Weed Technology 2014 28:626–632

Pepper and Tomato Root Uptake of Paraquat and Flumioxazin

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Fresh market pepper and tomato are important crops in Florida. Production primarily occurs on raised beds covered with plastic mulch. Weeds emerging between the rows are often controlled with multiple applications of burndown and soil-residual herbicides. Crop damage attributed to root uptake of herbicides applied between the rows has been reported. An experiment was conducted in a greenhouse at the Gulf Coast Research and Education Center to examine the effect of root uptake of paraquat and paraquat tank-mixed with flumioxazin on pepper and tomato growth and yield. Herbicides were applied via subsurface irrigation at 0.0625×, 0.125×, 0.25×, 0.5×, 1×, 2×, 4×, 8×, and 16× labeled rates. The 1× rate was based on the estimated label rate that would be applied per plant in the field and was 0.122 g ai plant^{-1} (1,542 g ai ha^{-1}) and 0.011 g ai plant^{-1} (143 g ai ha^{-1}) for paraquat and flumioxazin, respectively. Root uptake caused necrosis of the veins, followed by complete tissue death at higher rates. The percentage of crop damage increased with herbicide rate for both species ($P < 0.0001$), with greater damage observed at the lower rates with the tank mix than with the paraquat alone. A reduction in shoot biomass and fruit yield of both crops was observed following root uptake. These results suggest that uptake of paraquat or paraquat tank-mixed with flumioxazin by pepper and tomato roots in a field situation is possible.

Nomenclature: Flumioxazin; paraquat; pepper, *Capsicum annuum* L.; tomato, *Lycopersicon esculentum* L.

Key words: Herbicide absorption, plasticulture, translocation, vein necrosis.

El pimentón y el tomate para mercado fresco son cultivos importantes en Florida. La producción se da primariamente en camas elevadas con cobertura plástica. Las malezas emergen entre las hileras y son frecuentemente controladas con múltiples aplicaciones de herbicidas de amplio espectro y herbicidas residuales. Se ha reportado el daño al cultivo atribuido a la absorción por la raíz de herbicidas aplicados entre las hileras de siembra. Se realizó un experimento en un invernadero en el Centro de Investigación y Educación de la Costa del Golfo para examinar la absorción por la raíz de paraquat y paraquat en mezcla en tanque con flumioxazin en pimentón y tomate, y su efecto en el crecimiento y el rendimiento de estos cultivos. Los herbicidas fueron aplicados vía riego subterráneo a 0.0625×, 0.25×, 0.5×, 1×, 2×, 4×, 8×, and 16× de la dosis de etiqueta. La dosis 1× se basó en el estimado de la dosis de etiqueta que sería aplicada por planta en el campo y fue 0,122 g ai planta^{-1} (1,542 g ai ha^{-1}) y 0.011 g ai planta^{-1} (143 g ai ha^{-1}) para paraquat y flumioxazin, respectivamente. La absorción por la raíz causó necrosis de las venas, seguido de la muerte de tejidos a dosis altas. El porcentaje de daño al cultivo aumentó con la dosis de herbicida para ambas especies (P<0.0001), observándose un mayor daño a dosis bajas con la mezcla en tanque que con paraquat solo. Se observó una reducción en la biomasa aérea y en el rendimiento de fruto para ambos cultivos después de la absorción por la raíz. Estos resultados sugieren que la absorción de paraquat o paraquat en mezcla en tanque con flumioxazin por las raíces de pimentón y tomate es posible en una situación de campo.

Paraquat is a burndown herbicide that has been widely used in agriculture for more than 40 yr (Roberts et al. 2002). It is a rapidly absorbed, nonselective, foliar herbicide that diverts electrons within photosystem I. Paraquat translocation is limited to the apoplast, and as a result, it remains within leaves under most conditions and does not translocate to the roots (Senseman 2007). It also has limited to no soil activity because it readily binds with clay and soil humic substances via ion exchange. The cationic group on the paraquat molecule forms stable and unreactive bonds with the carboxyl groups of humic substances (Gevao et al. 2000) making it unavailable for plant roots. However, some soil activity is possible if a portion of the herbicide remains in solution.

