tillage to prepare a planting bed followed by an application of glyphosate to control weeds emerging between land preparation and planting are the standard choice to ensure fields are free of weeds at planting. Growers apply glyphosate because of its broad-spectrum activity on many of the common and troublesome weeds including yellow and purple nutsedge (*Cyperus esculentus* L. and *C. rotundus* L., respectively), wild radish (*Raphanus raphanistrum* L.), pink purslane (*Portulaca pilosa* L.), and cutleaf evening primrose (*Oenothera laciniata* Hill) (Culpepper et al. 2005; Culpepper and Randell 2022; Van Wychen 2019; Webster et al. 2008) and because, at least historically, the herbicide was thought to pose no threat to the succeeding crop. In fact, glyphosate's 47-d soil half-life typically does not offer residual activity because of its propensity to bind to soil (K_{oc} =24,000 mL g^{-1}; K_d = 324 to 600 mL g^{-1}) (Shaner et al. 2014).

However, literature nearly three decades old explains that residual herbicidal activity of glyphosate can occur, although it is quite rare (Cornish 1992; Eberbach and Douglas 1983; Salazar and Appleby 1982). Additionally, recent research has confirmed the residual activity of glyphosate can damage fruiting vegetable and cucurbit crops with subsequent yield losses on sandy soils with low organic matter when crops are transplanted. Goodman et al. (2019) reported watermelons transplanted into bareground systems were injured 30% with a 16% yield loss when 2.5 kg ha^{-1} glyphosate was applied 1 d before planting. That study also reported cucumber injury of 14% to 52% when glyphosate was applied at 2.5 or 3.7 kg ha^{-1} at 1, 4, or 7 d prior to transplanting; yield loss was again prevalent with most treatments. Randell et al. (2022) found similar results in squash with 11% to 56% injury when glyphosate was applied at 1.5, 3.1, or 4.6 kg ha^{-1} 1, 4, and 7 d prior to transplanting with yield loss ranging from 21% to 41%. Studies reported by Goodman et al. (2019) and Randell et al. (2022) were conducted on soils with sand content of 88% to 90% with 0.5% to 0.9% organic matter, which likely influenced glyphosate residual activity. Other researchers have also noted that glyphosate is not readily adsorbed by sandy soils, thus soils high in sand content have higher potential for glyphosate to remain in the soil solution where it can be taken up by plants (Salazar and Appleby 1982; Sprankle et al. 1975).

With recent research confirming that the residual activity of glyphosate can damage fruiting vegetable and cucurbit crops on sandy soils with low levels of organic matter, research is needed to determine the vulnerability of transplanted broccoli and collard to glyphosate applied preplant in similar production systems and soils. Additionally, if glyphosate applied preplant poses a risk to broccoli and collard, practical mitigation measures must be demonstrated.

Materials and Methods

Site Selection and Trial Establishment

Field studies were initiated October 24, 2019, and October 12, 2020, at the University of Georgia Ponder Research Farm near Ty Ty, Georgia (31.507°N, 83.657°W) to evaluate broccoli and collard responses to glyphosate applied preplant. Soil at this location was a Tifton loamy sand consisting of 92% sand, 6% silt, 2% clay, and 0.58% organic matter, pH 6.5; typical for the production region (Coolong et al. 2017). This experiment consisted of a three-factor factorial treatment arrangement in a randomized complete block design with four replications. The first factor, glyphosate rate, consisted of three levels: 0 kg ae ha^{-1}, 2.5 kg ha^{-1}, and 5.0 kg ha^{-1} (Roundup PowerMAX® II; Bayer CropScience LP, St. Louis, MO). The 2.5 kg ha^{-1} rate is the highest rate allowed in cole crops and is suggested for preplant control of nutsedge species (Anonymous 2020). The 5 kg ha^{-1} rate was included to evaluate crop safety at a 2× rate. The second factor in the treatment factorial consisted of two levels of tillage: roto-tilling soil to a depth of 5 cm after glyphosate application (prior to planting) or no tillage. The third factor also consisted of two levels of irrigation: sprinkler irrigation of 0.6 cm after glyphosate application (before planting) or no irrigation. Trials were maintained weed-free by selecting a site with low weed populations coupled with a preplant application of trifluralin (Treflan 4L; Loveland Products Inc., Greely, CO) at 35 g ai ha^{-1} and oxyfluorfen (Goal® 2XL; Corteva Agriscience, Indianapolis, IN) at 105 g ai ha^{-1}. Irrigation was implemented following this application, prior to planting. Weed escapes were removed by hand prior to reaching 4 cm in height or diameter.

