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ARTHROPOD MANAGEMENT AND APPLIED ECOLOGY

Impact of Nitrogen Application Rate on Tarnished Plant Bug (Heteroptera: Miridae) Populations and Management in Cotton

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ABSTRACT

The tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois), is one of the most economically important pests of cotton, *Gossypium hirsutum* L., in the mid-southern U.S. Experiments were conducted during 2012 and 2013 to evaluate the effect of nitrogen fertilizer application rate on tarnished plant bug populations and management as well as cotton growth, development, and yield. Fertilizer (N) was applied as a 32% urea ammonium nitrate (UAN) solution at pinhead square at five different application rates: 0, 45, 90, 134, and 179 kg N ha^{-1}. Plots were managed for tarnished plant bug with insecticides using treatment thresholds recommended by the Mississippi State University Extension Service. A corresponding set of plots for each N fertilizer application rate were not treated with insecticides fto determine tarnished plant bug infestation level and subsequent damage. The interaction of N fertilizer application rate and tarnished plant bug management level (treated or not treated) was significant for total number of plant bugs observed during the growing season. Fertilizer N application rate and tarnished plant bug management each had a significant impact on the mean number of plant bugs observed on a weekly basis and cotton lint yield. Fertilizer N application rate had a significant impact on the number of applications required to manage tarnished plant bug populations. This research demonstrated that there was an optimal level of N availability to balance yield and insecticide applications for tarnished plant bug, thus maximizing profits.

The tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois), is the primary insect pest of cotton, *Gossypium hirsutum* L., in Mississippi as well as most of the mid-southern growing region of the U.S. (Williams, 2013). Nearly 95% of infested hectares in the Mississippi Delta received an average of six insecticide applications for tarnished plant bug in 2012. The average cost for a single insecticide application for tarnished plant bug population management was $32.85 per hectare in 2012. Of the cotton hectares planted in the Mississippi Delta in 2015, 99% were infested with tarnished plant bug (Williams, 2016). Increased inputs for control of tarnished plant bug and other insect pests, as well as fees associated with transgenic seed varieties, seed treatments, and increased herbicide use due to resistant weed species has led to greatly increased costs associated with cotton production in the Mississippi River Delta region of the U.S. (Falconer et al., 2015; Laughlin et al., 1995).

Control of tarnished plant bug in the Mississippi River Delta region is challenging due to widespread insecticide resistance to multiple classes of insecticides (Portilla et al., 2018). Snodgrass (1994) reported that tarnished plant bug populations in the region were 54-fold more tolerant to permethrin and 35-fold more tolerant to bifenthrin than populations collected in the hill portion of Mississippi. Snodgrass (1996) documented resistance to pyrethroid insecticides in field populations of tarnished plant bug in 1996. Snodgrass and Scott (1988) found that tarnished plant bugs were resistant to dimethoate. In addition, resistance to other organophosphate insecticides was documented in 2009 (Snodgrass et al., 2009). In 2006, 497,976 and 137,651 hectares of cotton and corn, *Zea mays* L., respectively, were planted in Mississippi (NASS, 2006) and 3.2 applications were made for tarnished plant bug management in the Mississippi delta (Williams, 2007). In 2012, cotton and corn were planted on 192,308 and

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331,983 hectares, respectively, in Mississippi (NASS, 2012) and insecticide applications for tarnished plant bug management increased to 5.7 applications (Williams, 2013). Increased insecticide applications for tarnished plant bug in cotton is likely due in part to the shift in crop hectares in Mississippi. Corn serves as an alternate host for tarnished plant bug prior to senescence; however, upon corn senescence, tarnished plant bugs likely move into cotton (Snodgrass et al., 1984). As a result, increased populations of tarnished plant bugs in cotton have been observed since 2006 (Snodgrass et al., 2009).

Due to increased cost and difficulty controlling tarnished plant bug, alternative integrated pest management strategies are being evaluated for tarnished plant bug management. Adams et al. (2013) found that planting cotton early, between mid-April and early May in Mississippi, reduced the number of insecticide applications needed for tarnished plant bug. In addition, planting cotton in mid-April resulted in greater yields when compared to planting in early May, mid-May, and early June. Furthermore, early maturing cotton varieties treated for tarnished plant bug based on established treatment thresholds showed significantly greater yield than later maturing cotton varieties sprayed using the same thresholds. Managing for earliness through planting date and varietal maturity selection can maximize yield and reduce insecticide input costs (Adams et al., 2013).