Soil adsorptive capacity varies with soil type. As a general rule soils with greater clay or organic carbon content have greater adsorptive capacities than sands, and as a result, paraquat is more likely to

DOI: 10.1614/WT-D-13-00177.1

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be biologically active in sandy soils with low organic matter (Roberts et al. 2002). For example, Tucker et al. (1969) found that paraquat at 200 ppmw in sandy soil inhibited the germination of corn (*Zea mays* L.) and beans (*Phaseolus* L. spp.) whereas 1,200, 2,500, and 4,000 ppmw were required to inhibit germination of the same species in a loamy sand, loam, and muck soil, respectively.

Seedling or shoot damage caused by root absorption of paraquat is rare in most soils but incidents of root absorption and translocation to seedling shoots have been reported (DiTomaso et al. 1993). Damanakis et al. (1970a) found that paraquat, even when applied to muck soils, could inhibit seedling growth. They reported shoot inhibition as a secondary effect caused by root inhibition because no toxic symptoms were observed on the shoot (Damanakis et al. 1970b).

Soil activity of paraquat is rare, largely because the compound rapidly degrades when not bound with soil particles. Degradation is caused by microorganisms (Roberts et al. 2002) and light (Slade 1966), with microorganisms likely having the more significant role. Paraquat bound to soil particles persists for substantially longer periods but is not biologically active in most cases. Khan et al. (1976) reported recovery of 50% of the paraquat applied to an organic soil 15 mo after application, and Fryer et al. (1975) reported recovery of virtually all paraquat applied throughout a 7-yr period. Although highly persistent, the bound molecules have no effect on plant growth.

In Florida, many fruit and vegetable crops are grown using a plasticulture system, which consists of the formation of raised, fumigated beds covered with plastic mulch. Paraquat is broadcast for weed control after bed formation but before transplanting, as a directed spray to control weeds between the raised beds (row middles) following transplanting, and as a crop desiccant. Herbicide residues on the plastic following broadcast applications can cause crop damage. Grey et al. (2009) reported that the time required for 50% of the paraquat to dissipate was 1 h if paraquat residue was washed off with irrigation water and 32 h if no irrigation was applied. In the absence of irrigation, paraquat applications on the plastic reduced the heights and yields of tomato and squash (*Cucurbita pepo* L.) (Culpepper et al. 2009). Herbicide damage may also occur from drift during row-middle applications following crop transplant. Shielded applicators are used to minimize herbicide drift and the consequential contact with crop foliage. The potential for root absorption following row middle applications is low. However, Crespo et al (2013) speculated that carfentrazone, another herbicide frequently applied to row middles, could persist when applied during dry periods to row middles in Florida with sandy soils and cause subsequent crop damage following rainfall events. They were able to show carfentrazone damage caused by uptake through the roots in a greenhouse study and attributed herbicide damage observed in the field to carfentrazone applications. I speculate that a similar scenario could occur with paraquat. In Florida, vegetable crops, such as tomato and pepper, are typically grown on sandy soils with very low organic matter using drip irrigation. In drip irrigation systems, soils in the row middles can be very dry, especially during the winter months. It is likely in this environment that paraquat does not bind as readily to the soil, persists for longer periods, and could move to the root zone of the crops following a significant rainfall event.

Flumioxazin is another herbicide frequently used to control broadleaf weeds in row middles. It is a protoporphyrinogen oxidase inhibitor that aids in rapid burndown but is predominately used for residual weed control (Senseman 2007). It is absorbed by the roots and shoots of plants with limited symplastic movement because of the rapid foliar desiccation. It is rarely broadcast because of its persistence on plastic. Grey et al. (2009) found that flumioxazin persistence was much higher than paraquat on plastic at 6 h with irrigation and 57 h without irrigation. Like paraquat, flumioxazin is readily absorbed by soils, and the rate of adsorption is related to the clay and organic carbon content. Alister et al. (2008) reported 50% dissipation of flumioxazin in 10 to 32 d, with residues still found after 90 d. Similar dissipation rates were obtained by Ferrell and Vencill (2003) in two different soil types. This compound is not susceptible to photodegradation in the soil, temperature has minimal impact on persistence, and microbe populations are the primary source of degradation when in solution (Ferrell and Vencill 2003). Vegetable growers often tank-mix flumioxazin with a burndown product, such as paraquat or carfentrazone, to provide residual weed control. It is possible that under very specific conditions this type of tank mix could cause greater crop damage than paraquat applied alone.