The land was conventionally prepared using a disk harrow (International Harvester, Chicago, IL), followed by ripping and bedding (Kelley Manufacturing Co., Tifton, GA), and rototilling (Maletti, Modena, Italy), leaving a smooth, flat surface for planting prior to trial initiation. After the study area was prepared, glyphosate treatments requiring irrigation were applied. Three hours later, 0.6 cm of sprinkler irrigation was implemented across the entire study area. Overhead sprinkler irrigation was applied at a rate of 0.25 cm per 10 min. One to two hours after irrigation, the remaining glyphosate treatments were applied. Tillage commenced 3 h later. Tillage treatments were implemented by identifying all plots requiring tillage, driving a tractor equipped with a rototiller down each row, and lowering the rototiller in the alley prior to each identified plot, lightly tilling the plot, then raising the rototiller in the alley at the end of the plot. The rototiller was allowed to turn for several seconds following each plot to remove any treated soil prior to continuing. All glyphosate treatments were applied with a CO_2-pressurized backpack sprayer at 276 kPa and equipped with TTI 110015 nozzles (TeeJet Technologies, Glendale Heights, IL) calibrated to deliver 140 L ha^{-1}.

Eight hours after treatment initiation, transplant holes were made using a tractor-mounted twin-row transplant hole-punch wheel (Kennco Manufacturing, Inc., Ruskin, FL) with broccoli (cv. 'Emerald Crown') and collard (cv. 'Top Bunch') immediately transplanted by hand, a standard production practice in this region (Coolong et al. 2016, 2017). Plot dimensions were 1.8 m wide and 7.6 m long with one row of broccoli and one row of collard planted using a between-row spacing of 38 cm and an in-row spacing of 31 cm. Broccoli and collard fertility, irrigation, and insect and disease management followed University of Georgia recommendations (Coolong et al. 2016, 2017).

Data Collection and Analysis

Visible estimates of crop injury were obtained weekly beginning 1 wk after planting (WAP) and continuing through harvest, with the greatest level of injury recorded 4 WAP. Injury was evaluated on a scale of 0% to 100%, with 0% being no injury (chlorosis, necrosis, stunting) and 100% being crop death. Plant growth was measured by recording diameter, at the widest point, of 10 plants per plot weekly beginning 2 WAP and continuing until harvest for each crop. Fresh weight and root biomass for each crop was collected 4 WAP from seven plants per plot. Plants were lifted from the soil after irrigation with a shovel ensuring roots were not lost during the root and shoot harvesting process. The root ball was placed into a paper bag and taken to the greenhouse for 4 wk of drying to

Table 1. P-values for broccoli response variables.[a]

Factor	Injury	Plant diameter	Shoot biomass	Root biomass	Head weight
Glyphosate rate	<0.0001	<0.0001	<0.0001	0.1171	0.001
Tillage	<0.0001	<0.0001	<0.0001	0.0007	<0.0001
Irrigation	<0.0001	0.005	0.1399	0.5254	0.0029
Glyphosate rate × tillage	<0.0001	<0.0001	<0.0001	0.0256	0.004
Glyphosate rate × irrigation	<0.0001	0.02	0.0238	0.7334	0.025
Tillage × irrigation	<0.0001	<0.0001	0.0005	0.036	0.001
Glyphosate rate × tillage × irrigation	<0.0001	0.0004	0.0025	0.0468	0.0186

[a]P-values were determined from ANOVA.

