Palmer Amaranth (Amaranthaceae) and At-Plant Insecticide Impacts on Tarnished Plant Bug (Hemiptera: Miridae) and Injury to Seedling Cotton Terminals[1]

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J. Entomol. Sci. 56(4): 487–503 (October 2021)

Abstract The direct effect of Palmer amaranth, *Amaranthus palmeri* Watson, on cotton growth and development is well documented, but its indirect effect through harboring feeding insects is less understood. Palmer amaranth emerged with cotton and remaining in the field for 30 days increased tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois), populations compared with a weed-free system. Weedy systems noted up to 49% more damaged terminals than weed-free systems, with cotton yield decreasing as damaged terminals increased at one of two locations. Thrips (Thysanoptera: Thripidae) populations were effectively controlled with Aeris® (Bayer, St. Louis, MO) seed treatment (imidacloprid + thiodicarb at 0.375 mg active ingredient per seed), but there was no correlation between thrips infestations and increasing damaged cotton terminals. However, Aeris seed treatment significantly reduced the occurrence of damaged cotton terminals. In a second experiment, Palmer amaranth infesting an area adjacent to a weed-free cotton field had maximum damaged terminals of 51% on the cotton row proximal to the weedy area, with the distal cotton row (44 m away) having 8% terminal damage. Cotton yield significantly decreased as damaged terminals increased. A final bioassay experiment further evaluated the influence of seed treatment on tarnished plant bug feeding impacting cotton seedlings. With Aeris seed treatment, tarnished plant bug mortality was 97%, compared with 37% for nontreated seed. Results suggest tarnished plant bug infestations increased where Palmer amaranth was present in cotton fields. Additionally, greater Palmer amaranth infestations led to an increase in damaged cotton terminals and lower yields.

Key Words seedling cotton, tarnished plant bug, damaged cotton terminals, weed-insect interaction

Palmer amaranth, *Amaranthus palmeri* Watson, is the most important weed pest in the recent history of Georgia agriculture (Culpepper et al. 2006, Sosnoskie and Culpepper 2014, Webster 2009, 2013). In 2019, a survey of 1,737 agronomic growers also noted that Palmer amaranth has become the most challenging of all pests in Georgia agriculture (Culpepper et al. 2019). Those growers noted that Palmer amaranth was 7.5 times more challenging than *Ipomoea* species and 11.4

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times more challenging than sweetpotato whiteflies, *Bemisia tabaci* (Gennadius), to manage, which are the second and third most problematic pests, respectively. The ability of Palmer amaranth to effectively emerge and compete with cotton, *Gossypium hirsutum* L., throughout the growing season for light, water, nutrients, and space has been well documented, emphasizing the need for season-long control to maximize yields and maintain harvest efficiency (Buchanan and Burns 1970, Rowland et al. 1999, Shadbolt and Holm 1956, Tharp and Kells 2002). However, little research is available about the influence of Palmer amaranth on insect infestations that potentially damage cotton yield and profitability.

At an on-farm research site in Macon Co., GA, the site of the first confirmed glyphosate-resistant *Amaranthus* in the world (Culpepper et al. 2006), observations of a loss in apical dominance and the development of secondary vegetative branching were noted in cotton during 2015 and 2016. Interestingly, the loss in cotton terminals was more prevalent in areas with heavy infestations of Palmer amaranth. The Georgia Cooperative Extension Service determined that the likely cause of this early-season damage was due to thrips spp. (Thysanoptera: Thripidae) or tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois).

Thrips infested 87% and 98% of cotton in the United States and Georgia during 2018, respectively, accounting for national losses of nearly $67 million (Cook and Cutts 2018). Tobacco thrips, *Frankliniella fusca* (Hinds), is the most common thrips species infesting seedling cotton in Georgia and the Southeastern United States (Reay-Jones et al. 2017). Both adult and immature thrips feed on the contents of plant epidermal cells during the early stages of plant development, presenting a threat to seedling cotton. Heavy feeding during this time of early growth can result in damage to leaves and terminal buds, leading to plant stunting, delayed maturity, stand losses, and yield reductions (Allen 2018, Cook et al. 2011). Previous research has noted severe damage or death of terminals in cotton from feeding by thrips, leading to the loss of apical dominance and the development of secondary vegetative branching (Cook et al. 2011, Gaines 1934, Leigh et al. 1996). Due to the sensitivity of young cotton to feeding by thrips, it has become standard practice in cotton production to implement prophylactic management practices. At-plant insecticide seed treatments, for example imidacloprid, are commonly used to protect emerging cotton, with supplemental foliar insecticides, including acephate, used for continued control through periods of slow cotton growth and heavy thrips infestations (Cook et al. 2011, Roberts and Toews 2019).

The tarnished plant bug infested nearly 41% and 55% of United States and Georgia cotton, respectively, in 2018, with national losses of nearly $175 million (Cook and Cutts 2018). Significant injury and economic losses have been recorded from tarnished plant bug feeding on cotton from pinhead square through flowering, leading to fruit abortion and potential yield losses. Feeding, however, has been observed on emerging cotton through boll formation (Allen 2018, Graham and Stewart 2018, Layton 2000). Similar to thrips, feeding by tarnished plant bugs on seedling cotton has been reported to damage or abort plant terminals, leading to a loss of apical dominance and the development of secondary terminals and auxiliary branches (Cook et al. 2013, Hanny et al. 1977, Leigh et al. 1996). There are many contributing factors to the presence of tarnished plant bug populations in cotton, including planting date, varietal maturity, and host plant abundance. Tarnished plant bugs have been recorded on 385 hosts, including cotton, Palmer amaranth, and numerous other agronomic, horticultural, and weedy plants of significance present within the Southeastern United States (Snodgrass et al. 1983, Young 1986). Snodgrass et al. (1984) recorded increasing populations of tarnished plant bug in cotton planted near wild host plants, specifically *Amaranthus* species, during the summer months. When these wild host species matured or were eliminated from the area around cultivated fields, tarnished plant bugs moved into cotton for feeding and reproduction (Snodgrass et al. 1984, 2006). Control measures are not implemented, however, until populations reach an economically significant level of 8 tarnished plant bugs per 100 sweeps during the first 2 weeks of cotton squaring (Musser et al. 2009, Roberts and Toews 2019).

