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ARTHROPOD MANAGEMENT & APPLIED ECOLOGY

Evaluating Efficacy and Chemical Concentrations of Commonly Used Insecticides Targeting Tarnished Plant Bug in Mid-South Cotton

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ABSTRACT

Studies were conducted from 2017 to 2021 at nine locations across Arkansas, Louisiana, Mississippi, and Tennessee to evaluate efficacy, residual control, and effective chemical concentrations of commonly used insecticides targeting tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois), nymphs in Mid-South cotton. Foliar applications of imidacloprid, flonicamid, thiamethoxam, oxamyl, dicrotophos, acephate, novaluron, and sulfoxaflor were applied at locally recommended rates. Plots were sampled for nymphs at 4, 7, and 10 d after treatments (DAT), and leaves were analyzed for concentration of active ingredients from plots located in one site in 2021 at 4, 7, 10, and 14 DAT. Across all sampling dates, insecticide treatments reduced nymph infestations compared to untreated control, except for imidacloprid at 10 DAT. All insecticide treatments resulted in higher lint yields compared to untreated control. Overall, sulfoxaflor, novaluron, and acephate offered the best control of nymphs and provided the greatest yield protection among treatments. Moderate control was achieved with thiamethoxam, oxamyl, and dicrotophos. Imidacloprid and flonicamid resulted in less control. Concentrations of flonicamid, thiamethoxam, dicrotophos, acephate, and novaluron persisted up to 14 DAT in leaves. Imidacloprid and oxamyl were not detected at 7, 10, or 14 DAT, and sulfoxaflor was not detected at 14 DAT in leaves. In these studies, control of tarnished plant bug nymphs never exceeded 75% regardless of insecticide or sampling date. The moderate efficacy and short residual control shown in these studies explain why multiple insecticide applications within short intervals are needed to manage heavy tarnished plant bug populations.

Tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois), has been the most destructive insect pest of Mid-South cotton for several years (Cook and Threet, 2021). Management of this pest is essential in all midsouthern cotton producing states. Tarnished plant bugs can appear as early as cotton plants emerge, but most economic damage occurs from first square to early flowering stages (Scales and Furr, 1968). Squares (flower buds) are preferred feeding tissues of this destructive pest; however, tarnished plant bugs can feed on terminals or small bolls (Layton, 1995). Feeding by tarnished plant bug on young squares typically causes abscission, which can cause direct yield loss that is variable depending on year and location (Pack and Tugwell, 1976). Feeding on older squares can also cause abscission, but generally these squares remain attached to the plant (Pack and Tugwell, 1976). If abscission does not occur, the injury can result in malformed flowers, termed "dirty blooms," that might not pollinate properly. Little to no yield penalty is attributed to the malformed flowers until 30% of anthers are harmed (Pack and Tugwell, 1976). Feeding of older squares or young bolls can result in shed or malformed bolls, which can also cause yield loss (Pack and Tugwell, 1976).

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In the Mid-South, tarnished plant bug thresholds change according to the growth stage of cotton. Tarnished plant bug populations tend to move into cotton at the onset of squaring. Because squares are the preferred feeding site for this pest, to maintain early fruit set pest thresholds tend to be more aggressive; as fruiting structures increase over time thresholds subsequently become more relaxed (Catchot et al., 2009; Crow et al., 2021; George et al., 2021; Musser et al., 2009b). In addition to pest thresholds, sampling methods vary based on cotton's developmental stages. During the pre-flowering stage, a sweep net is recommended because adults are usually more common (Musser et al., 2009a). Nymphs are predominantly found during flowering stages of cotton development, so a drop cloth is the most efficient sampling technique (Musser et al., 2009a). Cultural practices, including planting early, choosing short maturing varieties, and removing wild host plants from field edges, are effective at suppressing tarnished plant bug populations migrating from the surrounding environment (Adams et al., 2013). However, management of this pest often requires insecticide applications to maintain high yield potential.