The objective of this experiment was to determine whether root uptake of paraquat or paraquat tank-mixed with flumioxazin at various rates by established tomato and pepper plants could damage crop foliage and reduce yield.

Materials and Methods

Experimental Setup and Design. Greenhouse trials were conducted at the Gulf Coast Research and Education Center in Wimauma, FL, to determine the effect of root uptake of paraquat (Gramoxone Inteon, Syngenta Crop Protection Inc., Greensboro, NC) and flumioxazin (Chateau SW, Valent U.S.A corporation, Walnut Creek, CA) on tomato and pepper growth, reproduction, and yield. 'Charger' tomato and 'Aristotle' pepper seedlings (Speedlings Inc., Ruskin, FL) were transplanted into 3-L pots filled with Myakka fine-sand soil collected from the field. Before transplant, 6 g of 14–9–15 (N–P–K) Plantacote PlusS (X-Calibur Plant Health Company, Summerville, SC) was mixed into the upper 5 cm of the soil to aid with plant growth. Pepper and tomato were exposed to the herbicide when they were, on average, 30 and 81 cm tall with two and four green fruit per plant, respectively. This stage of development was selected because damage in the field is typically observed near harvest.

The experiments were set up as a 2 by 10 factorial with five replicates and two iterations. The tomato and pepper experiments were run separately. The first factor was herbicide (paraquat vs. paraquat + flumioxazin), and the second factor was application rate relative to the label rate of each product for row middle use in vegetables. The rates included were a nontreated control, 0.0625×, 0.125×, 0.25×, 0.5×, 1×, 2×, 4×, 8×, and 16× the labeled rate. For the tank mix, the same '×' rate was used for both products although the actual g ai plant^{-1} was different (Table 1). Herbicide rates were based on typical spacing and application rates in commercial fields where both products are used for weed control between raised beds. The application rates on a per plant basis were calculated based on typical tomato spacing on the bed top of 61 cm and 64 cm of bare soil in the row middle on each side of the bed. This

Table 1. Herbicide rates applied via subsurface irrigation to tomato and pepper plants in a greenhouse study to evaluate herbicide root uptake. Paraquat was applied alone or as a tank-mix with flumioxazin.

	Paraquat		Flumioxazin	
Relative rate[a]	g ai ha^{-1}	g ai plant^{-1}	g ai ha^{-1}	g ai plant^{-1}
0.0625×	96.4	0.008	8.9	0.0007
0.125×	192.8	0.015	17.8	0.0014
0.25×	385.6	0.031	35.7	0.0028
0.5×	771.2	0.061	71.4	0.0055
1×	1,542.3	0.122	142.8	0.011
2×	3,084.6	0.244	285.6	0.022
4×	6,169.2	0.488	571.2	0.044
8×	12,338.4	0.976	1,142.4	0.088
16×	24,676.8	1.952	2,284.8	0.176

[a] The relative rate is the application rate relative to the label rate (1×) for row-middle use in vegetables.

gives a total area of 0.78 m^2 of interrow space per plant in which the herbicides of interest would typically be applied in a field situation. The 1× rate of paraquat was 0.122 g ai plant^{-1} (1.54 kg ai ha^{-1}) and the 1× rate for flumioxazin was 0.011 g ai plant^{-1} (0.14 kg ai ha^{-1}), respectively (Table 1).

Tomato and pepper were transplanted into pots and watered as needed with a surface drip system. One day before application of herbicides, the irrigation system was turned off. To simulate herbicide root uptake following heavy rains after a dry period, each pot was placed in a plastic tub with 1 L of water and the appropriate herbicide rate. Pots were left in the tub for 4 d with no additional irrigation. After 4 d, the pots were removed from the tubs and irrigated as needed throughout the remainder of the experiment.

