Research Article

Received: 12 August 2010 Revised: 6 December 2010 Accepted: 21 December 2010 Published online in Wiley Online Library: 16 March 2011

(wileyonlinelibrary.com) DOI 10.1002/ps.2119

Aminopyralid soil residues affect rotational vegetable crops in Florida

Brandon J Fast,[a*] Jason A Ferrell,[b] Gregory E MacDonald,[b] Brent A Sellers,[c] Andrew W MacRae,[d] L Jason Krutz[e] and William N Kline[f]

Abstract

BACKGROUND: Bahiagrass (*Paspalum notatum* Flueggé) is a poor host of several soilborne pests of vegetable crops; therefore vegetable crops are commonly grown in a rotation with bahiagrass pastures in Florida. The herbicide aminopyralid provides foliar and soil residual weed control and increases forage production in bahiagrass pastures; however, the soil residual activity of aminopyralid makes carryover injury likely in subsequent sensitive vegetable crops. Field research was conducted to determine the sensitivity of five vegetable crops to soil residues of aminopyralid.

RESULTS: At an aminopyralid soil concentration of 0.2 μg kg^{-1} (the limit of quantitation for aminopyralid in this research), crop injury ratings were 48% (bell pepper), 67% (eggplant), 71% (tomato), 3% (muskmelon) and 3% (watermelon), and fruit yield losses (relative to the untreated control) at that concentration were 61, 64, 95, 8 and 14% in those respective crops.

CONCLUSIONS: The crops included in this research were negatively affected by aminopyralid at soil concentrations less than the limit of quantitation (0.2 μg kg^{-1}). Therefore, it was concluded that a field bioassay must be used to determine whether carryover injury will occur when these crops are planted on a site where aminopyralid has been previously applied.

Keywords: crop injury; yield loss; carryover

1 INTRODUCTION

Florida is the second largest producer of fresh market vegetables in the United States, with nearly 2 million metric tonnes valued at $US 1.4 billion produced in 2009.[1] The warm, humid climate and sandy soils in Florida are a favorable environment for soilborne pests, including damping-off (*Rhizoctonia solani* Kühn and *Pythium* spp.), Fusarium wilt (*Fusarium oxysporum* Schltdl.), Phytophthora root rot (*Phytophthora* spp.), Verticillium wilt (*Verticillium dahliae* Kleb.), white mold [*Sclerotinia sclerotiorum* (Lib.) de Bary], sting nematode (*Belonolaimus longicaudatus* Rau) and root-knot nematode (*Meloidogyne* spp.).[2–4] These major soilborne pests of vegetable crops in Florida have been managed effectively since the 1960s with the use of methyl bromide as the primary method of pest control.[5] The production and import of methyl bromide in the United States was banned by the EPA in 2005 as a result of its negative effects on the stratospheric ozone layer.[6] Methyl bromide is currently being phased out, and it will not be available when existing supplies are depleted.[7] The reduction in the availability of methyl bromide for soilborne pest control has forced producers to rely more heavily on other control methods, and an effective and inexpensive way to control these soilborne pests is to rotate vegetable crops with crops that do not serve as host plants.[3,5,8]

Bahiagrass (*Paspalum notatum* Flueggé) is the most commonly planted warm-season grass in Florida, and it occupies an estimated 1 million ha area in the state.[9] It tolerates a wide range of environmental conditions and fertility regimes while requiring less intensive management than many other forage grasses.[10] Bahiagrass produces moderate- to low-quality forage which is typically grazed by cattle or used for hay production. Because of the abundance of bahiagrass pastures in Florida, and the fact that bahiagrass is not a suitable host plant for numerous soilborne pests, vegetable crops are commonly grown in rotation with bahiagrass pasture; furthermore, vegetable crops are typically planted once every 3–10 years.[11] Research has demonstrated that damping-off, Fusarium wilt, yellow nutsedge (*Cyperus esculentus* L.) and root galls from root-knot nematode decreased and crop yields increased when cucumber (*Cucumis sativus* L.), snap bean (*Phaseolus vulgaris* L.) and watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai.] were planted after 3 years of bahiagrass.[4,11] It has also been found that crops grown in rotation with bahiagrass have increased yields owing to improved soil water-holding capacity, nitrogen content, organic matter content and tilth.[11–14] It should