Research has defined the potential threat that thrips and tarnished plant bugs pose to cotton production (Allen et al. 2018, Cook and Cutts 2018, Hanny et al. 1977, Layton 2000, Leigh et al 1996, Roberts and Toews 2019). However, research has not effectively documented the influence of Palmer amaranth on these insects in regard to infestation levels and effects on cotton terminal development and cotton yield. Thus, three experiments were conducted to determine if Palmer amaranth populations directly influenced infestations of thrips or tarnished plant bugs and indirectly influenced cotton production through increased insect feeding.

Materials and Methods

Field experiments. Two field experiments each were conducted twice at an on-farm research site in Ideal, GA (latitude N 32.25°18′, longitude W 84.07°43′; elevation, 134 m), between 2017 and 2019 to investigate early-season infestations of thrips and tarnished plant bugs as a potential cause of the damaged or aborted cotton terminals previously noted at this location. Soil at the research location was a Dothan loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) consisting of 84% sand, 12% silt, 4% clay, 1.2 to 1.9% organic matter, and a pH of 6.2 to 6.3. Cotton fertilization and disease management were implemented throughout the season following university recommendations for the region, with rainfall supplemented through overhead irrigation to meet crop water requirements (Whitaker et al. 2018). For each experiment, 1,3-dichloropropene at 64 kg active ingredient (ai) per ha was broadcast applied to manage nematodes in accordance with university recommendations (Anonymous 2011, Kemerait 2019).

Systems experiment. After conventional land preparation, cotton (variety: Stoneville 6182 GLT) was planted on 26 April 2017 and 2 May 2018 by using a vacuum planter configured to plant 10 seed per m on a 91-cm row spacing. Experimental units consisted of 2 cotton rows, comprising an area 2 m wide by 12 m long. The experimental design was a split-split-plot, including four replications for each treatment combination. A weed management system, with plots maintained (a) weedy for 30 d after planting (DAP), consisting of Palmer amaranth at a density of 29 plants per m^2 in 2017 and 58 plants per m^2 in 2018 or (b) weed-free, represented the whole plot and allowed for blocking to increase the continuous areas infested or not infested with Palmer amaranth. Two additional sample cotton rows were established within the experimental area for the sole purpose of tarnished plant bug sampling from within whole-plot weed management system (total area of whole plot and sample rows equaled 10 cotton rows, 10 m wide by 12 m long), as to not negatively affect cotton plants that would be assessed for yield at the end of the season. At-plant insecticide seed treatment, initiated at planting, consisted of cotton seed treated with (a) seed-applied insecticide and nematicide treatment (Aeris® ST, Bayer, St. Louis. MO) (imidacloprid at 0.375 mg ai per seed + thiodicarb at 0.375 mg ai per seed) or (b) no seed-applied insecticide treatment (untreated), represented the split-plot (4 cotton rows, 4 m wide by 12 m long). Supplemental foliar insecticide applications represented the split-split-plot (2 cotton rows, 2 m wide by 12 m long), with either (a) foliar acephate (200 g ai per ha) or (b) no foliar insecticide applied 14 DAP.

The weedy treatment system followed practices not recommended by academics (namely, that at-plant residual herbicides were not used), allowing Palmer amaranth to emerge (Cahoon and York 2019, Culpepper 2019). At 30 DAP, weedy plots were treated with topical applications of glufosinate (600 g ai per ha). Two additional glufosinate applications were performed followed by directed layby applications of diuron (1,120 g ai per ha), MSMA (1,680 g ai per ha), and crop oil concentrate (1% v/v), eliminating the presence of weeds. Weed-free systems followed academic recommendations, which prevented Palmer amaranth from establishing in the study. Applications of fomesafen (175 g ai per ha) plus acetochlor (840 g ai per ha) were applied to the weed-free system at planting, followed by sequential topical applications of glufosinate (600 g ai per ha) during the growing season and a directed layby, similar to the weedy system for continuous weed control. All herbicide and insecticide applications were performed with a backpack sprayer equipped with 11002 Air Induction XR wide-angle flat-spray nozzles (Teejet Technologies, Wheaton, IL) delivering 140 L per ha at 165 kPa. Herbicide application did not negatively influence crop growth, development, or yield.

Thrips populations were sampled by individually submerging and swirling 5 cotton plants per plot in a container filled with 70% alcohol to dislodge thrips, beginning 7 DAP and continuing weekly until 28 DAP (Burris et al. 1989, Rummel and Arnold 1989). The number of immature and adult thrips present were counted in each sample by using a dissecting microscope. A subsample of adult thrips (maximum of 25 thrips) was identified to species on each sample date. Tarnished plant bug population levels were sampled from whole plots (weed management systems) by making 10 sweeps using a sweep net (38-cm diameter) in cotton established for sampling purposes, with counts then converted to population per 100 sweeps. Collection began 24 DAP and continued weekly through 49 DAP, with each tarnished plant bug sample then sorted into adults and nymphs. After cotton emergence and stand establishment, the total number of plants present in each plot was recorded. Beginning 21 DAP, damaged or aborted cotton terminals and the loss of apical dominance cotton plants from missing terminals (referred to collectively as damaged terminals) were assessed weekly through 42 DAP. Cotton yield, recorded in kg per ha, was collected once, 159 to 163 DAP, by using a spindle picker modified for small-plot harvesting. After harvest completion, a final postharvest damaged terminal count was collected.

