Field Evaluation of Biological and Conventional Insecticides for Managing Multiple Insect Pests in Cotton[1]

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Abstract Cotton, *Gossypium hirsutum* (L.), is an economically important crop in the United States that is plagued by a complex of insect pests. Two key pests of cotton in the midsouthern United States are the tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois) (Hemiptera: Miridae), and bollworm, *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae). A suite of highly effective synthetic insecticides is typically used for control of these pests. However, it is unclear how the combined management of these two insect pests with biological insecticides impacts the economics of cotton production. To address this shortcoming, we conducted a field experiment in the Mississippi Delta over 2 yr to study the effects of synthetic and biological insecticides for control of the tarnished plant bug and bollworm on cotton yield. The results indicated the control of tarnished plant bug with synthetic insecticides had the most significant impact on cotton yield and net returns. The conventional tarnished plant bug treatment also significantly increased bollworm density and damage, but these increases did not significantly alter yield or net return in non–*Bacillus thuringiensis* (Bt) or Bt cottons. The economic benefit of a conventional approach to tarnished plant bug control with synthetic insecticides was US$438.07/ha in non-Bt and $700.88/ha in Bt cotton relative to those treated with a biological insecticide. The biological insecticides used for this study were ineffective at significantly altering yield or net return. However, for insect management in cotton to be sustainable, alternatives must be found to complement conventional synthetic insecticides.

Key Words tarnished plant bug, bollworm, insecticide resistance, integrated pest management, biological insecticides

Worldwide production of cotton, *Gossypium hirsutum* (L.), has been estimated to have an economic impact of at least US$600 billion annually (Khan et al. 2020). In the United States, hemipteran and lepidopteran insect pests account for the majority of input costs in cotton production. The tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois) (Hemiptera: Miridae), and bollworm, *Helicoverpa zea* (Boddie) (Lepidoptera: Noctuidae), are the two major pests of cotton in the midsouthern United States. Management of tarnished plant bug in cotton generally relies on a rotation of broad-spectrum synthetic insecticides. Current bollworm management in transgenic cotton relies heavily on protection provided by toxins of the soil bacterium *Bacillus thuringiensis* (Berliner) (Bt). Synthetic insecticides are used on an ad hoc basis in transgenic cotton

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when Bt toxins fail to adequately control bollworm (Little et al. 2017a). In Mississippi, average control costs for tarnished plant bug approached US$200/ha between 2012 and 2014, whereas additional bollworm control costs above the price of transgenic Bt traits were nearly US$30/ha during the same period (Williams 2012, 2013, 2014). The tarnished plant bug is known to develop tolerance to synthetic insecticides following extended periods of exposure (Cleveland 1985, Cleveland and Furr 1979, Snodgrass 1996, Snodgrass and Elzen 1994). Extensive use of synthetic insecticides can lead to declining efficacy for control of many economically important insect pests in cotton (Sparks 1981). Using biological insecticides as a part of an overall integrated pest management (IPM) program in cotton may offer a way to slow the development of resistance to synthetic insecticides while promoting environmental benefits and preserving yield.

Beauveria bassiana (Balsamo) (Ascomycetes: Hypocreales) is an entomopathogenic fungus that has been previously recognized as a prospective candidate for biological control of the tarnished plant bug (Bidochka et al. 1993, Kouassi et al. 2003, Leland et al. 2005, Portilla et al. 2018, Sabbahi et al. 2008). Sprayable products containing *B. bassiana* have been commercially available for decades (Feng et al. 1994, Ferron 1978). However, applications of *B. bassiana* in production crop settings for control of the tarnished plant bug have been largely unsuccessful (Kouassi et al. 2003, Kovach and English-Loeb 1996, Snodgrass and Elzen 1994, Steinkrauss and Tugwell 1997). Numerous environmental factors (e.g., relative humidity, ultraviolet light, temperature) can negatively affect fungal proliferation and subsequent insect infection (Sabbahi et al. 2008). The strain NI8 of *B. bassiana*, isolated from tarnished plant bugs in Mississippi Delta region in 2002, has shown promising results (Leland and Snodgrass 2005). This strain has exhibited characteristics that make it favorable as a potential biological control agent for tarnished plant bug in the Mississippi Delta (e.g., high sporulation rate, highly entomopathogenic, lower concentrations needed relative to other commercially available strains) (Leland 2005, Leland and Snodgrass 2005, Leland et al. 2005, McGuire et al. 2006, Portilla et al. 2014, Ugine 2012).