* *Correspondence to: Brandon J Fast, 9330 Zionsville Rd, Indianapolis 46268, IN. E-mail: BJFast@dow.com*

a *Dow AgroSciences, Indianapolis, IN*

b *University of Florida Agronomy Department, Gainesville, FL*

c *University of Florida Range Cattle Research and Education Center, Ona, FL*

d *University of Florida Gulf Coast Research and Education Center, Wimauma, FL*

e *USDA-ARS Southern Weed Science Research Unit, Stoneville, MS*

f *Dow AgroSciences, Duluth, GA*

Table 1. Regression parameters (standard error) and R^2 values for graphs in Figs 1 and 2. The hyperbolic regression model $Y = AX/(B+X)$ was used, where Y is a dependent variable, X is an independent variable, A is the vertical asymptote of the dependent variable and B is the equation constant

Crop	Dependent variable	*A*	*B*	R^2
Bell pepper	Crop injury	91.108 (3.585)	0.178 (0.038)	0.95
Bell pepper	Plant height reduction	71.325 (4.211)	0.593 (0.136)	0.94
Bell pepper	Bloom number reduction	102.487 (2.053)	0.073 (0.010)	0.98
Bell pepper	Fruit yield loss	103.011 (2.962)	0.136 (0.023)	0.97
Eggplant	Crop injury	89.913 (4.323)	0.069 (0.024)	0.90
Eggplant	Plant height reduction	62.796 (12.212)	0.343 (0.302)	0.57
Eggplant	Bloom number reduction	91.919 (4.734)	0.082 (0.029)	0.90
Eggplant	Fruit yield loss	94.476 (3.102)	0.095 (0.021)	0.96
Tomato	Crop injury	89.163 (3.630)	0.052 (0.017)	0.92
Tomato	Plant height reduction	54.498 (5.727)	0.273 (0.138)	0.78
Tomato	Bloom number reduction	99.585 (4.539)	0.076 (0.024)	0.91
Tomato	Fruit yield loss	98.878 (2.566)	0.008 (0.005)	0.96
Muskmelon	Crop injury	63.436 (27.991)	3.608 (3.537)	0.58
Muskmelon	Plant height reduction	56.568 (12.441)	2.262 (1.429)	0.77
Muskmelon	Bloom number reduction	41.509 (7.676)	0.124 (0.141)	0.44
Muskmelon	Fruit yield loss	75.679 (15.306)	1.764 (0.995)	0.73
Watermelon	Crop injury	52.742 (17.174)	3.467 (2.538)	0.70
Watermelon	Plant height reduction	30.654 (6.841)	1.464 (0.974)	0.55
Watermelon	Bloom number reduction	92.089 (27.188)	3.875 (2.501)	0.66
Watermelon	Fruit yield loss	70.791 (8.100)	0.781 (0.320)	0.85

be noted that some weed species that grow in rotational crops can serve as alternative hosts for soilborne pests.[15] Tropical soda apple (*Solanum viarum* Dunal), for example, is a common and troublesome weed of pastures in Florida, and it can serve as a host plant for root-knot nematode.[16,17] Therefore, weed control is imperative in bahiagrass pastures that are employed in a vegetable crop rotation.