Significant interactions between treatment effects and study years were investigated to determine if weed management system, at-plant insecticide seed treatments, or supplemental foliar insecticide applications affected the occurrence of damaged cotton terminals, thrips populations, tarnished plant bug populations, or cotton yield. Data were subjected to an analysis of variance using the GLIMMIX procedure in SAS (SAS 9.4, SAS Institute., Cary, NC). Weed management system, insecticide seed treatments, and foliar insecticide applications were treated as fixed effects, with replication included as a random effect. Due to differences in weed pressure and environmental differences, year was treated as a fixed factor to facilitate data pooling. When appropriate, linear regression or Pearson product-moment correlation was used to describe continuous variable responses in Sigma Plot (Sigma Plot 14.0; Systat Software, San Jose, CA). Data presented for damaged cotton terminals are the percentage of damaged plants present.

Cotton proximity to Palmer amaranth. A second experiment was conducted in 2018 and 2019 to determine the relationship between damaged cotton terminals and the distance of their occurrence from a weedy, Palmer amaranth source. Field studies were conducted at the same on-farm location in Ideal, GA, as the previous experiment, because of the presence of damaged cotton terminals and large populations of Palmer amaranth. After conventional land preparation, cotton (variety: Deltapine 1646 B2XF) was planted on 2 May 2018 and 23 April 2019 by using the same equipment, seeding rate, and plant spacing as the previous experiment. The experimental area was 35 by 26 m in 2018, containing 28 cotton rows. In 2019, the experimental area was 46 by 45 m, containing 50 cotton rows. Inputs for management of cotton growth were maintained identically as the previous experiment; however, cotton production areas were maintained weed free following the previously described weed-free program for the systems experiment. A large area of Palmer amaranth, 45 by 80 m at a density of greater than 50 plants per m in both years, was naturally established parallel to cotton rows, along the east side of the experimental area, and served as a weedy source for the entire cotton season. Palmer amaranth and other weedy vegetation were removed from borders in all other directions to a distance equal to that of the cotton experimental area by using the same herbicide program implemented in the weed-free cotton.

One month before harvest each year, each cotton row within the experimental area was assessed for damaged or aborted terminals and loss of apical dominance (damaged terminals). The cotton row directly next to the source of Palmer amaranth was designated “row 1” or “0 m” that increased up to “row 50” or “44 m.” Each consecutive row was labeled in numerical order, moving in the direction away from the weedy area, with cotton rows spaced 91 cm apart. One hundred consecutive plants from the center of each row were assessed for damaged terminals. Collected data for total damaged terminals per row were converted to a percentage for analysis. In 2019, yield was collected 161 DAP in kg per ha from every other cotton row, beginning on row 1, directly next to the weedy area.

Damaged terminal assessments from 2018 and 2019 were combined across years for analysis, whereas yield data were presented only for 2019. The distance (m) at which the damaged terminals occurred, away from the Palmer amaranth source, was treated as a continuous variable; therefore, a regression analysis was used to investigate the relationship. Linear regression was used to further describe the continuous variable response through regression analysis in Sigma Plot.

Bioassay. A laboratory bioassay was conducted twice in Tifton, GA, during 2017 and 2018 to investigate the influence of Aeris ST on tarnished plant bug feeding and injury in seedling cotton. Cotton plants were grown in 30 specimen cups (120-ml capacity, 5.7 cm in diameter, 7 cm in height) with attachable arenas, which allowed for tarnished plant bugs to be confined to the plant. The effects of seed treatment on tarnished plant bug and cotton mortality were assessed. Field soil consisting of a Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) with 84% sand, 11% silt, 5% clay, 0.5% organic matter, and a pH of 6.3 was used as a growing medium for cotton, with 1 seed planted per bioassay sample cup. Cotton (variety: Stoneville 6182 GLT) seed treatment options included (a) Aeris ST with insecticide rates identical to those previously described for the field or (b) no seed-applied insecticide treatment (untreated), and treatments were arranged in a randomized complete block design among the sample cups. Fifteen replications were included each experimental run.

To prevent leaching of seed insecticide treatments, subirrigation was implemented throughout the entirety of the experiment by punching holes in the bottom of each sample cup and placing plants in trays filled with water maintained at a depth of 5 cm. Once cotton reached the cotyledon stage (7 cm in height), arenas (16 cm tall, 10 cm in diameter) were attached to the top of each sample cup to provide an enclosure to contain tarnished plant bugs around the cotton plant. When cotton was at the cotyledon stage, adult tarnished plant bugs were collected using a sweep net (38 cm in diameter) from Palmer amaranth plants in Ideal, GA, on 5 June 2017 and Tifton, GA, on 10 August 2018. After collection, samples were immediately placed in a mesh cage and vitality was observed for 2 to 4 h before transfer to bioassay arenas. The experiment was initiated when observation of collected tarnished plant bugs was complete. Five tarnished plant bugs were added to each arena and confined on the cotton for 60 h before removal. Bioassay sample cups and attached arenas remained in the laboratory throughout the entire experiment, exposed to 24 h of light daily and 24°C.

At the completion of the experiment, the arenas were removed and tarnished plant bug mortality was assessed. Tarnished plant bugs were considered "alive" if moving, and "dead" if not moving. Based on observations of plant health after experiment completion in 2017, cotton plants were placed in the greenhouse at the completion of the 2018 experiment, where they were maintained with irrigation for 14 d. After 14 d, cotton plant mortality was recorded, with plants indicated alive or dead.

Interactions between years and treatment effects were determined not significant for data concerning tarnished plant bug mortality; therefore, data were combined. Paired *t* tests were used to test for differences between treatments by using the TTEST procedure in SAS, with *P* values reported in parentheses.