Baculoviruses (nuclear polyhedrosis viruses [NPVs]) have been labeled in the United States for control of bollworms in cotton since the 1970s (Little et al. 2019). Newer products have been developed from different viral isolates of other *Helicoverpa* spp. and are now marketed for control of bollworms in various agricultural crops. Commercially available baculovirus formulations have proven economically effective in soybean, *Glycine max* L., in the midsouthern United States (Black et al. 2022). Baculoviruses can be highly effective for control of bollworms in small grains if applied when larvae are small, and the polyhedra are ingested (Black et al. 2022). However, their effectiveness for bollworm control in cotton has been inconsistent (Little et al. 2017b). This is likely due to the rapid degradation of NPVs in the environment and their high host specificity.

We conducted a field study across 2 yr to assess the potential for using biological insecticides as part of a holistic IPM strategy in cotton for two major insect pests. Cotton lint yield, insect density, damage to fruiting structures, and net returns above treatment costs were used to evaluate the potential of biological insecticides for economically controlling tarnished plant bugs and bollworms in cotton. Knowledge gained from this study should improve the potential for integrating biological insecticides into current insect management strategies.

Table 1. Application dates, insecticides, and rates for conventional tarnished plant bug treatments in 2015 and 2016.

Year	Application Date	Conventional Insecticide	Rate(s)
2015	17 June	Imidacloprid	146.2 ml/ha
	24 June	Imidacloprid	146.2 ml/ha
	3 July	Sulfloxaflor + Novaluron	157.6 g/ha + 511.5 ml/ha
	14 July	Acephate	1.12 kg/ha
	26 July	Sulfloxaflor	157.6 g/ha
2016	23 June	Imidacloprid	146.2 ml/ha
	20 July	Sulfloxaflor + Novaluron	157.6 g/ha + 511.5 ml/ha
	27 July	Sulfloxaflor	157.6 g/ha
	9 August	Acephate	1.12 kg/ha

Materials and Methods

Effects of two different biological insecticides and a suite of synthetic insecticides on bollworm and tarnished plant bug control were evaluated in Bt and non-Bt cotton cultivars in 2015 and 2016 on the Southern Insect Management Research Unit (SIMRU) research farm near Stoneville, MS. The experiment was laid out in a strip-split-plot within a randomized complete block design with three replications. Each strip consisted of 24 rows (101.6 cm in width) approximately 246 m in length, separated by four rows of corn (DEKALB® DKC68-24RR2®, Monsanto Company™, St. Louis, MO). Each 24-row strip was divided into three 80.7-m-long plots via 2-m alleys. Twelve rows on either side of a given plot were assigned randomly to one of two cotton varieties, either Bollgard II™ (DP1321B2RF®, Delta and Pine Land Company™, Scott, MS) or non-Bt (DP1441RF®, Delta and Pine Land Company), which yielded spit-plots approximately 0.1 ha in size. Ad hoc applications of herbicides and a plant growth regulator (mepiquat chloride, Loveland Products, Inc., Morgantown, KY) were applied equally to all plots within a given year of the study.