Populations of tarnished plant bugs have become resistant to organophosphate, pyrethroid, and neonicotinoid classes of insecticides, making control options for this pest even more limited (Catchot et al., 2022; Dorman et al., 2020; Parys et al., 2017; Snodgrass, 1996; Zhu and Snodgrass, 2003; Zhu et al., 2004). The development of resistance to these insecticides is likely the primary factor for the increasing number of foliar applications needed for management of this pest, thus, increasing input costs across the Mid-South. However, insecticides still provide some control, so several products are currently recommended, even some with known resistance issues. Foliar insecticides recommended for control of tarnished plant bugs in the Mid-South include organophosphates (acephate, dicrotophos, dimethoate), carbamates (oxamyl), neonicotinoids (thiamethoxam, imidacloprid), pyridinecarboxamides (flonicamid), pyrethroids (bifenthrin), insect growth regulators (novaluron), and sulfoximines (sulfoxaflor) (Crow et al., 2021; George et al., 2021). Tank-mixing and rotating insecticides are recommended to improve efficacy and minimize resistance development (Crow et al., 2021). Applications are needed every four to five days throughout the growing season to control heavy tarnished plant bug infestations (Cook and Threet, 2021; Crow et al., 2021).

Residual activity of insecticides used to control tarnished plant bugs is often short (< 7 d). Pyrethroids, one of the most common chemical classes used in agriculture, are characterized by fast knockdown and lethal activity (Hirano, 1989). Organophosphates, such as acephate, readily decompose when exposed to ultraviolet light, ultimately shortening the insecticide's residual activity (Szeto, 1978). Rainfall and overhead irrigation also have the potential to reduce insecticide residual; however, rainfall impact varies among insecticides. Novaluron, an insect growth regulator targeting tarnished plant bug, was less affected by a rainfall event than other insecticides, suggesting the insecticide could provide effective residual control despite rainy conditions (Barrett et al., 2021). The objective of this study was to evaluate residual chemical concentrations and tarnished plant bug control of several commonly used insecticides in Mid-South cotton to document annual evaluations of labelled products and their effectiveness.

MATERIALS AND METHODS

Field Experiment Details. From 2017 to 2021, 28 sites were replicated across Arkansas (10), Louisiana (5), Mississippi (8), and Tennessee (5) to determine the efficacy of commonly used insecticides targeting tarnished plant bug in Mid-South cotton. Eight commercially available insecticides were used at the locally recommended rates (Table 1). Cotton varieties planted and plot dimensions for these experiments varied across locations and years. Varieties were two or three gene Bt cotton that included Bollgard II®, Bollgard III® (Bayer Crop Science, St. Louis, MO), or WideStrike III™ (Corteva, Wilmington, DE). Cotton was cultivated and managed according to recommendations of extension services in each region. If insecticide applications were needed for other insect pests, then insecticides with no or minimal tarnished plant bug activity were used on the entire test area. Plots were four rows wide (3.9-4.1 m) and 9.1 to 15.2 m in length. All experiments were conducted as a randomized complete block design with four replications. Applications were made during flowering with a locally available compressed air sprayer calibrated to deliver 93.5 to 140.0 L ha^{-1} through TX-6 or TX-8 hollow cone nozzles at 4.8 to 8.0 km h^{-1} when tarnished plant bug populations were at or above a treatment threshold of three tarnished plant bugs per 1.52-row-m on a black drop cloth.

Table 1. Class, common names, trade names, and rates evaluated for control of tarnished plant bug nymphs from years 2017 to 2021 in the mid-south

Class	Common Name	Trade Name	Rate (kg ai ha^{-1})
Neonicotinoid	Imidacloprid	Admire Pro (Bayer CropScience, St. Louis, MO)	0.06
Pyridinecarboxamide	Flonicamid	Carbine (FMC, Corporation, Philadelphia, PA)	0.099
Neonicotinoid	Thiamethoxam	Centric (Syngenta, Greensboro, NC)	0.056
Carbamate	Oxamyl	Vydate (Corteva, Wilmington, DE)	0.40
Organophosphate	Dicrotophos	Bidrin (Amvac, Newport Beach, CA)	0.56
Organophosphate	Acephate	Orthene (Amvac, Newport Beach, CA)	0.84
Insect Growth Regulator	Novaluron	Diamond (ADAMA USA, Raleigh, NC)	0.065
Sulfoximines	Sulfoxaflor	Transform (Corteva, Wilmington, DE)	0.053

Insecticide Efficacy. Efficacy of treatments was evaluated with a 0.76-m-long black drop cloth by sampling the center two rows for tarnished plant bug nymphs. The black drop cloth was laid on the ground between two rows, and cotton plants were vigorously shaken to dislodge nymphs unto the cloth. Two samples were collected per plot at 4, 7, and 10 d after treatment (DAT). The center two rows of each plot were harvested with a mechanical cotton picker, weighed, and converted to kilograms per hectare (kg ha^{-1}). Seed cotton yields were converted to kg lint per hectare based on 40% lint turnout.