Tarnished plant bug is attracted to vigorously growing, vibrant cotton (Willers et al., 1999). Excessive fertilizer application to cotton can result in increased plant height as well as increased vegetative growth that can delay maturity (Varco et al., 1999). Current recommended N fertilizer application rates of the Mississippi State University Soil Testing Laboratory range from 56 to 90 kg N ha^{-1} bale^{-1} expected yield (Oldham and Dodds, 2017). In 2007, an average of 131 kg N ha^{-1} was applied to cotton in Mississippi (NASS, 2007). Although optimum N fertilizer application rates vary by region, growing conditions, and soil texture, previous research indicated that cotton yields in Mississippi are maximized when 90 kg N fertilizer ha^{-1} is applied (Parvin et al., 2003). Boquet (2005) observed similar findings in Louisiana in that yields were maximized following N fertilizer application at 90 kg N ha^{-1}. Clawson et al. (2006) observed that optimal N fertilizer application rates were never found due to significant increases in yield observed up to the maximum tested applied N rate of 151 kg ha^{-1}. However, that experiment included clay soils, whereas results from Parvin et al. (2003) and Boquet (2005) were obtained from silt loam soils, which likely accounts for the discrepancy in suggested N fertilizer application rates.

Excessive N fertilizer application rates could potentially attract more tarnished plant bugs into a given field, as well as delay crop maturity allowing for longer infestation times from tarnished plant bug. Given the status of tarnished plant bug resistance to insecticides and the cost required to manage this pest, adjusting N fertilizer application rates in cotton could make cotton less attractive to tarnished plant bug and allow the crop to mature earlier, while maintaining optimum yields. This could alleviate late season insecticide applications for tarnished plant bug, resulting in economic benefits for growers across the mid-southern growing region. Little-to-no data exist regarding the effect of N fertilizer application rate on infestation and control of tarnished plant bug in cotton. Therefore, research was initiated to evaluate the effect of N fertilizer application rate on tarnished plant bug infestation and management as well as cotton growth, development, and yield.

MATERIALS AND METHODS

Experimental Location and Layout. Experiments were conducted in Stoneville, MS at the Mississippi State University Delta Research and Extension Center in 2012 and 2013 to evaluate the effect of fertilizer N application rates on tarnished plant bug infestation and cotton growth and yield. Stoneville 5288 B2F (Bayer CropSciences, Raleigh, NC) was seeded at a depth of 2.5 cm and at a rate of 12.6 seeds per m of row on raised beds on 1 May 2012 and 14 May 2013. This variety expresses two *Bt* genes and was used to minimize the impact of lepidopteran pests on cotton yields. Cotton seed were treated with a commercial premix of imidacloprid, metalaxyl, ipconazole, thiodicarb, trifloxsystrobin, and triadimenol (Aeris Trilex, Bayer CropSciences, Raleigh, NC). Infestations of tarnished plant bug occurred naturally in both years. Prior to cotton establishment, a wheat, *Triticum aestivum* L., cover crop was planted to reduce the level of residual N remaining in the soil. Cotton plots were maintained in the same location using the same randomization in 2012 and 2013 to avoid confounding effects of N availability. Soils in the area where experiments were conducted were classified as a mix of Beulah very fine sandy loam (coarse-loamy, mixed, active, thermic Typic Dystrudepts) and a Bosket very fine sandy loam (fine-loamy, mixed, active, thermic Mollic Hapludalfs). Plots consisted of 16 rows that were 102-cm wide and 23-m in length.

Plant growth regulators were applied as blanket applications beginning at first square to all plots at a similar rate to not confound effects of N fertilizer application rate on cotton growth parameters. All other agronomic practices including weed management, management of lepidopteran pests, irrigation, and harvest aid applications were performed based on best management recommendations and were the same for all treatments within a year. Harvest aids were applied when cotton averaged 60% open bolls in all plots. Plots were harvested on 4 October 2012 and 10 October 2013. Cotton was furrow irrigated as needed for the duration of the study. Nitrogen was applied as 32% urea-ammonium nitrate (UAN) solution in a single application made 35 d after planting (approximately first square) in 2012 and 2013. Nitrogen solution was injected into the soil 21 cm away from the plant row at a depth of 10 cm using an applicator equipped with a John Blue piston pump driven by an AccuRate Rawson hydraulic drive controller.