Data Collection. Data collection included plant damage ratings 2, 4, and 8 wk after application (WAA) using a 0 to 100 scale, where zero represents no damage and 100 complete death. Plant heights were taken before application of the herbicide and throughout the experiment. Aboveground shoot biomass and crop yields were taken at the end of the experiment. Aboveground shoot biomass was determined by weighing the shoot after drying at 43 C for 7 d. Biomass is presented as a percentage of the nontreated control and does not include fruit weights. Crop yields are presented as fresh weight on a per-plant basis and were divided into damaged and nondamaged fruit. In most cases, all of the

https://doi.org/10.1614/WT-D-13-00177.1 Published online by Cambridge University Press

solution in the tub had been absorbed when the pots were returned to the irrigation system.

Statistical Analysis. Statistical analysis was conducted using SAS software (Version 9.2, SAS Institute, Cary, NC). Each species was analyzed separately. Data were subjected to ANOVA using Proc Mixed with block as the random variable to determine significant main and interaction effects. Damage ratings were collected on multiple dates and were analyzed using the repeated statement, with days after application (DAA) as the repeated variable. Repeats of the experiment were combined into a single analysis if the treatment effects did not differ between iterations as determined by the lack of significant iteration by herbicide type or iteration by herbicide-rate interaction. Treatment means were compared using the least-squares means statement in SAS. All data were inspected to ensure the assumptions of the ANOVA were met before analysis.

Regression analysis was conducted in SigmaPlot 11 software (Systat Software, San Jose CA). Regression of damage ratings with paraquat and paraquat plus flumioxazin over herbicide dose was achieved using a three-parameter, exponential rise to a maximum model as indicated below:

$$y = y_0 + a(1 - e^{-bx})$$

where y is the response (damage rating) at various herbicide rates (x), y_0 is the herbicide rate where injury approaches its maximum, a is the maximum injury achieved, e is the natural log, and b is the rate of increase.

Regression of pepper yield, tomato fruit number, and tomato and pepper aboveground biomass with paraquat and paraquat plus flumioxazin over herbicide dose was achieved using a three-parameter exponential decay model as indicated below:

$$y = y_0 + ae^{-bx}$$

where y is the response (yield, fruit number, or biomass) at various herbicide rates (x); y_0 is the yield, fruit number, or biomass as it approaches its maximum or minimum; a is a shape parameter; e is the natural log; and b is a scale parameter.

Regression of tomato yield with paraquat and paraquat plus flumioxazin over herbicide dose was achieved using a three-parameter sigmoidal model as indicated below:

$$y = a/\left\{1 + e^{-(x-x_0)/b}\right\}$$

where y is the tomato yield at various herbicide rates (x), a is the maximum yield, x_0 is the herbicide rate to inhibit 50% of the final yield, and b is the slope around x_0.

Results and Discussion

Pepper and Tomato Damage Ratings. Root uptake of paraquat and paraquat tank-mixed with flumioxazin significantly damaged pepper and tomato shoot growth compared with the untreated control (Figure 1). Damage initially appeared as necrosis of the vein tissue, followed by complete shoot death at the highest rates. This is contrary to what was found by Damanakis et al. (1970b) who attributed shoot inhibition caused by paraquat uptake at rates of 0.5 to 1.5 ppm to root inhibition and reported no toxic symptoms on the shoot. Damage symptoms on the pepper and tomato clearly illustrated the uptake of the herbicides and the consequential death of the veins and surrounding tissue. Herbicide rate had a significant effect on crop injury with both species ($P < 0.0001$), and the effect of rate varied with the herbicide applied ($P < 0.0001$). Significantly more damage was observed between the 0.25× and 2× rate for pepper and between the 0.25 and 4× rates for tomato with the tank mix compared with the paraquat alone. Paraquat alone caused as much damage as the tank mix at rates above and below that range. Our results are similar to those reported by Crespo et al (2013) who observed slightly lower levels of tissue injury caused by carfentrazone compared with the untreated control.