Aminopyralid, a synthetic auxin herbicide registered in 2005, is labeled for annual and perennial broadleaf weed control in rangeland, permanent grass pastures and non-cropland areas at rates of 0.05–0.12 kg ae ha^{-1}.[18,19] Because it is relatively persistent in the soil (average half-life = 34.5 days), aminopyralid provides both foliar and soil residual weed control; moreover, it provides excellent control of tropical soda apple for up to 1 year after application.[20,21] Because of its high efficacy and residual activity on several common and troublesome pasture weed species, aminopyralid is used for weed control in pastures throughout Florida. However, an aminopyralid product label states that pastures treated with aminopyralid are not to be rotated to any crop within 1 year after treatment. Further label restrictions state that a broadleaf crop should not be planted in a treated area until an adequately sensitive field bioassay has revealed that the crop will not be adversely affected.[18] While the residual activity of aminopyralid is desirable from a pasture weed control standpoint, injury in subsequent broadleaf crops arising from aminopyralid carryover is a potential negative consequence. As a result of the use of aminopyralid for pasture weed control, and the fact that vegetable crops are commonly planted in rotation with bahiagrass pasture, there is a need for information on the soil concentration of aminopyralid that can cause injury in vegetable crops and the method of detection that is the most well suited to determining soil concentrations of aminopyralid. The objective of this research was to quantify the sensitivity of bell pepper (*Capsicum annuum* L.), eggplant (*Solanum melongena* L.), tomato (*Lycopersicon esculentum* Mill.), muskmelon (*Cucumis melo* L.) and watermelon to soil residues of aminopyralid.

2 MATERIALS AND METHODS

Field experiments were conducted on a Lakeland fine sand (thermic, coated Typic Quartzipsamments) at the University of Florida North Florida Research and Education Center near Live Oak, Florida, and on an Arredondo fine sand (loamy, siliceous, semi-active, hyperthermic Grossarenic Paleudults) at the University of Florida Plant Science Research and Education Unit near Citra, Florida. Bell pepper, eggplant and tomato were seeded on 7 March 2008 in a greenhouse in Gainesville, Florida, and were transplanted in the field on 18 April 2008 (Live Oak) and 23 April 2008 (Citra). Muskmelon and watermelon were directly seeded in the field when the other species were transplanted. Plants were grown on polyethylene-mulched beds in plots that were five beds wide (one bed per crop species) by 4.6 m long. Eggplant, tomato, muskmelon and watermelon were planted in a single row in the center of the beds, while beds for bell pepper contained two rows of plants per bed.

Aminopyralid was applied to plots lengthwise 3 weeks before planting at rates of 1.4, 2.8, 5.6, 11.2, 22.4 and 44.8 g ae ha^{-1}. These application rates (all of which are less than the lowest labeled application rate) were used to create soil concentrations of aminopyralid that would be representative of the concentrations present in field sites where aminopyralid had been applied in the past 2–7 months (based on aminopyralid's soil half-life of 34.5 days).[20] The herbicide was broadcast over bare soil in the plots in a water carrier volume of 187 L ha^{-1} with an ATV-mounted sprayer equipped with XR11002 nozzles. The soil was tilled with a disk, beds were formed using a PTO-driven power bedder, methyl bromide was applied and polyethylene mulch was set in place the day following aminopyralid application.