Experimental Design and Sampling. Experiments were conducted using a factorial arrangement of treatments within a randomized complete block design. Factor A consisted of fertilizer N application rates of 0, 45, 90, 134, and 179 kg N ha $^{-1}$. Factor B consisted of management of tarnished plant bug and included treatments applied based on Mississippi State University Extension Service thresholds (Catchot, 2013, 2014) or no treatment for tarnished plant bug. All plots were scouted for tarnished plant bug once per week starting at pinhead square (35 d after planting). During pre-flowering stages, tarnished plant bug densities were determined by taking 25 sweeps with a 38-cm diameter sweep net in each plot. Prior to flowering, each plot in which tarnished plant bugs were managed based on thresholds was treated when the average number of tarnished plant bugs from all replications reached or exceeded eight tarnished plant bugs per 100 sweeps (Catchot, 2013). Once flowering began (~60 d after planting), all plots were sampled at two locations in each plot once weekly with a black drop cloth that sampled 1.52 m of row. The total number of tarnished plant bug adults and nymphs per sample was recorded. Insecticide applications were made when the average number of tarnished plant bugs from all replications reached or exceeded three tarnished plant bugs per 1.52 m of row (Catchot, 2013). Plots in which tarnished plant bugs were managed based on thresholds were treated with single insecticides or insecticide mixtures at their highest labeled rates to maximize tarnished plant bug control. Insecticide classes utilized included organophosphates, pyrethroids, insect growth regulators, carbamates, neonicotinoids, and sulfoximines. Insecticides were selected and rotated based on recommended practices intended to achieve good control of infestations and minimize insecticide resistance. Insecticide applications were terminated when cotton reached a maturity of five nodes above white flower plus 300 heat units based on a 15.6°C lower development threshold. Nodes above white flower were determined by counting the number of mainstem nodes from the uppermost first position white flower to the uppermost harvestable boll on 10 plants per plot (Bourland et al., 1992). Russell et al. (1999) observed that bolls that have accumulated at least 300 heat units did not sustain further damage due tarnished plant bugs.

Additional data collection consisted of cotton height (cm), total nodes, and nodes above white flower at first bloom (~60 d after planting); as well as cotton height (cm), total nodes, nodes above cracked boll, and node of first fruiting branch immediately prior to application of the harvest aid. All data were collected from five randomly selected plants per plot. Seed cotton yield was determined by harvesting rows 5, 6, 11, and 12 with a John Deere 9900 two-row spindle picker modified for small plot research. Yields were adjusted to kg ha^{-1} and turnout was determined from each harvested sample using a 10-saw Continental Eagle laboratory gin (Continental Eagle Corp., Prattville, AL). Gin turnout was determined by dividing the mass of lint after ginning by the mass of seed cotton prior to ginning and multiplying by 100. Twenty grams of lint were sent to the Louisiana State University Fiber Quality Laboratory where fiber quality was determined using high volume instrumentation (HVI) (Sasser, 1981).

Data Analysis. Tarnished plant bug densities were analyzed using analysis of variance (PROC GLIMMIX, SAS version 9.4, SAS Institute Inc., Cary, NC) and regression analysis (PROC GLM, SAS version 9.4). In the analysis of variance, N fertilizer application rate, spray treatment (or lack thereof), sample date, and their interactions were considered fixed effects in the model. Replication, replication by spray treatment nested in environment, and replication by spray treatment by sample data nested in environment were considered random effects in the model. In the regression analysis, the independent variable was sample week and the dependent variable was tarnished plant bug number. This analysis was performed to determine the effect of N fertilizer application rate on the relative population of tarnished plant bug over time in an unsprayed situation. All other data were analyzed using analysis of variance (PROC GLIMMIX, SAS version 9.4). Means were separated using Fisher's protected LSD ($p \leq 0.05$). Degrees of freedom were calculated using the Kenward-Roger method. A similar statistical method has been used by researchers using a factorial arrangement of treatments in a randomized complete block design (Bond et al., 2008; Walker et al., 2008).