The data for both species was adequately fitted with a three-parameter exponential rise to a maximum model with damage increasing rapidly and leveling off around the 4× rate with the tank mix or the 8× rate with paraquat alone (Figure 1). Based on the fitted models, maximum injury ratings were achieved at lower rates with the tank mix than with the paraquat alone. Trends were similar for both species, with tomato slightly more tolerant of herbicide uptake at lower rates then pepper. Complete shoot death following exposure to the tank mix was observed at 2× the recommended application rate with pepper, whereas it was not observed until 8× the recommended application

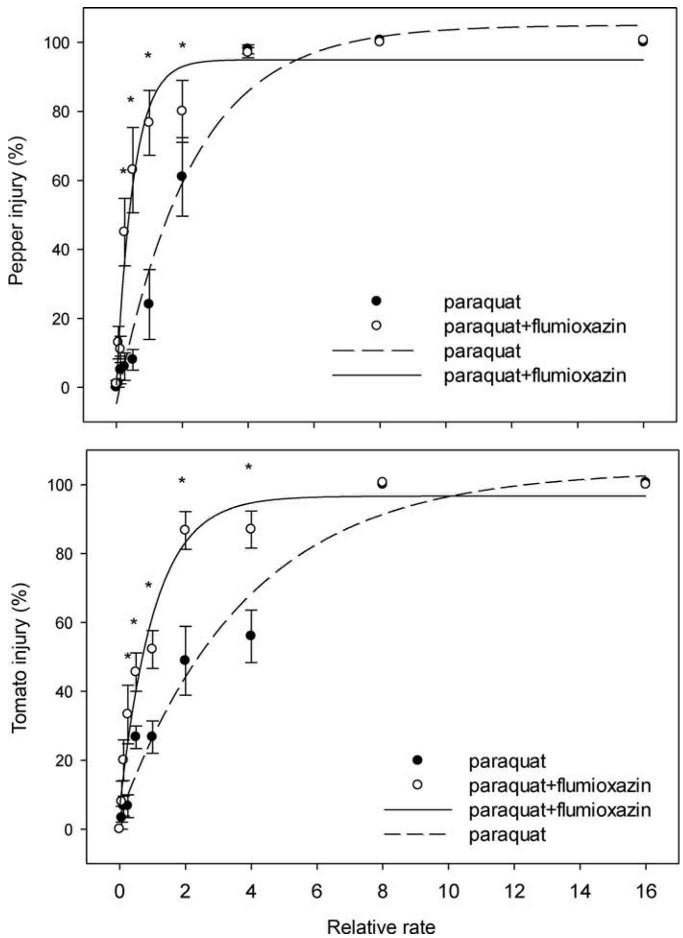

Figure 1. The effect of paraquat alone vs. paraquat tank-mixed with flumioxazin at various rates on pepper and tomato injury 7 d after spraying. The 1× rate for paraquat and flumioxazin was 1,542.3 and 142.8 g ai ha^{-1}, respectively. Vertical bars are the standard error of the mean and the asterisk (*) represents significant differences between the herbicide treatments at $P < 0.05$. The lines represent the fitted three-parameter, exponential rise to a maximum models. For pepper, the dashed line represents the model $y = 4.76 + 109.5(1 - e^{-0.44x})$, $R^2 = 0.98$, $P < 0.0001$ fitted to the data for paraquat, and the solid line represents the model $y = 0.56 + 94.2(1 - e^{-1.9x})$, $R^2 = 0.98$, $P < 0.0001$ fitted to the data for the paraquat–flumioxazin tank mix. For tomato, the dashed line represents the model $y = 3.7 + 100.5(1 - e^{-0.3x})$, $R^2 = 0.98$, $P < 0.0001$ fitted to the data for paraquat, and the solid line represents the model $y = 6.1 + 90.5(1 - e^{-1x})$, $R^2 = 0.99$, $P < 0.0001$ fitted to the data for the paraquat–flumioxazin tank mix

rate in tomato. At 21 DAA, tomato damage remained very similar to 7 DAA, whereas it tended to increase with pepper (data not shown).

Pepper and Tomato Shoot Weight. Herbicide applications reduced shoot weight of both crop species compared with the untreated control (Figure 2). Herbicide rate had a significant effect on pepper shoot weight ($P = 0.0026$) but the effect of rate was not affected by the herbicide applied ($P = 0.3582$). Similar trends occurred with tomato, where rate was significant ($P < 0.0001$), but the interaction between rate and herbicide was not ($P = 0.3447$). Therefore, shoot biomass was averaged for paraquat alone or paraquat tank-mixed with flumioxazin (Figure 2). Herbicide root absorption at 16× reduced shoot biomass by 20 and 32% compared with the nontreated control in pepper and tomato, respectively. Maximum reduction in biomass occurred at roughly 2× the label rate. Reductions in biomass were less than damage ratings would suggest because both living and dead tissue were dried and weighed, and as a result, the biomass never reaches zero. Shoots were completely necrotic at the higher rates, and plants were dead. Crespo et al. (2013) observed similar trends in shoot weight following absorption of carfentrazone. However, higher rates were needed to achieve the maximum shoot reduction than was found with paraquat.