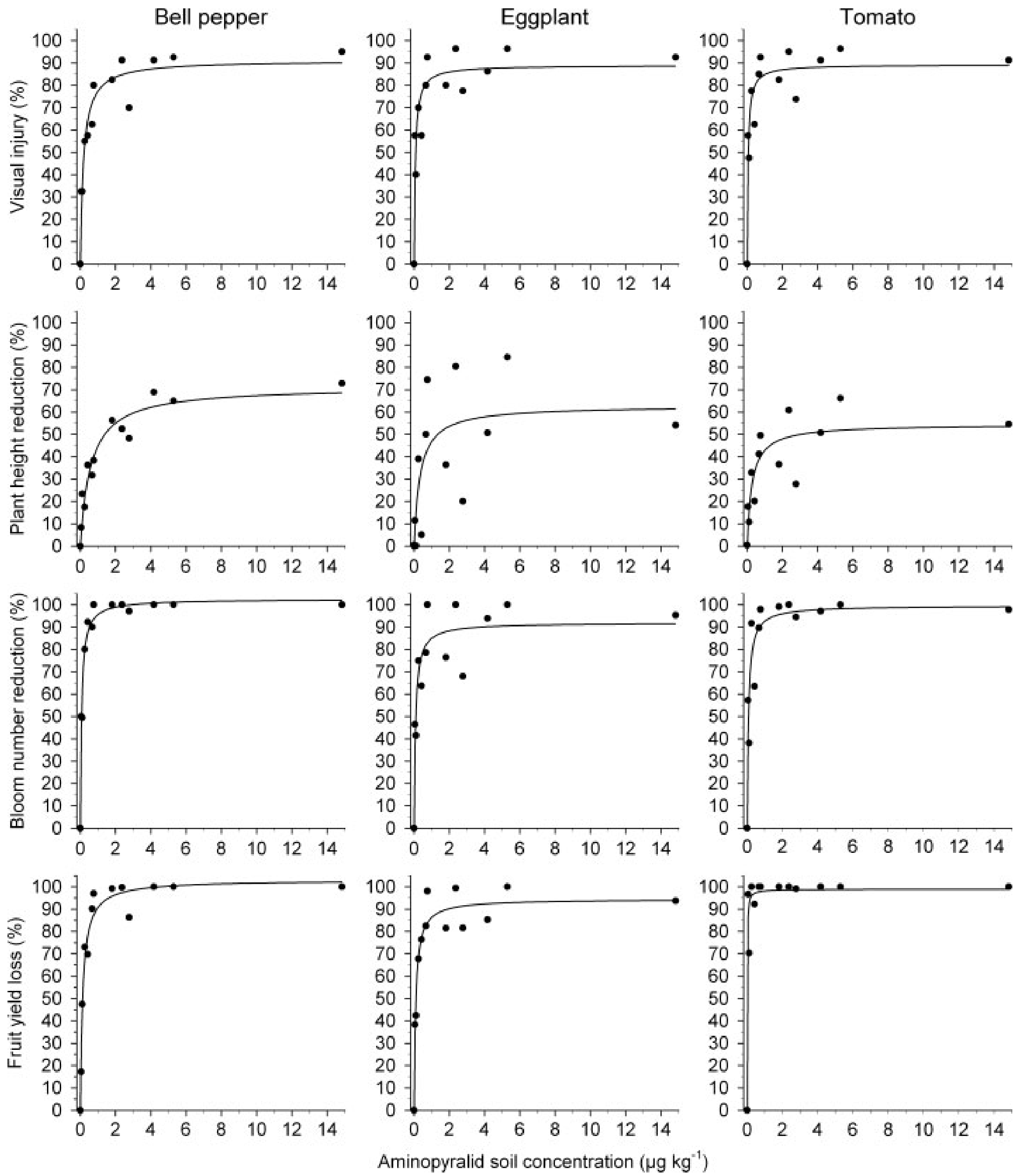

Figure 1. Crop injury, plant height reduction, bloom number reduction and fruit yield loss (%) of bell pepper (*Capsicum annuum*), eggplant (*Solanum melongena*) and tomato (*Lycopersicon esculentum*) as a function of aminopyralid soil concentration (µg kg^{-1}). Crop injury, plant height reduction and bloom number reduction data were collected 6 weeks after planting.

A soil sample was collected from the center of the beds in each plot (one sample per treatment) to a depth of 15 cm on the day the vegetables were transplanted. Samples were transported to the laboratory on ice and ultimately stored at −10 °C. Aminopyralid was extracted from the soil samples by solid-phase extraction and quantified via high-performance liquid chromatography with tandem mass spectrometry (HPLC/MS/MS) at a commercial laboratory (Carbon Dynamics Institute, LLC, Springfield, IL). The limit of quantitation (LOQ) for the method of aminopyralid extraction was 0.2 µg kg^{-1}. At 6 weeks after planting (WAP), crop injury was visually estimated on a scale of 0–100 (0 = no injury, 100 = plant death), plant height or vine length of three random plants within each plot was measured and open blooms were counted on those same plants. For simplicity, 'vine length' will be referred to as 'plant height' herein. Marketable fruit was harvested 4 times at both locations (19 June, 26 June, 3 July and 10 July 2008), with the culls being discarded.