Economic Analysis. Sample data were used to form distributions of crop yields. Yield data were fit to normal distributions for comparative purposes (data not shown). Just and Weninger (1999) reported that the rejection of normality for crop yields from previous studies was unwarranted. The researchers focused largely on results from Day (1965) related to Mississippi cotton, corn, and oat yields. Just and Weninger (1999) stated that normal distribution assumptions are not unreasonable and offer the benefit of ease of interpretation and communication. Results from Upadhyay and Smith (2005) supported the use of normal crop yield distributions, although cotton was not included in their analysis. Findings from Norwood et al. (2004) found that a semi-parametric approach is optimal for out-of-sample yield forecast but noted that normality was not rejected as a plausible distribution. A risk assessment model using standard deviation was developed utilizing data from these experiments. Mean cotton yield and associated standard deviation as well as mean profit considering fiber quality, lint yield, and number of applications for tarnished plant bug control were determined for each treatment. Fixed cost associated with herbicide application, soil fertility (excluding N fertilizer), labor, and equipment remained constant across treatments. Cost for N fertilizer at rates used in these experiments as well as insecticides for tarnished plant bug control and cost per application were included for each treatment. Risk was measured by either adding or subtracting the standard deviation of lint yield from the mean lint yield. The larger the difference in these values indicates greater risk. Mean variability in profit was determined by evaluating differences in lint yield and variable costs from each replication over years.

RESULTS

Overall, N fertilizer application rate and spray treatment affected tarnished plant bug densities in this trial. There was a significant N fertilizer application rate by spray treatment by sample date interaction (F = 2.06; df = 20, 403; $p < 0.01$) for tarnished plant bug density. Given this interaction as well as the objective of measuring the impact of N fertilizer application rate on tarnished plant bug population estimates, the relationship between tarnished plant bug densities over time was analyzed using regression analysis by spray treatment. Where no insecticide applications were made for tarnished plant bugs, there was a significant N fertilizer application rate by sample date interaction (F = 2.13; df = 20, 197.6; $p < 0.01$). For all N fertilizer application rates, there was a significant quadratic relationship between tarnished plant bug density and sample date (Table 1, Fig. 1). Based on the analysis of variance by spray treatment and sample date, N fertilizer application at any rate significantly increased tarnished plant bug density during weeks five (F = 4.57; df = 4, 24.4; $p < 0.01$) and six (F = 3.17; df = 4, 24.4; $p < 0.01$) of sampling (Fig. 1). In the sprayed environment, there was a significant spray treatment by sample date interaction (F = 2.20; df = 20, 203.2; $p < 0.01$). For all N fertilizer application rates except 45 kg N ha^{-1}, there was a significant quadratic relationship between tarnished plant bug density and sample date (Table 1, Fig. 2). Similar to the unsprayed environment, N fertilizer application rate significantly impacted tarnished plant bug density during weeks five (F = 3.20; df = 4, 35; $p = 0.02$) and six (F = 5.67; df =4, 68; $p < 0.01$) of sampling. Nitrogen fertilizer applied at 179 kg N ha^{-1} resulted in cotton with greater infestation of tarnished plant bugs than all other N fertilizer application rates during week five. Nitrogen fertilizer applied at 45 kg N ha^{-1} resulted in greater tarnished plant bug infestation compared to infestation levels following application of all other N fertilizer rates during week six (Fig. 2). Data for number of insecticide applications required for tarnished plant bug control following various N fertilizer application rates were not analyzed with analysis of variance as insecticide applications were made based on the average number of tarnished plant bugs across all four replications within a year. As a result, the only variability in the number of insecticide applications occurred between the two years of the study, which is not sufficient for analysis of variance. However, linear regression was performed to demonstrate observed trends. There was a significant positive relationship between N fertilizer application rate and number of insecticide applications required for tarnished plant bug management ($r^2 = 0.49$; $F = 7.62$; df = 1, 8; $p = 0.02$). The mean (SEM) number of insecticide applications over the two years was 2.5 (0.5), 3.5 (0.5), 3.0 (1.0), 4.0 (1.0), and 5.0 (0.0) following N fertilizer application rates of 0, 45, 90, 134, and 179 kg N ha^{-1}, respectively.