Each of the following tarnished plant bug treatments was randomly assigned to strips within each block of the experiment: (a) untreated check, (b) *B. bassiana* strain NI8, or (c) a combination of synthetic insecticides selected from the Mississippi Insect Control Guide (Catchot et al. 2015). Synthetic insecticides selected for tarnished plant bugs included imidacloprid (Wrangler®, Loveland Products, Inc.™, Loveland, CO), sulfloxaflor (Transform WG®, Corteva Agriscience™, Indianapolis, IN), novaluron (Diamond®, Makhteshim Agan of North America™, Raleigh, NC), and acephate (Bracket 97®, Winfield Solutions™, LLC, St. Paul, MN). Application dates for tarnished plant bug treatments, conventional insecticide(s) used, and associated rates are listed in Table 1. Care was taken to select synthetic insecticides with low or no known lepidopteran activity whenever possible. However, novaluron, an insect growth regulator that is known to have some insecticidal activity on bollworm, was used in combination with an adulticide during peak tarnished plant bug adult migration (second treatment application for both 2015 and 2016) to increase efficacy. NI8 (liquid and solid-state fermentation) was produced at the USDA-ARS SIMRU by using a medium-scale biphasic culture system as described by Portilla et al. (2016). Harvested technical powder was assessed for conidia quantification (spores per milliliter) and germination, as in Portilla et al. (2017). Spore powder (250 g) of NI8 was mixed in 3.79 L of water containing 60 ml of Tween 80 (0.04%), giving each application a concentration of 2.5×10^{11} spores/ha. Tarnished plant bugs were sampled weekly with sweep nets (100 sweeps per conventional strip). Treatment applications for tarnished plant bugs were based on thresholds established by the Mississippi Insect Control Guide (Catchot et al. 2015). All treatments were applied once thresholds for tarnished plant bugs were reached in the conventional strips.

Plots within each strip were assigned one of the following treatments randomly for bollworm control: (a) untreated check, (b) a commercially available baculovirus formulation (Heligen®, AgBiTech™, Queensland, Australia) at 175.4 ml/ha, or (c) chlorantraniliprole (Prevathon®, DuPont™, Wilmington, DE] at 1.1 L/ha. One hundred plants (a single terminal, square bloom and boll per plant) within plots were evaluated weekly for bollworm density and damage to fruiting structures. Bollworm treatments were applied to individual plots when larval density and/or plant damage reached thresholds outlined in the Mississippi Insect Control Guide for heliothines (Catchot et al. 2015). All treatments were applied delivering 93.5 L/ha of tankmix with TX-VS8 hollow cone nozzles (TeeJet Technologies, Glendale Heights, IL) at approximately 276 kPa once thresholds were reached.

For statistical analyses, strips (tarnished plant bug treatment: untreated, *B. bassiana*, conventional) functioned as the main unit, which were organized within three blocks. Main units were divided into three plots for bollworm treatments (untreated, NPV, conventional). Plots were split according to cotton type (Bt and non-Bt). This design was repeated over 2 yr in 2015 and 2016. Cotton lint yield was determined with a mechanical harvester on two rows in the center of each split-plot and the weight of seed cotton was recorded. Lint yield for this study was set at 37% of seed cotton weight. A general linear model for a strip-split-plot design was used to analyze yield (R v.4.2.3, R Core Team 2022; lme4 package v1.1-31, Bates et al. 2015; emmeans package v1.8.5, Lenth 2023; multcomp package v 1.4-20, Hothorn et al. 2008). Fixed effect coefficients were fit for tarnished plant bug treatment; bollworm treatment; cotton type; year; and all two-, three-, and four-way interactions. Random intercepts were fit to block nested within year, strip within block, plot within strip, and split-plot within plot. We confirmed that the model residuals and random effects distributions met assumptions of normality and homogeneity by examining diagnostic plots. Least squares means were estimated and compared using paired *t* tests at $\alpha = 0.05$, with the Sidak correction for multiple comparisons when significant fixed effects (tarnished plant bug treatment, bollworm treatment, cotton type, or year) or interactions were encountered. Net returns above treatment control costs, bollworm density, and bollworm damage were compared using a similar model structure as developed for yield. Prices of all insecticides, which were obtained locally, were converted to cost per hectare for each treatment. Relationships among yield, net return above treatment costs, numbers of larvae in plant structures (terminals, squares, blooms, bolls, and total), and numbers of damaged plant structures (squares, bolls, and total) were examined using Pearson's correlation coefficients.