The experimental design was a randomized complete block, and herbicide treatments were replicated 4 times. Plant height, bloom number and yield data were converted to percentage reduction relative to the untreated control. No location interactions were detected using analysis of variance (ANOVA); therefore, data were pooled across experiment sites. Aminopyralid soil concentration was averaged across reps within each treatment, and crop injury, plant height reduction, bloom number reduction and crop yield loss were regressed as a function of mean aminopyralid soil concentration. The regression model, parameters, and R^2 values for the dependent variables of each crop are provided in Table 1. Pearson's correlation coefficients were also calculated to determine the correlation between crop yield loss and crop injury, plant height reduction and bloom number reduction (Table 3).

3 RESULTS AND DISCUSSION

Soil residues of aminopyralid caused severe crop injury and plant height reduction in bell pepper, eggplant and tomato (Fig. 1). Plant height was reduced 30–40% as aminopyralid soil concentration increased from 0 to 1 $\mu g\ kg^{-1}$, with the crop injury level approximately twice that of plant height reduction. Conversely, little additional increase (<20%) in plant response was documented as aminopyralid concentration increased from 1 $\mu g\ kg^{-1}$ up to the maximum of 14.8 $\mu g\ kg^{-1}$. Maximum values of crop injury were 90% (bell pepper), 90% (eggplant) and 89% (tomato), and maximum plant height reductions were 69, 61, and 54% respectively. These results were not surprising given that synthetic auxin herbicides such as picloram and clopyralid are highly efficacious on members of the Solanaceae family, which includes bell pepper, eggplant and tomato.[22,23]

In addition to affecting the vegetative growth of bell pepper, eggplant and tomato, aminopyralid also affected the reproductive capacity of these crops. Response curves of bloom number reduction and fruit yield loss for bell pepper, eggplant and tomato were similar to those of crop injury and plant height reduction. Interestingly, there was a dramatic initial reduction between 0 and 1 $\mu g\ kg^{-1}$ aminopyralid, with very little further reduction (≤10%) at concentrations above 1 $\mu g\ kg^{-1}$. At the maximum concentration recorded (14 $\mu g\ kg^{-1}$), aminopyralid caused bloom number reductions of 100, 92 and 100% and yield losses of 100, 95 and 100% in bell pepper, eggplant and tomato respectively.

The effects of aminopyralid on muskmelon and watermelon were less severe than those observed on bell pepper, eggplant and tomato. As aminopyralid soil concentration increased, muskmelon and watermelon crop injury, reductions in plant height and bloom number and fruit yield loss increased in a curvilinear manner (Fig. 2). This contrasts with the more drastic biphasic increase that occurred in bell pepper, eggplant and tomato. Maximum crop injury, plant height reduction, bloom number reduction and fruit yield loss were respectively 51, 49, 41 and 68% in muskmelon and 42, 28, 73 and 67% in watermelon at an aminopyralid soil concentration of 14 $\mu g\ kg^{-1}$.

The LOQ for aminopyralid in soil was 0.2 $\mu g\ kg^{-1}$ for the extraction method that was used in this research, which indicates that aminopyralid soil concentrations below that level cannot be reliably detected. The values of crop injury, plant height reduction, bloom number reduction and fruit yield loss that were predicted to occur in those crops evaluated at this concentration are provided in Table 2. Crop injury values for bell pepper, eggplant, tomato, muskmelon and watermelon were 48, 67, 71, 3 and 3% respectively, and yield losses for these respective crops were 61, 64, 95, 8 and 14% at 0.2 $\mu g\ kg^{-1}$ aminopyralid. This demonstrates that aminopyralid can cause substantial injury and yield loss in bell pepper, eggplant and tomato at soil concentrations below the LOQ.