Table 1. Regression analysis for tarnished plant bug population estimates at five N fertilizer application rates across six sample dates in unsprayed and sprayed cotton averaged across 2013 and 2014 in Stoneville, MS

Unsprayed					
	Nitrogen Fertilizer Application Rate (kg N ha^{-1})				
	0	**45**	**90**	**134**	**179**
Intercept	**-11.1**	**-20.6**	**-15.9**	**-16.5**	**-20.6**
Slope	**14.2**	**20.4**	**17.7**	**18.1**	**20.6**
Quadratic	**-1.9**	**-2.4**	**-2.1**	**-2.1**	**-2.4**
R-Squared	**0.34**	**0.30**	**0.21**	**0.27**	**0.24**
***P* > F**	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**
Sprayed					
	Nitrogen Fertilizer Application Rate (kg N ha^{-1})				
	0	**45**	**90**	**134**	**179**
Intercept	**-1.4**	**-0.9**	**-5.0**	**-3.5**	**-4.0**
Slope	**3.4**	**2.8**	**6.6**	**5.7**	**6.0**
Quadratic	**-0.5**	**-0.3**	**-0.9**	**-0.8**	**-0.8**
R-Squared	**0.19**	**0.08**	**0.21**	**0.33**	**0.20**
***P* > F**	**< 0.01**	**0.10**	**< 0.01**	**< 0.01**	**< 0.01**

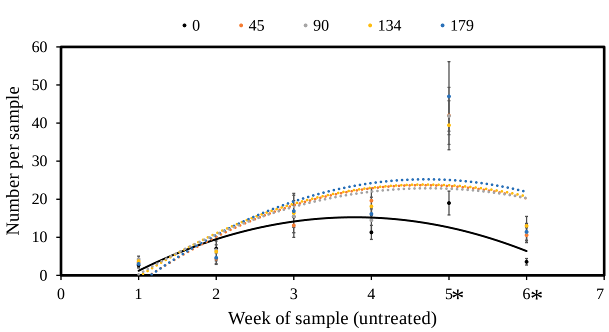

Figure 1. Relationship between tarnished plant bug numbers per sample (3.0 m of row) and week of sample in unsprayed cotton. Points on the graph represent mean (SEM) numbers of tarnished plant bugs per sample using a black drop cloth. Asterisks represent sample dates when a significant difference was observed between N fertilizer application rates (cotton with no N fertilizer applied had fewer tarnished plant bugs than cotton where any rate of N fertilizer was applied).

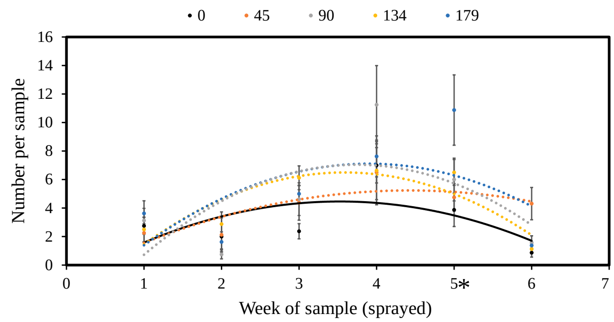

Figure 2. Relationship between tarnished plant bug numbers per sample (3.0 m of row) and week of sample in sprayed cotton. Points on the graph represent mean (SEM) numbers of tarnished plant bugs per sample using a black drop cloth. Asterisks represent sample dates when a significant difference was observed between N fertilizer rates (cotton with N fertilizer applied at 179 kg N ha^{-1} had more tarnished plant bugs than all other treatments during the fifth week of sample and cotton with N fertilizer applied at 45 kg N ha^{-1} had more tarnished plant bugs than all other treatments during the sixth week of sample).

Cotton height at first square and first bloom, number of main stem nodes at first square and first bloom, first fruiting branch, and nodes above cracked boll were not affected by N fertilizer, insecticide applications or their interactions in this study ($p > 0.05$). There was a significant interaction between N fertilizer application rate and spray treatment ($F = 3.34$; df = 4, 69.1; $p = 0.02$) on nodes above white flower. Cotton where tarnished plant bug was not managed using insecticides and where 134 kg N fertilizer ha^{-1} was applied had a greater number of nodes above white flower at first bloom than all other unsprayed treatments as well as sprayed treatments receiving 45 and 134 kg N fertilizer ha^{-1} (Table 2). Similarly, there was a significant interaction between N fertilizer application rate and spray treatment ($F = 3.06$; df = 4, 57.7; $p = 0.02$) on cotton height at the end of the season. Cotton was tallest at the end of the season when tarnished plant bug populations were not managed with insecticides and 90, 134, and 179 kg N fertilizer ha^{-1} was applied with heights ranging from 109 to 111 cm (Table 2). Where tarnished plant bugs were managed with insecticide applications based on thresholds, no differences in end of season cotton heights were present due to N fertilizer application rate and ranged from 88 to 99 cm. The main effects of N fertilizer application rate ($F = 14.24$; df = 4, 62.1; $p < 0.01$) and spray treatment ($F = 10.14$; df = 1, 62.1; $p < 0.01$) were significant for end of season number of main stem nodes, but the interaction of N fertilizer application rate and spray treatment was not significant ($F = 0.85$; df = 4, 62.1; $p = 0.50$). Cotton receiving at least 134 kg N fertilizer ha^{-1} had more mainstem nodes compared to cotton that received 0 or 45 kg N fertilizer ha^{-1} (Table 3). Cotton where tarnished plant bug was managed using insecticides produced fewer nodes compared to cotton that was not managed for tarnished plant bug with insecticides (Table 3).