Results

The average number of applications for bollworms in 2015 (2.00 ± 0.23, mean ± SE) was similar to the average reported for the Mississippi Delta for that year of two (Williams 2016). In 2016, the average number of applications (0.58 ± 0.13) was less than the average of two reported for the Mississippi Delta (Williams 2017). The average number of applications for tarnished plant bugs in 2015 of five and 2016 of four were similar to averages reported for the Mississippi Delta of six and five for 2015 and 2016, respectively (Williams 2016, 2017). Across both years of the study, treatment for tarnished plant bug was the only factor to significantly impact cotton lint yield ($F = 27.94$; df = 2, 8; $P < 0.001$). Year was nearly significant ($F = 7.21$; df = 1, 4; $P = 0.055$), with higher yield in 2015 (1,361 ± 36 kg/ha) than 2016 (1,109 ± 47 kg/ha). The effect of tarnished plant bug treatment was different across cotton types with a nearly significant three-way interaction of treatment by cotton type by year for lint yield ($F = 3.21$; df = 2, 36; $P = 0.052$). In 2016, the conventional tarnished plant bug treatment had significantly higher lint yield than the untreated control and *B. bassiana* treatment in both Bt and non-Bt cottons (Table 2). The yield increase relative to the untreated control was greater in Bt (734.4 kg/ha) than non-Bt (512.2 kg/ha) cotton (Table 2). The *B. bassiana* treatment did not significantly alter yield compared with the untreated control in Bt or non-Bt cotton (Table 2). In 2015, there were no significant effects of the *B. bassiana* treatment or cotton-type treatments on lint yield (Table 2). There was no significant effect of bollworm treatment on yield ($F = 0.79$; df = 2, 24; $P = 0.467$) or as part of any interaction for yield ($P \geq 0.160$).

Costs for the tarnished plant bug conventional insecticides, which were obtained from a local supplier and converted to a per hectare basis, were US$4.53, $20.99, $50.43, and $21.99/ha for imidacloprid, acephate, sulfloxaflor, and novaluron, respectively. The estimated cost of *B. bassiana*, which was based on spores per hectare relative to a similar commercially available product, was US$1.06/ha. For bollworm treatments, the cost of chlorantraniliprole was US$36.32/ha, whereas the NPV was US$19.64/ha. The cost of each insecticide application in this study was estimated to be US$15.81/ha (Cotton 2023 Planning Budgets 2022). For this study, the cost of the Bt technology fee in Bollgard II cotton was estimated to be US$50.40/ha (Cotton 2016 Planning Budgets 2015), and the price of lint was set at US$1.76/kg. Results for net returns above insect control costs closely resembled those from lint yield. Across both years of the study, the tarnished plant bug treatment was the only treatment to significantly impact net return ($F = 14.44$; df = 2, 8; $P = 0.002$). Year in which the study was conducted nearly impacted net return above insect control costs ($F = 5.29$; df = 1, 4; $P = 0.083$), with a higher net return in 2015 (2,207 ± 60 US$/ha) than 2016 (1,815 ± 72 US$/ha). In addition, the three-way interaction of tarnished plant bug treatment by cotton type by year nearly had a significant impact on net returns ($F = 3.08$; df = 2, 36; $P = 0.059$). In 2016, the conventional tarnished plant bug treatment had a significantly higher net return compared with the untreated control and the *B. bassiana* treatment in Bt, but not non-Bt cotton (Table 2). The net return increase compared with the untreated control was significantly greater in Bt (US$1,071.30/ha)

Table 2. Mean lint yield of cotton plots and net returns above insect treatment costs by year, cotton type, and tarnished plant bug treatment. Yields and net returns followed by the same letter do not significantly differ ($P \leq 0.05$).