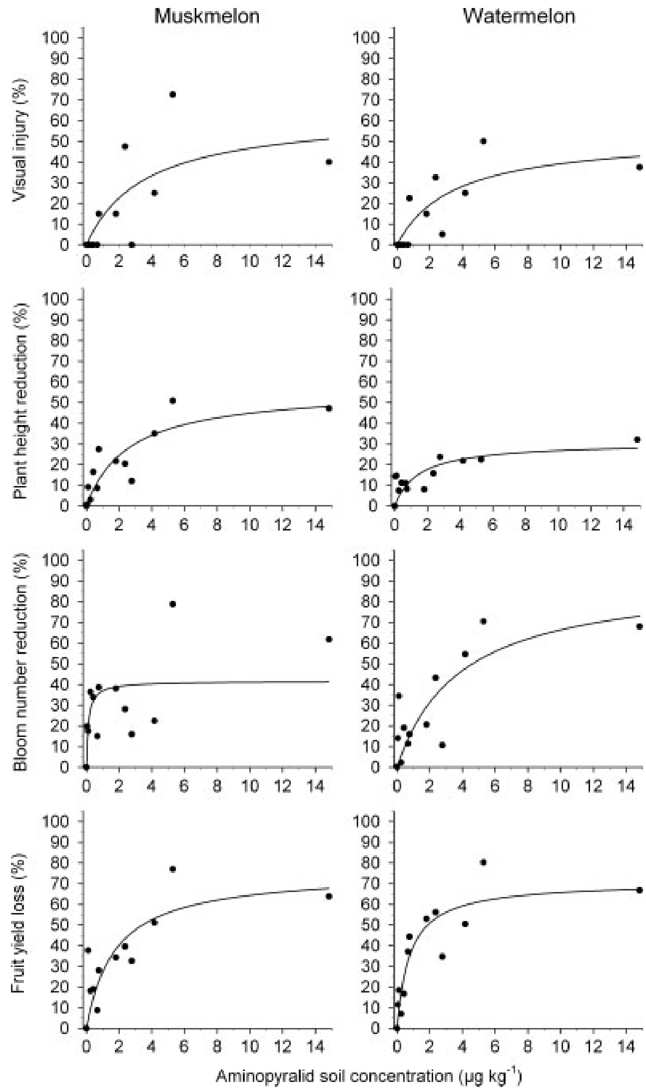

Figure 2. Crop injury, plant height reduction, bloom number reduction and fruit yield loss (%) of muskmelon (*Cucumis melo*) and watermelon (*Citrullus lanatus*) as a function of aminopyralid soil concentration ($\mu g\ kg^{-1}$). Crop injury, plant height reduction and bloom number reduction data were collected 6 weeks after planting.

The fact that aminopyralid can injure vegetable crops at soil concentrations that cannot be reliably detected suggests that an alternative method of detection (e.g. a field bioassay as indicated on aminopyralid product specimen labels) must be used to determine whether the aminopyralid soil concentration is sufficient to cause unacceptable crop injury and yield loss. Pearson's correlation coefficients were calculated to determine the strength of the correlation between fruit yield loss and crop injury, plant height reduction and bloom number reduction (Table 3). With the exception of muskmelon, correlation coefficients for crop injury were ≥0.91 and *P*-values were <0.0001 for all crops. The correlation coefficients for plant height reduction and bloom number reduction were ≥0.80 and *P*-values were ≤0.0006 in all crops except watermelon and tomato. The correlation between fruit yield loss and crop injury, plant height reduction and bloom number reduction suggests that aminopyralid soil concentration and the resulting fruit yield loss can be reliably predicted using a field bioassay; moreover, the stronger correlation in bell pepper

Table 2. Values of crop injury, plant height reduction, bloom number reduction and fruit yield loss that are predicted to occur at an aminopyralid soil concentration of 0.2 μg kg^{-1} using the regression model and parameters from Table 1