Results and Discussion

Systems experiment. The occurrence of damaged cotton terminals, 21 through 42 DAP, was tested for significance between years and treatments to determine if data should be pooled. Due to a significant interaction, a further analysis indicated differences in experimental years for weed management system ($F = 7.45$; df $= 1, 240$; $P = 0.0068$) and at-plant insecticide seed treatment ($F = 7.00$; df $= 1, 240$; $P = 0.0087$); therefore, each variable was presented separately. In 2017, at-plant insecticide significantly affected the occurrence of damaged terminals throughout the season ($F = 20.16$; df $= 1, 114$; $P \leq 0.0001$), and data collected in 2018

Table 1. Significant effects of weed management system (W), at-plant insecticide seed treatment (API), supplemental foliar insecticide (F), and interactions between treatments on the occurrence of damaged terminals, immature thrips populations, and cotton yield collected during 2017 and 2018 in Ideal, GA.*

	Damaged Terminals		Immature Thrips		Cotton Yield	
Effect	2017	2018	2017	2018	2017	2018
W	0.2640	**0.0019**	0.5042	**0.0015**	0.6264	0.5072
API	<**0.0001**	<**0.0001**	**0.0186**	**0.0012**	0.2286	0.1928
W × API	0.2675	0.1877	0.1535	0.7587	0.2378	0.6046
F	0.2844	0.8028	0.6911	0.7716	0.9436	0.9703
W × F	0.2113	0.9936	0.7578	0.2635	0.6838	0.2126
API × F	0.1082	0.6217	0.2779	0.5855	0.4104	0.1341
W × API × F	0.5569	0.6610	0.7991	0.3640	0.2244	0.1776

*The progression of damaged terminals 21 to 42 days after planting (DAP), immature thrips populations 21 DAP, and cotton yield was separated into 2017 and 2018 for analysis due to a year by treatment interaction. *P* values for treatment effects within columns were determined using Tukey's honestly significant difference (α=0.05), with significance noted by boldface font.

observed no differences (Table 1). Combined across weed management system and supplemental foliar insecticide applications, 6 ± 0.80%, 8 ± 0.61%, 10 ± 0.94%, and 11 ± 1.05% damaged terminals were recorded with Aeris ST 21, 28, 35, and 42 DAP, respectively. Regression models estimated a 0.23% increase in damaged terminals for each increase in DAP within Aeris ST (Fig. 1). Without the insecticide seed treatment, 8 ± 0.83% to 16 ± 1.52% damaged terminals were recorded, with the untreated model indicating a 0.41% increase in damaged terminals for each increase in DAP (Fig. 1). Comparisons between slopes of Aeris ST and untreated, however, were not different ($F = 3.05$; df = 1, 124; $P = 0.0830$). Final postharvest assessments of Aeris ST (F=2.91; df=1, 30; P=0.0980) and seed not treated with insecticide ($F = 1.56$; df = 1, 28; $P = 0.2230$) did not differ from the previous assessment, indicating that injury to cotton resulting in an increasing occurrence of damaged terminals did not occur between 42 DAP and final postharvest assessments. Weed management systems, supplemental foliar insecticide applications, and interactions between the two effects did not affect damaged terminals during 2017.

Both weed management system ($F = 30.10$; df = 1, 3; $P = 0.0019$) and at-plant insecticide ($F = 179.16$; df = 1, 90; $P \leq 0.0001$) affected the occurrence of damaged terminals during the 2018 season, which observed higher Palmer amaranth densities than that of 2017 (Table 1). Combined across at-plant and foliar insecticides, weekly assessments collected 21 to 42 DAP in weedy systems noted 4 ± 0.42% to 35 ± 2.83% damaged terminals, with regression models estimating a 1.5% linear increase in damaged terminals within weedy systems for each increase

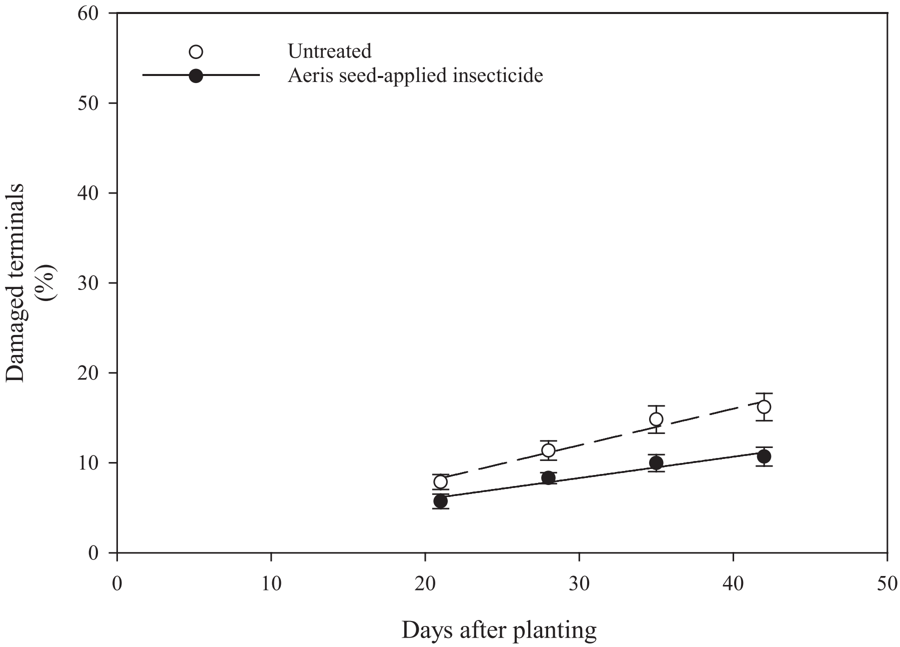

Fig. 1. Influence of at-plant insecticide seed treatments on the progression of damaged terminals in cotton during 2017 in Ideal, GA. Damaged terminals (mean ± SE) of Aeris at-plant insecticide treatments were linearly regressed against observations 21 (5.72 ± 0.80), 28 (8.30 ± 0.61), 35 (9.97 ± 0.94), and 42 (10.68 ± 1.05) days after planting (DAP) using by the equation y_{Aeris} = 1.220+0.236*x (R^2 = 0.23). Damaged terminals of the untreated were linearly regressed against observations 21 (7.87 ± 0.83), 28 (11.36 ± 1.07), 35 (14.81 ± 1.51), and 42 (16.20 ± 1.52) DAP by using the equation $y_{untreated}$ = −0.242+0.406*x (R^2 = 0.29). Data were combined across weed management system and supplemental foliar insecticide applications in 2017.

in DAP (Fig. 2). Damaged terminals were less than 19 ± 1.70% across all assessment intervals in weed-free systems. Models within weed-free systems indicated a 0.66% increase in damaged terminals for each DAP (Fig. 2). Regression analysis indicated that slopes of weedy and weed-free systems significantly differed (F = 25.40; df = 1, 124; $P \leq 0.0001$). Similar to observations in 2017, final postharvest damaged terminal assessments were not different (weedy: F = 1.10; df = 1, 30; P = 0.3020; weed free: F = 0.71; df = 1, 30; P = 0.4070) from the previous assessment, indicating no additional injury to cotton plants resulting in damaged terminals occurred after 42 DAP.