Cotton Type	Lygus Treatment	Lint Yield*	Net Return**
2015			
Bt	Conventional	1,541.4a	2,367.8a
	B. bassiana	1,289.0a	2,108.6a
	Untreated	1,251.1a	2,122.2a
non-Bt	Conventional	1,562.9a	2,417.1a
	B. bassiana	1,317.3a	2,160.1a
	Untreated	1,209.6a	2,064.5a
2016			
Bt	Conventional	1,653.8a	2,623.2a
	B. bassiana	908.2c	1,480.6b
	Untreated	910.4c	1,551.9b
non-Bt	Conventional	1,379.9b	2,172.0b
	B. bassiana	936.2c	1,552.9b
	Untreated	867.7c	1,511.6b
Combined			
Bt	Conventional	1,597.6a	2,495.5a
	B. bassiana	1,098.6b	1,794.6c
	Untreated	1,080.8b	1,837.0bc
non-Bt	Conventional	1,471.4a	2,294.6ab
	B. bassiana	1,126.7b	1,856.5bc
	Untreated	1,038.6b	1,788.0c

* Lint yield (kg/ha) estimated to be 37% of seed cotton.
** Net return ($/ha) above treatment costs.

than non-Bt (US$660.40/ha) cotton (Table 2). *Beauveria bassiana* did not significantly alter net return compared with the untreated control in Bt or non-Bt cottons (Table 2). In 2015, although the conventional tarnished plant bug treatment had the greatest net return in Bt and non-Bt cottons, there were no significant effects of tarnished plant bug, bollworm, or cotton-type treatments on net return. There was some economic benefit from the *B. bassiana* treatment in non-Bt (US$68.40/ha), but a loss of US $42.41/ha in Bt cotton when years were combined. There was no significant effect of bollworm treatment on net return ($F = 0.63$; df $= 2, 24$; $P = 0.540$) or as part of any interaction for net return ($P \geq 0.218$).

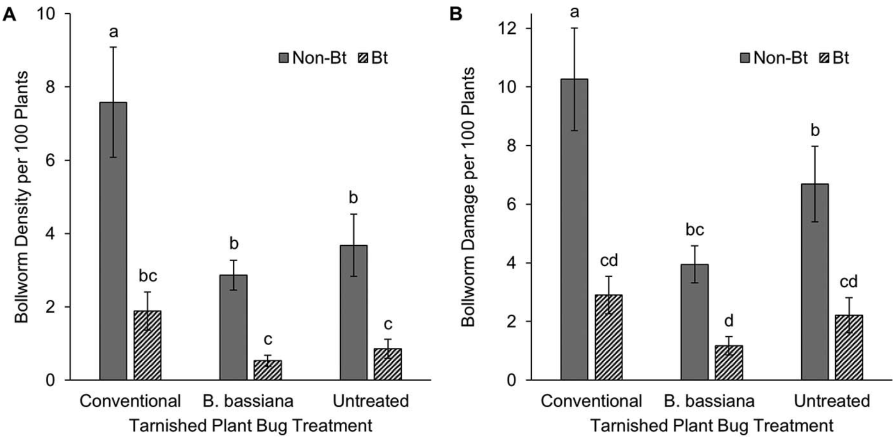

Fig. 1. Mean total bollworm density (A) and total bollworm damage (B) per sampling period per 100 cotton plants by cotton type and tarnished plant bug treatment combined across years. Different letters above bars indicate significant differences between means ($P \leq 0.05$).