Crop	Crop injury (%)	Plant height reduction (%)	Bloom number reduction (%)	Fruit yield loss (%)
Bell pepper	48	18	75	61
Eggplant	67	23	65	64
Tomato	71	23	72	95
Muskmelon	3	5	26	8
Watermelon	3	4	5	14

Table 3. Pearson's correlation coefficients for the correlation between fruit yield loss and crop injury, plant height reduction and bloom number reduction

Crop	Dependent variable	Pearson's correlation coefficient	*P*
Bell pepper	Crop injury	0.97	<0.0001
Bell pepper	Plant height reduction	0.89	<0.0001
Bell pepper	Bloom number reduction	0.96	<0.0001
Eggplant	Crop injury	0.97	<0.0001
Eggplant	Plant height reduction	0.81	0.0005
Eggplant	Bloom number reduction	0.98	<0.0001
Tomato	Crop injury	0.94	<0.0001
Tomato	Plant height reduction	0.74	0.0025
Tomato	Bloom number reduction	0.93	<0.0001
Muskmelon	Crop injury	0.83	0.0002
Muskmelon	Plant height reduction	0.92	<0.0001
Muskmelon	Bloom number reduction	0.80	0.0006
Watermelon	Crop injury	0.91	<0.0001
Watermelon	Plant height reduction	0.71	0.0048
Watermelon	Bloom number reduction	0.83	0.0002

and tomato suggests that these two crops are the best indicators of aminopyralid soil concentration. Although the aminopyralid soil concentration can be predicted using a field bioassay, it should be noted that these parameters were collected 6 WAP; therefore, a substantial amount of time is required to use this method. Symptoms of synthetic auxin herbicide injury were observed as early as 1 WAP (data not shown); therefore, it is likely that the field bioassay could be used to predict aminopyralid soil concentration earlier than 6 WAP.

The amount of time required for the aminopyralid soil concentration to reach a level that will not affect subsequent crops is dependent on the rate of herbicide dissipation in the soil. Therefore, the rate of aminopyralid dissipation in the soil will be influenced by management practices and environmental conditions that affect crop residue decomposition and release of the herbicide back into the soil.[24] When clopyralid is applied in grass crops, the herbicide can be sequestered in the crop residue and then be re-released into the soil in a biologically active form as the crop residue decomposes.[25,26] Based on aminopyralid label statements regarding plant residues that contain aminopyralid, it appears that aminopyralid behaves in a similar manner to clopyralid and picloram.[18] This introduces an additional factor that influences the rate of aminopyralid dissipation because environmental conditions and management practices affect the rate and timing at which the crop residue decomposes and aminopyralid is re-released into the soil. Owing to the extreme sensitivity of the crops included in this research to low aminopyralid soil concentrations (less than 1 μg kg^{-1}) and the unpredictability of the rate of aminopyralid dissipation in the soil, it is imperative that a field bioassay be conducted before planting a broadleaf crop on a site where aminopyralid has been applied.

REFERENCES

1 Vegetables 2009 summary, *US Department of Agriculture–National Agricultural Statistics Service (USDA-NASS)*, US Department of Agriculture, Washington, DC, p. 9 (2010).

2 Koike ST, Subbaro KV, Davis RM and Turini TA, Vegetable diseases caused by soilborne pathogens. University of California Publication 8099, Davis, CA, p. 1 (2003).

3 Noling JW, Nematodes and their management, in *Vegetable Production Handbook for Florida 2007–2008*, ed. by Olson SM and Simmone E. University of Florida, Gainesville, FL, pp. 73–82 (2007).

4 Sumner DR, Minton NA, Brenneman TB, Burton GW and Johnson AW, Root diseases and nematodes in bahiagrass–vegetable rotations. *Plant Disease* **83**:55–59 (1999).

5 Chellemi DO, Nonchemical management of soilborne pests in fresh market vegetable production systems. *Phytopathology* **92**:1367–1372 (2002).

6 *Reregistration eligibility decision (RED) for methyl bromide*, US Environmental Protection Agency (USEPA), Washington, DC, p. 12 (2008).