Table 2. Effect of N fertilizer application rate and the presence/absence of insecticide applications for tarnished plant bug management on nodes above white flower (No.) at bloom in cotton and plant height (cm) at the end of the growing season averaged across 2013 and 2014 in Stoneville, MS

N Application Rate kg N ha^{-1}	NAWF[z] Mean (SEM)[y]	End of Season Height Mean (SEM)[y]
	No Insecticides	
0	6.3 (0.5) c	84 (4) c
45	6.9 (0.4) bc	98 (5) b
90	7.0 (0.6) bc	111 (3) a
134	8.5 (0.6) a	109 (3) a
179	6.9 (0.4) bc	110 (7) a
	Insecticides Applied	
0	7.6 (0.5) ab	88 (4) bc
45	7.1 (0.6) bc	99 (2) b
90	7.4 (0.3) abc	96 (3) b
134	6.9 (0.5) bc	96 (4) b
179	7.6 (0.6) ab	97 (4) b

[z] Nodes Above White Flower

[y] Means within a column followed by the same letter are not significantly different (α = 0.05).

Table 3. Effect of N fertilizer application rate and tarnished plant bug management on number of cotton nodes at the end of the season averaged across 2013 and 2014 in Stoneville, MS

N Application Rate (kg N ha^{-1})	End of Season Mainstem Nodes Mean No. (SEM)[z]
0	17.3 (0.4) d
45	19.1 (0.4) c
90	19.8 (0.4) bc
134	21.1 (0.5) a
179	20.5 (0.5) ab
Insecticide Treatment	
Sprayed	19.0 (0.3) b
Unsprayed	20.2 (0.4) a

[z] Means within a column and within N application rates and spray treatment followed by the same letter are not significantly different (α = 0.05).

A significant N fertilizer application rate by spray treatment interaction ($F = 2.52$; df = 4, 34.5; $p = 0.05$) was present for cotton yield. Cotton lint yields were greater where any rate of N fertilizer was applied and tarnished plant bug was managed with insecticides compared to where N fertilizer was not applied and tarnished plant bug was managed with insecticides as well as when tarnished plant bugs were not managed with insecticides, regardless of N fertilizer application rate (Fig. 3). Nitrogen fertilizer application rate and insecticide applications for tarnished plant bug (or lack thereof) for tarnished plant bug control did not affect lint turnout or any fiber quality parameters.

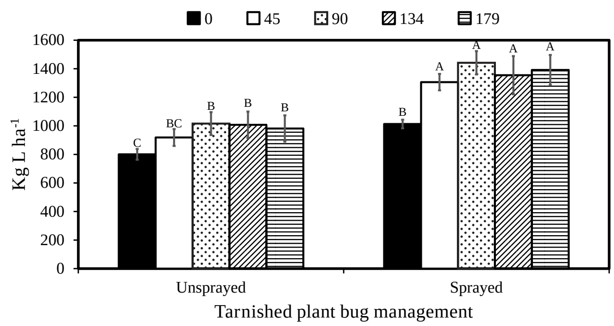

Figure 3. Effect of the interaction between N fertilizer application rate and insecticide applications for tarnished plant bug management on cotton lint yields.