Bollworm density and damage measurements, which were recorded every week to determine treatment triggers in each plot, were also significantly impacted by the tarnished plant bug treatment ($F \geq 20.02$; df = 2, 8; $P \leq 0.001$). In non-Bt cotton, the conventional tarnished plant bug treatment had nearly double the bollworm density and damage compared with the untreated control when years were combined (Fig. 1). Bollworm density and damage in the *B. bassiana* treatment were not significantly different from the untreated control (Fig. 1). In Bt cotton, there were no significant differences between tarnished plant bug treatments (Fig. 1). However, bollworm density and damage displayed the same numerical trends as non-Bt cotton with the conventional tarnished plant bug treatment having the greatest and the *B. bassiana* treatment having the least bollworm density and damage. Overall, bollworm density was significantly greater in non-Bt cotton compared with Bt cotton across all tarnished plant bug treatments ($F = 125.67$; df = 1, 36; $P < 0.001$) (Fig. 1). The only exception was the conventional tarnished plant bug treatment in Bt cotton, which was not significantly different from non-Bt cultivar under the *B. bassiana* and untreated tarnished plant bug treatments (Fig. 1). Bollworm density and damage were not strongly correlated (maximum Pearson correlation coefficient [r] = 0.479) within a year or across years with yield or net return in either cotton type, which was consistent with the lack of significant effects from the bollworm treatments on yield and net return (Table 3).

Discussion

Studies focusing on the integrated management of multiple insect pests concurrently infesting cotton are generally lacking. Because of IPM strategies being heavily focused on the control of a single pest species, transitioning to approaches for multiple pests concurrently infesting cotton remains a challenge (Brewer and Goodell 2012, Kogan 1998, Luttrell et al. 2015). Management of tarnished plant bug in cotton can be

Table 3. Pearson correlation coefficients (r) and significance (*P*) of bollworm density and damage to cotton yield and net return above treatment cost by year.

	Non-Bt				Bt			
	Yield*		Net Return**		Yield*		Net Return**	
	r	*P*	r	*P*	r	*P*	r	*P*
2015								
Larvae/100 terminals	0.007	0.974	−0.019	0.923	−0.347	0.076	−0.426	0.027†
Larvae/100 squares	0.258	0.194	0.201	0.315	0.233	0.243	0.158	0.432
Larvae/100 bolls	−0.003	0.989	−0.080	0.692	0.205	0.306	0.164	0.414
Larvae/100 blooms	0.132	0.513	0.048	0.811	0.101	0.615	0.093	0.643
Total larvae/100 plants	0.179	0.371	0.101	0.617	0.097	0.632	0.004	0.985
Damage/100 squares	0.158	0.432	0.141	0.483	0.233	0.243	0.229	0.250
Damage/100 bolls	0.105	0.602	0.049	0.807	0.065	0.748	0.010	0.961
Total damage/100 plants	0.152	0.450	0.119	0.556	0.252	0.205	0.238	0.232
2016								
Larvae/100 terminals	0.381	0.050†	0.379	0.051	0.468	0.014†	0.479	0.011†
Larvae/100 squares	0.183	0.360	0.189	0.345	−0.048	0.813	−0.063	0.753
Larvae/100 bolls	0.140	0.485	0.101	0.618	−0.015	0.941	−0.048	0.812
Larvae/100 blooms	0.230	0.249	0.167	0.406	0.374	0.054	0.343	0.079
Total larvae/100 plants	0.373	0.055	0.324	0.099	0.435	0.023†	0.405	0.036†
Damage/100 squares	0.453	0.018†	0.421	0.029†	0.312	0.113	0.302	0.126

Table 3. Continued.

	Non-Bt				Bt			
	Yield*		Net Return**		Yield*		Net Return**	
	r	*P*	r	*P*	r	*P*	r	*P*
Damage/100 bolls	0.146	0.467	0.113	0.576	0.300	0.129	0.261	0.188
Total damage/100 plants	0.446	0.020†	0.405	0.036†	0.351	0.073	0.331	0.092
Combined								
Larvae/100 terminals	0.269	0.049†	0.253	0.065	0.010	0.944	−0.042	0.765
Larvae/100 squares	0.428	0.001†	0.403	0.003†	0.238	0.083	0.201	0.145
Larvae/100 bolls	0.124	0.371	0.071	0.612	0.170	0.219	0.146	0.292
Larvae/100 blooms	0.239	0.082	0.176	0.203	0.265	0.052	0.248	0.071
Total larvae/100 plants	0.389	0.004†	0.343	0.011†	0.271	0.047†	0.219	0.112
Damage/100 squares	0.424	0.001†	0.408	0.002†	0.340	0.012†	0.338	0.013†
Damage/100 bolls	0.225	0.102	0.188	0.173	0.215	0.119	0.171	0.216
Total damage/100 plants	0.394	0.003†	0.369	0.006†	0.367	0.006†	0.358	0.008†