7 Montreal protocol on substances that deplete the ozone layer. Report of the Technology and Economic Assessment Panel: Evaluations of 2009 critical use nominations for methyl bromide and related matters. United Nations Environment Programme (UNEP), 111 pp. (2009).

8 Momol TJ, Marois J, Pernezy K and Olson S, Integrated disease management for vegetable crops in Florida, in *Vegetable Production Handbook for Florida 2007–2008*, ed. by Olson SM and Simmone E. University of Florida, Gainesville, FL, pp. 89–93 (2007).

9 Chambliss CG, Florida forage handbook. University of Florida Publication No. SP 253, Gainesville, FL, pp. 17–23 (1999).

10 Ball DM, Hoveland CS and Lacefield GD, *Southern Forages*, 3rd edition. Potash and Phosphate Institute, Norcross, GA, p. 26 (2002).

11 Hopkins DL and Elmstrom GW, Effect of nonhost crop plants on watermelon Fusarium wilt. *Plant Disease* **68**:239–241 (1984).

12 Beaty ER and Tan KH, Organic matter, N, and base accumulation under Pensacola bahiagrass. *J. Range Manag* **25**:38–40 (1972).

13 Brenneman TB, Summer DR, Baird RE, Burton GW and Minton NA, Suppression of foliar and soilborne peanut diseases in bahiagrass rotations. *Phytopathology* **85**:948–952 (1995).

14 Burton GW, DeVane EH and Carter RL, Root penetration, distribution and activity in southern grasses measured by yields, drought symptoms, and P^{32} uptake. *Agron J* **46**:229–233 (1954).

15 Rich JR, Brito JA, Kaur R and Ferrell JA, Weed species as hosts of *Meloidogyne*: a review. *Nematopica* **39**:157–185 (2009).

16 Mullahey JJ and Cornell J, Biology of tropical soda apple (*Solanum viarum*), an introduced weed in Florida. *Weed Technol* **8**:465–469 (1994).

17 Church GT and Rosskopf EN, First report of the root-knot nematode *Meloidogyne arenaria* on tropical soda apple (*Solanum viarum*) in Florida. *Plant Disease* **89**:527 (2005).

18 Milestone herbicide product label. Dow AgroSciences Publication No. D02-879-002, Indianapolis, IN, 9 pp. (2008).

19 *Aminopyralid Pesticide Fact Sheet.* [Online]. United States Office of Prevention, Pesticides, Environmental Protection, and Toxic Substances (USOPPEPTS) (2005). Available: http://www.epa.gov/opprd001/factsheets/aminopyralid.pdf [8 May 2010].

20 Senseman SA (ed.), *Herbicide Handbook*, 9th edition. Weed Science Society of America, Champaign, IL, pp. 331–332 (2007).

21 Ferrell JA, Mullahey JJ, Langeland KA and Kline WN, Control of tropical soda apple (*Solanum viarum*) with aminopyralid. *Weed Technol* **20**:453–457 (2006).

22 O'Sullivan J, Thomas RJ and Bouw WJ, Effect of flumetsulam plus clopyralid soil residues on several vegetable crops and on

sweet corn (*Zea mays*) cultivars grown in rotation. *Weed Technol* **13**:303–307 (1999).
23 Rocha E and Yamashita OM, Initial development of vegetable crops cultivated in soils with 2,4-D + picloram residues. *Semina-Ciencias Agrarias* **30**:47–54 (2009).
24 Nash RG, Dissipation from soil, in *Environmental Chemistry of Herbicides, Vol. 1*, ed. by Grover R. CRC Press, Boca Raton, FL, pp. 131–169 (1988).
25 Branham BE and Lickfeldt DW, Effect of pesticide-treated grass clippings used as mulch on ornamental plants. *HortScience* **32**:1216–1219 (1997).
26 Brinton WF, Evans E and Blewett TC, Reliability of bioassay tests to indicate herbicide residues in compost of varying salinity and herbicide levels. *Comp Sci Util* **14**:244–251 (2006).