Table 2. Broccoli injury, plant diameter, and marketable head weights as influenced by glyphosate rate, tillage, and irrigation.[a,b,c]

Glyphosate rate	Tillage	Irrigation	Injury	Plant diameter	Shoot biomass	Root biomass	Head weight
kg ae ha^{-1}			%	% relative to nontreated			
0	None	None	0 d	100 a	100 a	100 a	100 a
		0.6 cm	0 d	100 a	100 a	100 a	100 a
	5 cm	None	0 d	100 a	100 a	100 a	100 a
		0.6 cm	0 d	100 a	100 a	100 a	100 a
2.5	None	None	43 b	67 c	19 c	88 ab	65 bc
		0.6 cm	15 cd	88 ab	64 b	84 ab	89 ab
	5 cm	None	0 d	103 a	96 a	106 a	102 a
		0.6 cm	6 d	99 a	86 ab	96 ab	100 a
5.0	None	None	79 a	44 d	19 c	67 b	37 c
		0.6 cm	31 bc	79 bc	24 c	88 ab	92 ab
	5 cm	None	5 d	102 a	101 a	115 a	98 ab
		0.6 cm	5 d	94 ab	90 ab	92 ab	97 ab

[a]Injury, plant diameter, shoot biomass, and root biomass measurements taken 4 wk after planting when maximum injury was observed. Broccoli marketable heads harvested up to 15 times.
[b]Data are combined over 2019 and 2020. Means were separated using Tukey's honestly significant difference test with a significance level of $\alpha = 0.05$. Means followed by the same letter within a column are not significantly different.
[c]All variables except injury are presented as a percent of the nontreated control (no herbicide) for each irrigation and tillage treatment. Averages for each variable in the control are as follows: plant diameter, 31.0 cm; shoot biomass, 34.7 g; root biomass, 8.2 g, broccoli marketable head number, 9.8; and broccoli marketable head weight, 3.1 kg.

facilitate soil separation from the roots naturally, followed by weighing. Aboveground shoots were placed in their own bag and weighed immediately. Yield data were collected at plant maturity from 10 plants per plot, with broccoli harvested up to 15 times over 7 wk and collard three times over 3 mo. For each plot at each harvest, broccoli marketable heads and collard marketable leaves were counted and weighed (USDA-AMS 2008a, 2008b)

Maximum injury, plant diameter, shoot and root biomass, broccoli head numbers and weights, and collard leaf numbers and weights were determined relative to the control plots having the same irrigation and tillage treatments but no glyphosate. Data were analyzed using the MIXED procedure in JMP Pro 15 software (SAS Institute, Cary, NC). Replication was nested within year and was treated as a random effect, while glyphosate rate, irrigation, and tillage were fixed effects. The two-way and three-way interactions between variables were also evaluated. An ANOVA was conducted, and means were separated using Tukey's honestly significant difference test with a significance level of $\alpha = 0.05$.

Results and Discussion

Broccoli

Visible injury estimates were influenced by glyphosate rate, tillage, and irrigation at 4 WAP (Table 1). Glyphosate at 2.5 and 5.0 kg ha^{-1} caused 43% and 79% injury, respectively, when neither tillage nor irrigation followed application (Table 2). The level of injury observed was severe and was likely influenced by the transplant wheel hole-punch method, which is standard for current production in the region. When punching the hole, soil from the surface is pushed downward, placing herbicide-treated soil throughout the plant hole, thereby increasing direct contact of the herbicide with the moist transplant root ball. When implementing irrigation as a method to mitigate the residual activity of glyphosate, visible injury was reduced 28% to 48%; however, injury observed remained unacceptable at 15% with the low rate of glyphosate and 31% with the higher rate (Table 2). Tillage was more effective than irrigation in mitigating injury, with less than 7% injury observed with either rate of glyphosate if tillage was implemented. Tillage plus irrigation was no more effective than tillage alone. These results reflect those observed by Randell et al. (2022), when tillage following glyphosate applications of 3.1 and 6.2 kg ha^{-1} was sufficient to eliminate injury to squash, while irrigation was less beneficial. Additionally, Cornish (1992) suggested that mixing glyphosate with soil would mitigate its effects on sensitive crops due to increased adsorption.

Plant diameters 4 WAP were similarly influenced by glyphosate rate, tillage, and irrigation (Table 1). Without mitigating damage with tillage or irrigation, glyphosate reduced plant diameter measurements by 33% to 56% with 2.5 to 5.0 kg ha^{-1} of glyphosate compared to the control plants. The addition of irrigation resulted in healthier plants, but plant diameters remained 12% to 16% smaller than that of the control. Tillage eliminated the negative impacts from glyphosate applied preplant, regardless of rate, with plant diameters being 102% to 103% of the control.