Mean economic gains of \$969.50 ha^{-1} and \$1851.76 ha^{-1} above variable costs were maximized when 90 kg N fertilizer ha^{-1} was applied at pinhead square when tarnished plant bugs were not managed using insecticides and were managed with insecticides, respectively (Table 4). The greatest mean economic gain for cotton that was not managed for tarnished plant bugs (\$969.50 ha^{-1}) was only as high as that of cotton that did not receive any supplemental N fertilizer at pinhead squares but was managed for tarnished plant bugs using insecticides (\$993.05 ha^{-1}). When adding and subtracting the standard deviation of the profit, a summary of risk can be determined for each treatment. For cotton that was not managed for tarnished plant bug using insecticides, the standard deviation of cotton lint yield was greatest for treatments receiving no supplemental N fertilizer at pinhead square. With the exception of this treatment, lint yield standard deviation generally increased as the application rate of N fertilizer increased, before plateauing followed by a small decline. The standard deviation of mean lint yield for cotton receiving 45, 90, 134, and 179 kg N ha^{-1} was 188, 254, 294, and 292 kg ha^{-1}, respectively (Table 4). Similarly, standard deviation of mean cotton lint yield increased with each increase in N fertilizer rate applied to cotton that was managed for tarnished plant bug based on thresholds with the highest rate of supplemental N fertilizer resulting in a decreased standard deviation (a plateau then declined as with no tarnished plant bug management). Cotton that was managed for tarnished plant bug using insecticides following application of 134 and 179 kg N fertilizer ha^{-1} resulted in a larger mean lint yield standard deviation, 424 kg ha^{-1} and 333 kg ha^{-1}, respectively, when compared to lower N fertilizer application rates where tarnished plant bug was managed with insecticides (183 kg ha^{-1} and 259 kg ha^{-1}) (Table 4). For cotton managed for tarnished plant bug, profit risk was minimized when no supplemental N fertilizer was applied at pinhead square, when measured using the coefficient of variation (standard deviation divided by mean) (Table 4). However, this treatment produced the lowest mean yield and mean profit. Based on the standard deviation, there is potential for cotton receiving > 90 kg N fertilizer ha^{-1} to outperform cotton receiving 90 kg N fertilizer ha^{-1}; however, cotton grown using > 90 kg N fertilizer ha^{-1} is subject to greater risk. Cotton managed for tarnished plant bug and grown with 134 kg N fertilizer applied ha^{-1} resulted in greatest risk, considering coefficient of variation, when compared to cotton that received 90 kg N ha^{-1} (Table 4). The coefficient of variation indicates smaller dispersion for all sprayed treatments compared to the non-sprayed treatments (Table 4).

DISCUSSION

In general, tarnished plant bug density and management was impacted by N fertilizer use in cotton. During the fifth and sixth weeks of flowering where cotton was not treated with insecticides, tarnished plant bug populations were greater where any rate of N fertilizer was applied compared with plots where no N fertilizer was applied. This was not unexpected as previous research has shown that tarnished plant bug is attracted to more vigorously growing cotton compared to stressed cotton (Willers et al., 1999). The fifth and sixth weeks of flowering corresponded to the late flowering period when cotton plants would still have a high demand for nutrients and the effects of N deficiency would likely be expressed at their greatest levels (Bouquet, 2005; Clawson et al., 2006; Main et al., 2013; Varco et al., 1999). Nitrogen deficiency was evident based on cotton height, mainstem node counts, and visual symptomology at the end of the season relative to earlier in the season. Cotton where no N fertilizer was applied was generally shorter and had fewer main stem nodes at the end of the season compared to cotton that received any rate N fertilizer. Similar observations were made by Main et al. (2013). Reduced cotton height and mainstem node counts were not observed at first square or first bloom in the current study when tarnished plant bug numbers were similar across N rates. More insecticide applications were needed to manage tarnished plant bugs, based on

Table 4. Analysis of economic gains above variable costs with associated standard deviations for risk analysis based on mean yield values across both years of study