Similar to 2017, at-plant insecticide significantly affected the occurrence of damaged terminals in 2018 (Table 1). Combined across weed management system and foliar insecticide treatments, damaged terminals were recorded in up to 33 ± 3.69% of the cotton stand when at-plant insecticide was not used. The untreated

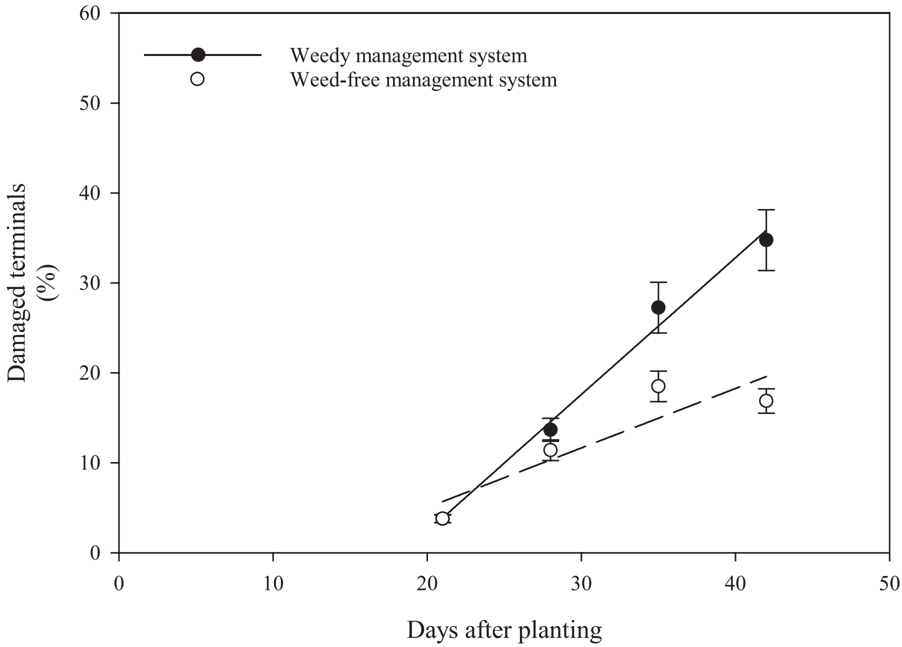

Fig. 2. Influence of weed management systems on the progression of damaged terminals in cotton during 2018 in Ideal, GA. Damaged terminals (mean ± SE) of weedy systems were linearly regressed against observations 21 (3.79 ± 0.42), 28 (13.68 ± 1.28), 35 (27.26 ± 2.83), and 42 (34.77 ± 3.75) days after planting (DAP) by using the equation $y_{weedy} = -28.067 + 1.522^{*}x$ ($R^2 = 0.64$). Damaged terminals of weed-free systems were linearly regressed against observations 21 (3.81 ± 0.46), 28 (11.41 ± 1.15), 35 (18.50 ± 1.70), and 42 (16.87 ± 1.35) DAP by using the equation $y_{weed\text{-}free} = -8.185 + 0.661^{*}x$ ($R^2 = 0.48$). Data were combined across at-plant insecticide seed treatments and supplemental foliar insecticide applications in 2018.

regression models estimated a liner increase of 1.4% in damaged terminals for each increase in DAP (Fig. 3). Damage was reduced to less than 19 ± 1.83% when Aeris ST was used, with models estimating a 0.75% linear increase in terminal damage for each increase in DAP (Fig. 3) for treated seed. An analysis indicated that slopes of Aeris ST significantly differed from the untreated ($F = 17.39$; df = 1, 124; $P \leq 0.0001$). Again, postharvest assessments of damaged terminals were not different from the previous assessment (Aeris ST: $F = 1.12$; df = 1, 30; $P = 0.2990$; untreated: $F = 0.09$; df = 1,30; $P = 0.7670$), confirming that injury to cotton that would have resulted in damaged terminals did not occur between 42 DAP and cotton harvest. In 2018, supplemental foliar insecticide applications did not influence the occurrence of damaged terminals throughout the season.

Thrips are a consistent pest of cotton during its early growth stages in the Southeastern United States; therefore, populations were sampled weekly,