Aboveground fresh weight biomass was reduced 81% by both rates of glyphosate at 4 WAP (Table 2). Irrigation resulted in a 45% increase in biomass weight when applying glyphosate at 2.5 kg ha^{-1}, but benefits were not significant for the higher rate. Tillage was once again more effective than irrigation, with biomass weights similar to that of the control when tilling after applying

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Table 3. P-values for collard response variables.[a]

Factor	Injury	Plant diameter	Shoot biomass	Root biomass	Leaf weight
Glyphosate rate	<0.0001	<0.0001	<0.0001	0.0029	<0.0001
Tillage	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Irrigation	<0.0001	<0.0001	0.007	0.0244	0.1289
Glyphosate rate × tillage	<0.0001	<0.0001	<0.0001	0.0001	<0.0001
Glyphosate rate × irrigation	0.0002	0.0057	0.1459	0.107	0.5219
Tillage × irrigation	<0.0001	<0.0001	0.0366	0.1466	0.3075
Glyphosate rate × tillage × irrigation	0.0003	0.001	0.0214	0.3939	0.7192

[a]P-values were determined from ANOVA.

Table 4. Collard injury, plant diameter, and shoot biomass influenced by glyphosate rate, tillage, and irrigation.[a,b,c]

Glyphosate rate	Tillage	Irrigation	Injury	Plant diameter	Shoot biomass
kg ae ha^{-1}			%	% relative to nontreated	
0	None	None	0 d	100 a	100 a
		0.6 cm	0 d	100 a	100 a
	5 cm	None	0 d	100 a	100 a
		0.6 cm	0 d	100 a	100 a
2.5	None	None	71 b	52 d	17 d
		0.6 cm	30 c	75 c	51 bc
	5 cm	None	3 d	92 ab	92 a
		0.6 cm	6 d	88 abc	85 a
5.0	None	None	93 a	30 e	5 d
		0.6 cm	63 b	53 d	21 cd
	5 cm	None	17 cd	87 bc	75 ab
		0.6 cm	8 d	87 bc	90 a

[a]Injury, plant diameter and shoot biomass measurements taken 4 wk after planting when maximum injury was observed.
[b]Data are combined over 2019 and 2020. Means were separated using Tukey's honestly significant difference test with a significance level of $\alpha = 0.05$. Means followed by the same letter within a column are not significantly different.
[c]All variables except injury are presented as a percent of the nontreated control (no herbicide) for each irrigation and tillage treatment. Averages for each variable in the control are as follows: plant diameter, 28.1 cm and shoot biomass, 33.6 g.

either rate of glyphosate. Root biomass was influenced less than shoot biomass; glyphosate at 5.0 kg ha^{-1} without tillage or irrigation was the only treatment to significantly reduce dry weight biomass (33%). Eberbach and Douglas (1983) reported a 6.5% reduction in root growth of subterranean clover following an application of glyphosate at 2 μg g^{-1} made to soil with 82% sand when plants were grown in a greenhouse (equivalent to a 1× field application of glyphosate in this study).

Glyphosate at both 2.5 and 5.0 kg^{-1} reduced total head weights by 35% and 63%, respectively, when no mitigation was implemented (Table 2). Previous research indicated that glyphosate uptake through roots can reduce vegetable yields (Semidey and Almodóvar 1987). The number of broccoli heads produced was reduced by glyphosate only at 5.0 kg ha^{-1} (56%), indicating that the impact from glyphosate, especially at the lower rate, was predominately through reducing head size (data not shown). Using irrigation, tillage, or irrigation plus tillage to mitigate the residual activity of glyphosate were all successful with head weights harvested from these treatments similar to that of the nontreated control. The ability of the broccoli to recover from injury levels observed with these treatments during early season is feasible, especially in production systems providing ample irrigation and fertilizer (Bhowmik and McGlew 1986).