Nitrogen App. Rate	Sprayed	Mean Lint Yield	Standard Deviation of Lint Yield	Mean Lint Yield -Std. Dev.	Mean Lint Yield + Std. Dev.	Mean Profit	Standard Deviation of Profit	Mean Profit -Std. Dev.	Mean Profit + Std. Dev.	Variability in Profit[z]	Coefficient of Variation[y]
-- kg ha^{-1} --	------	-- kg ha^{-1} --	-- kg ha^{-1} --	-- kg ha^{-1} --	-- kg ha^{-1} --	--- \$ ha^{-1} ---	--- \$ ha^{-1} ---	--- \$ ha^{-1} ---	--- \$ ha^{-1} ---	--- \$ ha^{-1} ---	----- % -----
0	No	785	334	451	1119	602.98	240.93	362.05	843.91	481.86	0.3996
45	No	1029	188	841	1217	810.74	404.89	405.84	1215.64	809.80	0.1661
90	No	1138	254	884	1392	969.50	549.12	420.38	1518.62	1098.24	0.5664
134	No	1129	294	835	1423	871.77	634.51	237.26	1506.28	1269.02	0.7278
179	No	1099	292	807	1391	731.28	629.37	101.91	1360.65	1258.74	0.8606
0	Yes	1135	96	1039	1231	993.05	227.45	765.60	1220.50	454.90	0.2290
45	Yes	1464	183	1281	1647	1576.04	413.19	1162.84	1989.24	826.40	0.2622
90	Yes	1616	259	1357	1875	1851.76	602.98	1248.78	2454.74	1205.96	0.3256
134	Yes	1517	424	1093	1941	1514.38	963.57	550.81	2477.95	1927.14	0.6363
179	Yes	1559	333	1226	1892	1501.19	743.37	757.82	2244.56	1486.74	0.4952

[z] Variability in profit was determined by evaluating differences in lint yield and variable costs (i.e., insecticide costs, nitrogen fertilizer cost) from each replication over years.

[y] Coefficient of Variation is measured as standard deviation divided by mean.

current treatment thresholds, where more N fertilizer was applied further supporting the conclusion that N fertilizer rate impacted tarnished plant bug density in cotton and supporting the previous conclusions by Willers et al. (1999).

Cotton height at the end of the season was also impacted by tarnished plant bug. Generally, cotton that was treated with insecticides when tarnished plant bug populations exceeded economic thresholds was significantly shorter than cotton that was not treated for tarnished plant bug. Holman and Oosterhuis (1999) also observed that cotton that had not been sprayed for tarnished plant bug early in the growing season was taller than cotton that was managed for tarnished plant bug. This increased height was likely the result of higher levels of square and boll loss caused by tarnished plant bug feeding, resulting in more N being allocated toward continued plant growth rather than boll maturation. Cook and Kennedy (2000) observed up to a 12% increase in cotton height when 40% of the floral buds were hand removed 10 to 14 days after the first floral bud had emerged. Samples et al. (2015) observed a significant increase in cotton height at the end of the season when 50% of the floral buds and fruiting structures were removed at first bloom. Pettigrew et al. (1992) also observed that when floral buds were removed cotton height was increased.

Where cotton was managed for tarnished plant bugs using insecticides, lint yields were maximized when 45 kg N fertilizer ha^{-1} was applied. Cotton yield did not significantly improve when > 45 kg N fertilizer ha^{-1} was applied. In contrast, previous research has shown that cotton yields were not maximized until at least 90 kg N fertilizer ha^{-1} was applied (Main et al. 2013; McConnell et al., 2000;Varco et al., 1999). Differences between these studies could be attributed to numerous factors; however, different soil texture could partially explain the differences observed. Regardless of the specific N fertilizer application rate, these data suggest that growers could reduce N fertilizer application rates to at least 90 kg N fertilizer ha^{-1} without risking substantial yield loss. Compared with higher N fertilizer rates, this would also reduce the number of sprays required for tarnished plant bug management. Considering N fertilizer and tarnished plant bug management cost relative to yield in the overall economic analysis, these data suggest that growers can optimize yields and economic gains as well as reduce risk by applying no more than 90 kg N fertilizer ha^{-1}. On soils with greater clay content (heavier soils), proportionally greater rates of N fertilizer might be needed to maximize yields and economic gains (Benson et al., 1998; Clawson et al., 2006; Constable and Rochester, 1988).

Numerous cultural practices such as planting date and varietal maturity (Adams et al., 2013), pubescence (Wood et al., 2017), and irrigation (Wood et al., 2018) have been shown to reduce the impact of tarnished plant bug and the number of insecticide sprays targeting this pest in cotton. These data suggest that applying excessive N fertilizer increases the need for insecticide applications to manage infestations of tarnished plant bug. Eliminating excessive N fertilizer applications combined with other cultural practices should improve integrated pest management and reduce the reliance on foliar insecticide applications. Growers following these recommendations could make cotton production more profitable and reduce negative environmental effects associated with higher N fertilizer application rates and more foliar insecticide applications.

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