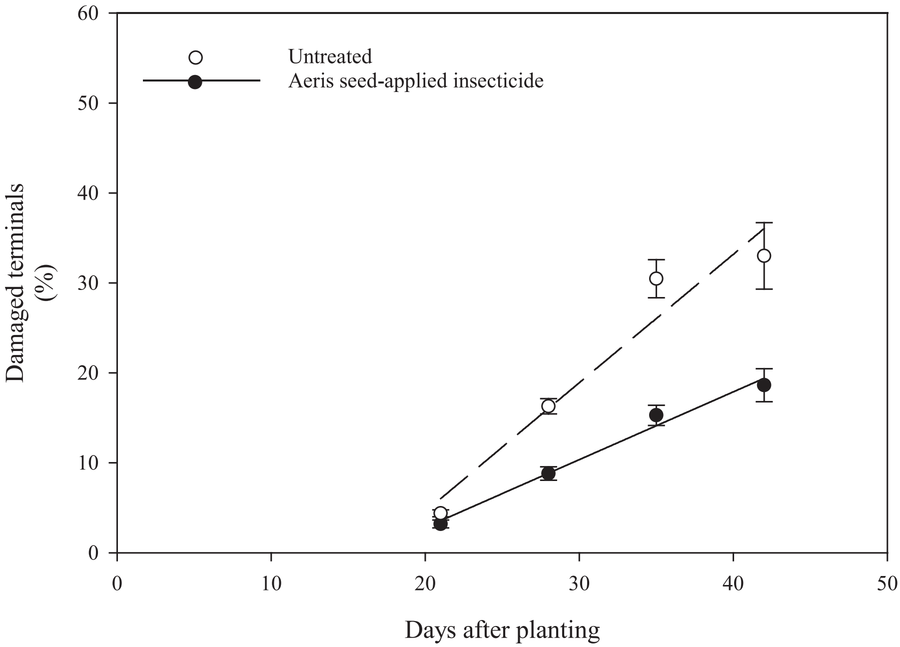

Fig. 3. Influence of at-plant insecticide seed treatments on the progression of damaged terminals in cotton during 2018 in Ideal, GA. Damaged terminals (mean ± SE) of Aeris at-plant insecticide treatments were linearly regressed against observations 21 (3.20 ± 0.44), 28 (8.81 ± 0.75), 35 (15.28 ± 1.12), and 42 (18.63 ± 1.83) days after planting (DAP) by using the equation $y_{Aeris} = -12.256+0.754*x$ ($R^2=0.63$). Damaged terminals of the untreated were linearly regressed against observations 21 (4.39 ± 0.39), 28 (16.28 ± 0.85), 35 (30.48 ± 2.12), and 42 (33.01 ± 3.69) DAP by using the equation $y_{untreated} = -23.996+1.430*x$ ($R^2 = 0.61$). Data were combined across weed management system and supplemental foliar insecticide applications in 2018.

beginning 7 DAP and continuing through 28 DAP, to investigate their possible influence on the presence of damaged terminals. A significant interaction between year and treatment was further investigated to determine yearly differences within weed management systems ($F = 67.29$; df = 1, 43; $P \leq 0.0001$) and at-plant insecticide seed treatment ($F = 16.11$; df = 1, 43; $P = 0.0002$); therefore data were separated by 2017 and 2018 for analysis. Tobacco thrips comprised >95% of adult thrips sampled during both years. Immature thrips sampled at 21 DAP were used for analysis because they represent maximum thrips infestation throughout the sampling period during both years. Immature thrips populations at 21 DAP were significantly affected when an at-plant insecticide was used in 2017 ($F = 10.23$; df = 1, 6; $P = 0.0186$) (Table 1). Combined across weed management system and foliar insecticide applications, 19 ± 2.21 thrips per 5 plants were collected in the no at-plant insecticide treatment, which was reduced by 22% with Aeris ST (data not

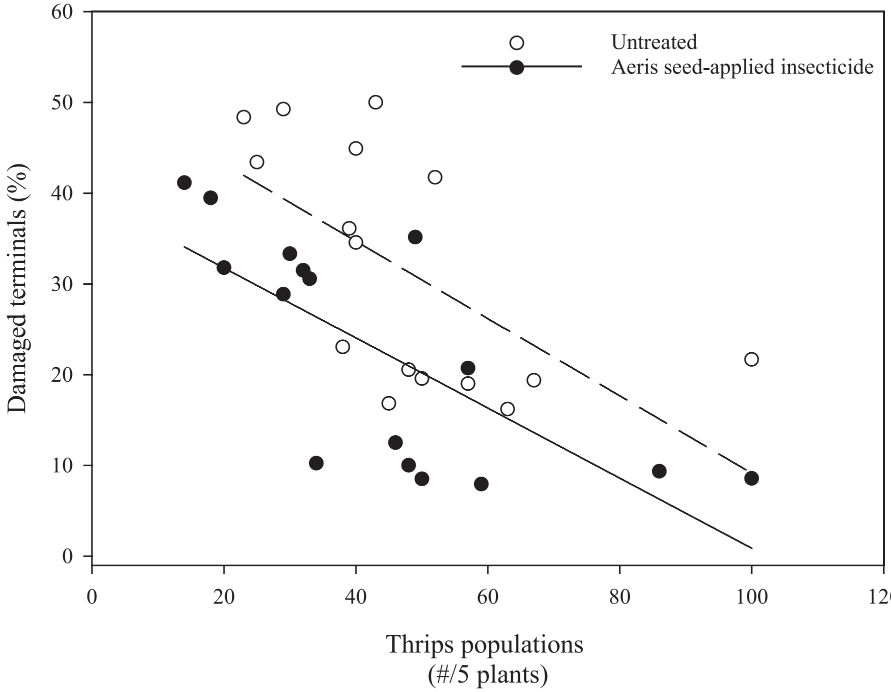

Fig. 4. Influence of immature thrips populations, 21 days after planting (DAP), on the occurrence of damaged terminals in cotton during 2018 in Ideal, GA. Damaged terminals were linearly regressed against immature thrips populations by using the equations $y_{Aeris} = 39.493 - 0.386^{*}x$ ($R^2 = 0.52$) and $y_{untreated} = 51.767 - 0.427^{*}x$ ($R^2 = 0.37$). Data were combined across weed management system and supplemental foliar insecticide applications in 2018.

shown). When regressed against postharvest damaged terminal assessments, however, no significant linear trends were detected between immature thrips and the occurrence of damaged cotton terminals (Aeris ST: $P = 0.5619$; untreated: $P = 0.2572$), and populations were not influenced by weed management system ($F = 0.57$; df = 1, 3; $P = 0.5042$) or supplemental foliar insecticide applications ($F = 0.17$; df = 1, 10; $P = 0.6911$). In 2018, immature thrips were influenced by weed management systems ($F = 127.69$; df = 1, 3; $P = 0.0015$) and at-plant insecticide ($F = 32.86$; df = 1, 6; $P = 0.0012$) (Table 1). When assessed 21 DAP, weed-free systems recorded 25% more immature thrips than weedy systems; however, no significant linear trends were detected between thrips populations sampled from either weed management system and the occurrence of damaged terminals (weedy: $P = 0.7281$; weed free: $P = 0.9196$). Aeris ST reduced immature thrips populations 31% compared with the untreated in 2018, with regression models estimating a linear decrease of 0.39% in treated and 0.43% in untreated damaged terminals for each increasing unit of thrips (Fig. 4). The analysis indicated, however,