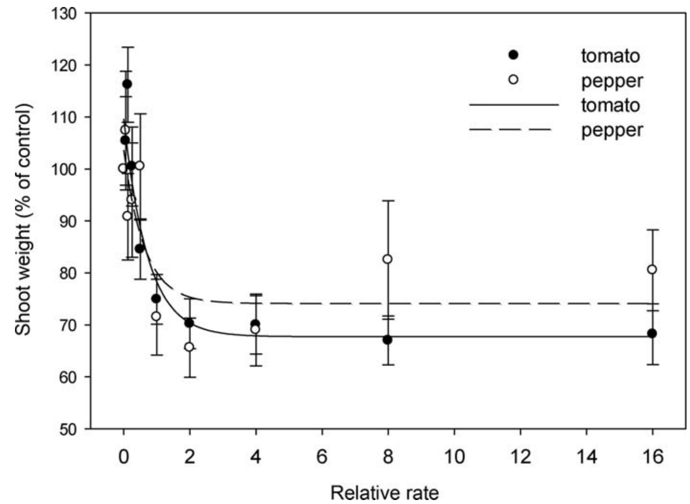

Figure 2. The effect of paraquat and paraquat tank-mixed with flumioxazin at multiple rates on aboveground shoot weight of pepper and tomato. The 1× rate for paraquat and flumioxazin was 1,542.3 and 142.8 g ai ha^{-1}, respectively. Vertical bars are the standard error of the mean. The lines represent the fitted three-parameter, exponential decay models. The dashed line represents the model $y = 74.1 + 29.5e^{-1.6x}$, $R^2 = 0.69$, $P = 0.0164$ fitted to the pepper data. The solid line represents the model $y = 67.7 + 41.9e^{1.38x}$, $R^2 = 0.90$, $P = 0.0004$ fitted to the tomato data.

At low rates, when averaged across herbicide treatments, an increase in tomato shoot biomass was observed with no reduction observed until the 0.5×

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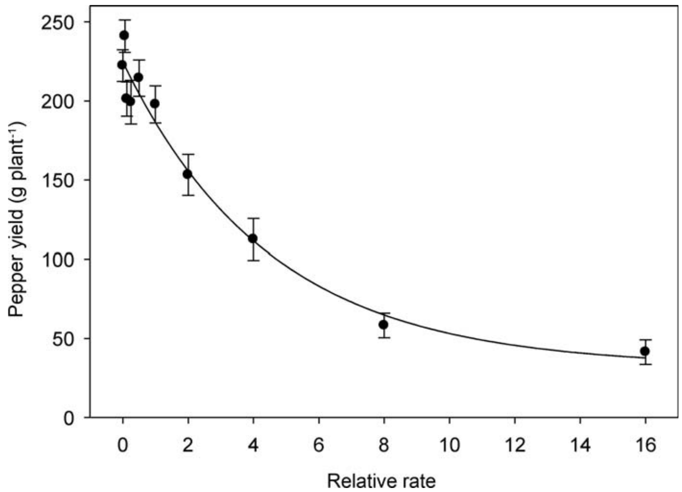

Figure 3. The effect of paraquat and paraquat tank-mixed with flumioxazin at multiple rates on pepper yield. The 1× rate for paraquat and flumioxazin was 1,542.3 and 1428 g ai ha^{-1}, respectively. Vertical bars are the standard error of the mean. The lines represent the fitted three-parameter exponential decay model. The line represents the fitted model $y = 32.2 + 192.5e^{-0.2x}$, $R^2 = 0.97$, $P < 0.0001$.