Collard

Collard visible injury estimates were influenced by glyphosate rate, tillage, and irrigation (Table 3). Collard transplants were more sensitive to glyphosate applied preplant than broccoli transplants, with injury ranging from 71% with glyphosate at 2.5 kg ha^{-1} to 93% with glyphosate at 5.0 kg ha^{-1} (Tables 2 and 4). Similar to the result observed in broccoli, irrigation did lessen injury observed in collard, but damage remained severe, ranging from 30% to 63% (Table 4). In contrast to broccoli, tillage did not reduce crop damage to a level below 10% for all treatments. Even with tillage, collard injury of 17% was observed with the high rate of glyphosate applied preplant.

By 4 WAP, plant diameter was reduced 48% to 70% by glyphosate (Table 4). Similar to injury, irrigation alone did not mitigate the impact of either glyphosate rate. Tillage was again more effective than irrigation, but a 13% reduction in plant diameter remained when the high rate of glyphosate was followed by tillage. In fact, only tillage or tillage plus irrigation following the low rate of glyphosate produced growth diameter parameters similar to that of the control.

Aboveground fresh weight of collard was reduced 83% to 95% at 4 WAP (Table 4). When irrigation was implemented, shoot biomass was still reduced 49% to 79%; tillage more effectively mitigated glyphosate damage with biomass levels similar to that of the control. Collard root biomass was influenced by glyphosate rate and tillage (Table 3). When combined over irrigation options, glyphosate reduced root biomass 25% to 34%, whereas implementing tillage following either rate of glyphosate alleviated root biomass losses (Table 5).

Collard leaf number harvested and relative weights were influenced only by glyphosate rate and tillage, with leaf number reduced by 46% (data not shown) and weights reduced by 50% when glyphosate was applied at 2.5 kg ha^{-1} (Table 5). When glyphosate was

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Table 5. Collard root biomass and leaf weight influenced by glyphosate rate and tillage.[a,b,c]

Glyphosate rate	Tillage	Root biomass	Leaf weight
kg ae ha^{-1}		——% relative to nontreated——	
0	None	100 a	100 a
	5 cm	100 a	100 a
2.5	None	75 b	50 c
	5 cm	108 a	83 ab
5.0	None	66 b	29 d
	5 cm	103 a	69 bc

[a]Root biomass measurement was taken 4 wk after planting when maximum injury was observed. Collard marketable leaves harvested three times.
[b]Data are combined over 2019 and 2020 and averaged over irrigation treatment. Means were separated using Tukey's honestly significant difference test with a significance level of $\alpha = 0.05$. Means followed by the same letter within a column are not significantly different.
[c]All variables are presented as a percent of the nontreated control (no herbicide) for each irrigation and tillage treatment. Averages for each variable in the control are as follows: root biomass, 4.7 g; shoot biomass, 34.7 g; root biomass, 8.2 g, collard marketable leaf number, 249; and collard marketable leaf weight, 4.4 kg.

applied at 5.0 kg ha^{-1}, leaf number and weight were reduced by 70% to 71%. Leaf number and weight remained 26% and 31% lower, respectively, than the control even when implementing tillage after applying the higher rate of glyphosate. Leaf number and weight response by collard indicate crop safety when tillage follows a glyphosate application of only 2.5 kg ha^{-1}.

In conclusion, these results confirm that care must be taken when applying glyphosate prior to transplanting broccoli and collard. There is evidence that a pretransplant glyphosate application can result in significant injury, plant growth reductions, and yield loss in these crops. The residual damage of glyphosate to these crops is likely influenced by soil type, planting method, irrigation scheduling, herbicide rate, tillage between application and planting, and interval between application and planting. In this study, overhead irrigation effectively reduced the impact from the residual activity of glyphosate on these crops. However, irrigation of 0.6 cm was not adequate enough to alleviate glyphosate damage. Rainfall or irrigation of at least 1.3 cm and waiting 7 d to plant is recommended to mitigate injury if tillage is not implemented (Culpepper and Randell 2022). Tillage to a depth of 5 cm was more effective than irrigation and can be used to mitigate injury when applying glyphosate at rates equal ≤2.5 kg ha^{-1} for these crops.

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[USDA-AMS] U.S. Department of Agriculture–Agricultural Marketing Service Fruit and Vegetable Programs (2008b) Pages 1–39 *in* Kale and greens (beet, broccoli, collard, dandelion, mustard, and turnip) shipping point and market inspection instructions. Fruit and Vegetable Programs

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