Table 2. Tarnished plant bug populations, sampled 24 to 49 days after planting (DAP) cotton, recorded from whole plot, weed management systems during 2017 and 2018 in Ideal, GA.*

Weed Management System	Number of Tarnished Plant Bug per 100 Sweeps			
	24 DAP	35 DAP	42 DAP	49 DAP
Weedy	28 a	5	5	6
Weed-free	0 b	1	4	9

*Means within columns followed by the same letter do not significantly differ at a significance of α=0.05.

that the slopes of Aeris ST and the untreated were not different ($F = 0.05$; df = 1, 28; $P = 0.8195$). Foliar insecticide applications did not influence thrips populations in 2018 ($F = 0.09$; df = 1, 12; $P = 0.7716$) (Table 1). Although similar damaged terminals in cotton have been documented in previous research as a result of thrips feeding, the decrease in damaged terminals noted as immature thrips populations increased in this study suggest immature thrips were not the causal agent of the observed damaged terminals (Cook et al. 2011, Gaines 1934, Leigh et al. 1996).

Tarnished plant bug populations sampled during 2017 and 2018 were not significantly different between years; therefore, data were combined for analysis ($P = 0.6443$). To account for insect movement and small plot size, population samples were collected weekly, only within whole-plot weed management systems. Previous research has indicated the attractiveness of weedy species, such as Palmer amaranth, to tarnished plant bugs for feeding and reproduction; therefore, greater populations were expected from weedy systems (Jackson et al. 2014). Assessments 24 DAP (3-leaf cotton) recorded 28 $\pm$ 4.60 tarnished plant bugs per 100 sweeps from weedy systems (Table 2). Collected populations were greater than threefold the threshold of cotton during the first 2 weeks of squaring; however, thresholds currently are not set for cotton in the three-leaf stage (Roberts and Toews 2019). With Palmer amaranth present at this point in the season, it is uncertain whether tarnished plant bugs were collected from the cotton or Palmer amaranth within the weedy systems. Weed-free systems observed significantly fewer tarnished plant bugs, with no populations recovered 24 DAP (Table 2). Notably, weeds were eliminated from the study 30 DAP, after which populations began to converge, and no population differences were noted between weed management systems at 35 to 49 DAP. This reduction could be attributed to tarnished plant bug movement from weed species to cultivated species, or to a new location, once weedy reproductive hosts matured or were eliminated (Fleischer and Gaylor 1987, Snodgrass et al. 2006). Differences in populations collected from weed management systems indicated that tarnished plant bugs were attracted to and could be collected from weedy presquaring cotton systems with high populations of Palmer amaranth present. Additionally, in these systems, a higher percentage of damaged terminals were observed than that in weed-free systems.

The influence of damaged terminals on cotton yield noted a significant year interaction within weed management system ($F = 67.29$; df = 1, 43; $P \leq 0.0001$); therefore, data were analyzed separately for 2017 and 2018. Main effects did not influence cotton yield during either year (Table 1). In 2017, cotton yield exhibited a moderately negative correlation ($R = -0.52$; $P = 0.0030$) to the occurrence of increasing damaged terminals. Greater cotton yields were reported in 2018; however, no significant correlation ($P = 0.7580$) was detected between cotton yield and the occurrence of damaged terminals (data not shown). Regional reports from the 2018 cotton growing season noted high yields throughout the Southeastern United States for cotton harvested before a major hurricane hit the region; therefore, the yield differences between 2017 and 2018 may be attributed to excellent growing conditions (Whitaker et al. 2018). Collected yield data suggest that early-season injury to cotton resulting in damaged terminals 21 to 42 DAP could result in yield reductions, as influenced by at-plant insecticide and weed management system.

Cotton proximity to Palmer amaranth. Damaged cotton terminals in 2018 and 2019 were significantly influenced by the distance in which the damaged terminals occurred from the source of Palmer amaranth; data were combined across years for analysis. During both years, regression analysis indicated a strong nonlinear relationship between variables, with the occurrence of damaged terminals decreasing as distance from the weedy source increased ($P = 0.0176$). Maximum damaged terminals of 51% were noted on the cotton row directly next to the weedy area, with the furthest cotton row (44 m away from weedy source) recording minimum damaged terminals of 8% (Fig. 5). Cotton yield data collected from the site in 2019 further supports the relationship, with subsequent yield significantly decreasing as the percentage of damaged terminals increased ($P = 0.0276$) (Fig. 6). The decrease in damaged terminals moving away from the weedy source supports previous research indicating tarnished plant bugs prefer Palmer amaranth and will use it as a host before moving into cotton (Snodgrass et al. 1984, 2006). Results further support previous observations of high tarnished plant bug populations within weedy, Palmer amaranth populations in cotton. Overall, these results suggest that tarnished plant bugs feed on and injure cotton terminals, with the potential for subsequent reductions in yield.

Bioassay. In 2017 and 2018, no differences were detected between experimental years and tarnished plant bug mortality; therefore, data were combined for analysis. When Aeris ST was used, tarnished plant bug mortality was 97% compared with 37% when seeds were not treated with insecticide ($t = 8.42$; $P < 0.0001$). Data on cotton mortality were collected only in 2018, and assessments of plant health after the removal of tarnished plant bugs from cotton noted 100% cotton mortality when no insecticide seed treatment was used. Cotton mortality was reduced to 7% when Aeris ST was used, indicating tarnished plant bug feeding on unprotected seedling cotton resulted in plant injury or death ($t = -14.00$; $P < 0.0001$). Although many tarnished plant bugs were forced to feed on the seedling cotton, resulting in a high mortality rate, this may offer a possible explanation of reduced damaged terminals observed in the field with Aeris seed treatment.