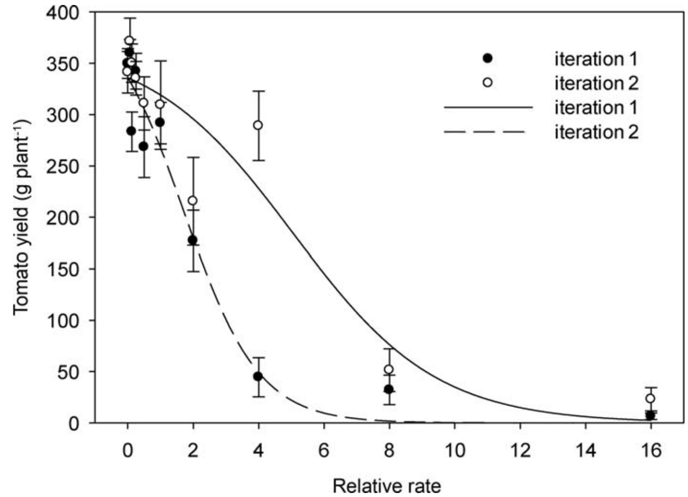

Figure 4. The effect of paraquat and paraquat tank-mixed with flumioxazin at multiple rates on tomato yield. The 1× rate for paraquat and flumioxazin was 1,542.3 and 142.8 g ai ha^{-1}, respectively. Vertical bars are the standard error of the mean. The solid line represents the model $y = 411/\{1 + e^{[-(x-1.7)/-1.1]}\}$, $R^2 = 0.96$, $P < 0.0001$ fitted to the tomato yield data in iteration 1, and the dashed line represents the model $y = 370/\{1 + e^{[-(x-5.0)/-2.2]}\}$, $R^2 = 0.91$, $P < 0.0003$ fitted to the tomato yield data in iteration 2.

rate. For example, there was a 14% increase in shoot biomass at the 0.125× rate, compared with the untreated control, which was significantly different ($P < 0.05$). Similar results were observed with pepper, but the shoot biomass had greater variability among rates. The stimulation of tissue growth at sublethal herbicide concentrations has been studied for many years and is a common phenomenon (Wiedman and Appleby 1972). However, the author knows of no published account of shoot stimulation following root uptake of paraquat.

Crop Yield. Pepper yield decreased exponentially with increasing herbicide rate (Figure 3). There was no interaction between herbicide and rate on yield ($P = 0.27$), and data were averaged across both herbicide treatments. Fruit yields began to decline significantly at the 2× rate and continued to decrease. At 16× the label rate, fruit yields had declined by 83% compared with the untreated control. Any fruit on the shoot at the higher rates had begun to develop before root absorption of the herbicide. Tomato yield also decreased with herbicide rate. There was a significant interaction between herbicide rate and experiment iteration ($P < 0.0001$), and as a result, the two iterations are presented separately (Figure 4). The reason for that difference is unknown, but both iterations followed similar trends. Tomato yield decreased significantly with herbicide rate, almost reaching 100% reduction at the highest rate, compared with the untreated control. Similar to pepper, yield began to decline significantly around the 2× herbicide rate.

Root uptake of paraquat and paraquat tank-mixed with flumioxazin caused significant tissue damage and, at higher rates, plant death. Damage was initially observed as necrosis of the vein tissue, followed by chlorosis and necrosis of the interveinal tissue. Plants did not fully recover from the damage, and fruit yields decreased significantly. These results indicate that paraquat or paraquat tank-mixed with flumioxazin applied as a row-middle treatment in the unique growing conditions found in Florida may lead to root absorption and shoot damage by the crops. I speculate that the environmental conditions required to observe this type of damage are most likely rare and include very dry soils during and following herbicide application to the row middles, followed by heavy rainfall once the crop roots have grown adequately to reach the edges of the bed. It is likely that herbicide injury from root uptake of paraquat or paraquat tank-mixed with flumioxazin is possible

https://doi.org/10.1614/WT-D-13-00177.1 Published online by Cambridge University Press

but is a rare event that is correlated with specific soil and environmental conditions. These results may help explain crop damage that is observed on rare occasions in commercial fields in Florida.

Acknowledgments

The author would like to acknowledge the assistance of Rick Kelly, Michael Sweat, and Amy Hays with this project. The input of Andrew MacRae was also appreciated.

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Received November 27, 2013, and approved June 23, 2014.