* Lint yield estimated to be 37% of seed cotton.
** Net return above treatment costs.
† Dagger indicates significant correlation ($P \leq 0.05$).

economically challenging given their ability to develop tolerance to chemical control measures (Snodgrass 1996, Snodgrass and Scott 2000, Snodgrass et al. 2009). Likewise, bollworms, which have a propensity for developing tolerance to insecticides, remain a major lepidopteran pest of cotton (Luttrell and Jackson 2012). However, given their well-documented negative impact on cotton yield, managing these two insect pests is paramount to profitable cotton production in the midsouthern United States. Current IPM strategies have relied heavily on a rotation of synthetic insecticides as the primary means of controlling these two pests in cotton. Using alternative control measures may reduce selection pressure for resistance to synthetic insecticides while maintaining high net return for producers.

Lint yield is the standard for evaluating *Lygus* damage to cotton (Barkley and Ellsworth 2004). In our study, the conventional tarnished plant bug treatment, which consisted of a rotation of synthetic insecticides, was the only treatment that demonstrated its utility by maximizing yield and net return. Our study confirms the economic benefits of the conventional approach for tarnished plant bug management in cotton. Another effect of the conventional tarnished plant bug treatment was increased bollworm density and damage. These insecticides have been shown to have a negative impact on natural enemy populations (Bacci et al. 2007, Croft and Whalon 1982, Ruberson and Tillman 1999, Tillman 1995, Wilkinson et al. 1979), which may have allowed bollworm densities to increase. In our experiment, we experienced low bollworm pressure in untreated non-Bt control plots, as indicated by the number of application triggers in our study, which was lower than the average for the Mississippi Delta. If the effects of the conventional tarnished plant bug treatment on bollworm density and damage remain consistent during higher bollworm pressure, the synthetic insecticides associated with conventional tarnished plant bug management could increase the impact of bollworm in cotton.

Biological insecticides have the benefits of reduced selection pressure for insecticide resistance and environmental impact, conservation of natural enemies and pollinators, and decreased costs relative to their synthetic counterparts. Although the biological insecticides utilized in this study did not significantly increase yield, they did not negatively impact net return. NI8 has been shown to be effective in the laboratory, with mixed results in the field (Portilla et al. 2017, 2018). The lack of efficacy of the *B. bassiana* treatment may be partially explained by the spore rate applied in our experiment, which was lower than commercial *B. bassiana* products, as these were shown to have similar efficacy in the field (Portilla et al. 2018). Biologicals are not necessarily expected to have the same acute mortality as conventional synthetic insecticides, but their ability to suppress pest populations over time and low cost was expected to have a more substantial impact on yield and net return. Cotton also has unique challenges for biological insecticides, including high pest pressure, environmental conditions within the canopy, and pH of the leaf surface (Lacey et al. 2001, Padmavathi et al. 2003). Although biological control of tarnished plant bug with NI8 did not impact yield or net return in this study, alternatives to synthetic insecticides may still be needed in the future due to the development of resistance. A new transgenic cotton (ThryvOn, Bayer CropScience, St. Louis, MO), which targets control of tarnished plant bug and thrips, may facilitate a reduction in synthetic insecticide applications (Mann et al. 2022).

Holistic management of insect pests in cotton is still a challenge. Future research should focus on the integration of multiple strategies for multiple pests, adopting biological insecticides whenever feasible. Future research on the integration of biologicals should concentrate on improving efficacy through the timing of applications, synergism with synthetics, and incorporation into traditional management thresholds. Despite some limitations, biologicals offer a practical step towards sustainable IPM in cotton.

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