Results from field studies suggest Palmer amaranth present in cotton can increase populations of tarnished plant bug. In this research, when Palmer amaranth was present in cotton at a density of 58 per m^2 compared to 27 per m^2,

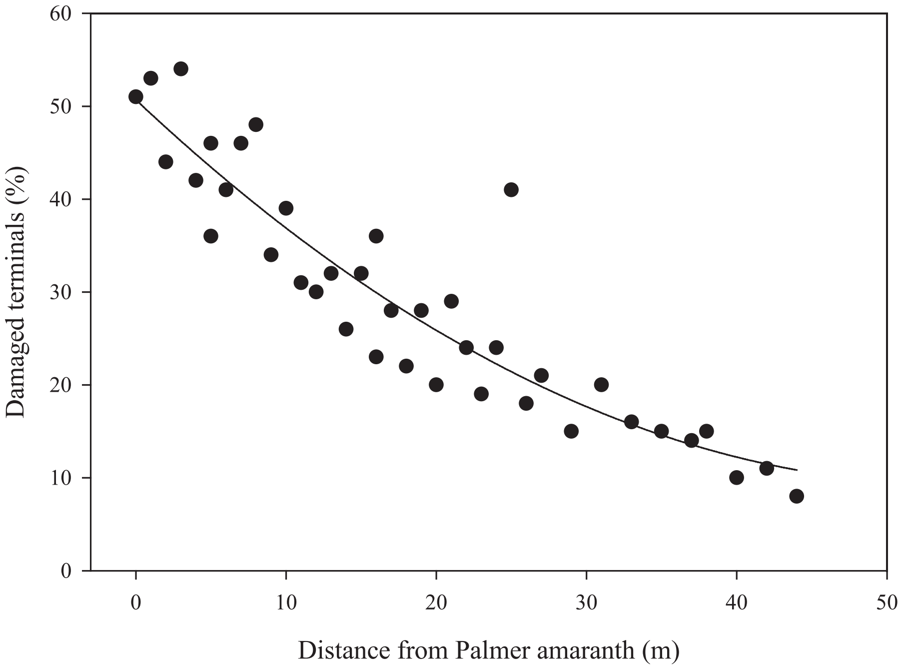

Fig. 5. Damaged cotton terminals in response to increasing distance from Palmer amaranth source during 2018 and 2019 in Ideal, GA. Damaged terminals were regressed against increasing distance from Palmer amaranth source by using the equation $y_{terminals} = 50.701 - 1.520{*}x + 0.014{*}x^2$ ($R^2 = 0.84$).

more damaged terminals were recorded. Similarly, the occurrence of damaged terminals in cotton decreased as distance increased from a weedy source, consisting of Palmer amaranth at densities greater than 50 per m^2. Thus, weed management programs using at-plant residual herbicides and in-season postemergence herbicides should be implemented to limit weed emergence and their negative effects on crop growth and minimize attracting tarnished plant bugs to the field. Also, when economically sustainable, Palmer amaranth should be removed from areas adjacent to cotton production.

In both 2017 and 2018, Aeris seed treatment significantly reduced the occurrence of damaged cotton terminals in the field compared to untreated seed, and results from bioassays suggest that Aeris may provide protection from tarnished plant bug feeding. The use of insecticide-treated seed also affected thrips; however, observations across both years indicated an inverse relationship between increasing damaged terminals and increasing thrips populations. Results from field and laboratory bioassay studies suggest that further research is needed regarding direct feeding by tarnished plant bug on seedling cotton.

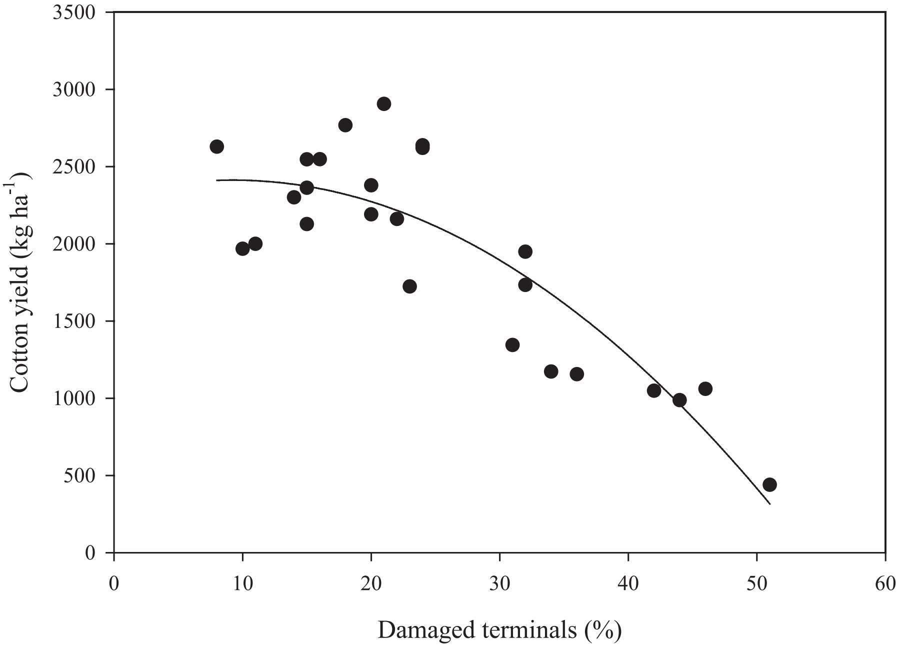

Fig. 6. Cotton yield in response to damaged terminals noted for increasing distance from Palmer amaranth source during 2019 in Ideal, GA. Cotton yield data were regressed against the increasing occurrence of damager terminals by using the equation $y_{yield} = 2{,}310.800 + 22.179 * x - 1.202 * x^2$ ($R^2 = 0.75$).

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