Chemical Analysis. The insecticide efficacy trial conducted at the Delta Research and Extension Center in Stoneville, MS during 2021 also was used to determine the concentration of insecticide residues. During this study, approximately 3.3 cm of rain occurred at 11 DAT, and no other rainfall events or overhead irrigation occurred during the study period. Fifteen leaves per plot were removed from the center two rows at 4, 7, 10, and 14 DAT. Leaves were removed by counting four nodes down from the top of the plant to ensure leaf tissue collected was present at the time of the spray. Leaf samples were placed, using disposable gloves, in 946-ml self-sealed plastic bags (Ziploc, S. C. Johnson & Son, Inc., Racine, WI) and transported back to the laboratory. Samples were kept in a freezer at -18 °*C until samples from three replications could be transported to the Chemical Analysis Lab at Mississippi State University. Cotton leaf samples were analyzed using a modified* QuEChERS by LC/MS/MS and GC/MS/MS procedure established by Anastassiades and Lehotay (2003), and concentrations were presented in parts per billion (PPB) of active ingredient. Recovery of residual insecticide ranged from 85 to 100% (mostly > 95%) (Anastassiades and Lehotay, 2003).

Data Analysis. All data were subjected to analysis of variance using generalized linear mixed model procedures (PROC GLIMMIX, SAS 9.4, SAS Institute Inc., Cary, NC). For the insecticide efficacy study, treatment was considered a fixed effect. Year, site, and replication nested within year by site were designated as random effects. Chemical analysis data were log transformed for statistical analysis, but non-transformed means and standard errors are reported. For chemical analysis data, DAT was considered a fixed effect, whereas replication was a random effect. Untreated controls were omitted from the chemical analysis. The Kenward-Roger method was used to calculate degrees of freedom. Means and standard errors were calculated using PROC MEANS statement. Least square means were separated using Fisher's Protected LSD test for $\alpha = 0.05$.

RESULTS

Insecticide Efficacy. At 4 DAT, all insecticide treatments reduced tarnished plant bug nymph numbers compared to the untreated control ($F = 39.6$; df = 8, 890; $p < 0.01$) (Table 2). Nymph densities ranged from 40% control for imidacloprid to 70% control from sulfoxaflor compared to the untreated control. All insecticides had decreased plant bug nymph densities at 7 DAT relative to the untreated control ($F = 51.1$; df = 8, 968; $p < 0.01$) (Table 2). Tarnished plant bug nymph densities remained consistent in untreated plots from 3 to 7 DAT. Imidacloprid provided significantly lower efficacy compared to all other treatments, providing only 25% control. Other treatments ranged from 37% control (flonicamid) to 68% control (sulfoxaflor). By 10 DAT, all insecticide treatments, except for imidacloprid, had reduced tarnished plant bug nymph densities ($F = 17.1$; df = 8, 420; $p < 0.01$) (Table 2). However, no differences were observed among flonicamid, thiamethoxam, oxamyl, and dicrotophos treatments, and these treatments only provided nymph control ranging from 29 to 38%. In contrast, by 10 DAT, acephate provided 54% control, novaluron provided 61% control, and sulfoxaflor provided 64% control, and these treatments provided significantly better control than all other treatments.

All the insecticide treatments resulted in higher lint yields compared to the untreated control (Table

2). Imidacloprid, flonicamid, and thiamethoxam resulted in an 8 to 12% lint yield increase compared to the untreated control. A yield increase of 15 to 17% was observed in oxamyl and dicrotophos treatments. Acephate, novaluron, and sulfoxaflor resulted in significantly greater lint yield (20%) compared to the untreated control.

Insecticide Concentrations. Imidacloprid and oxamyl were not detected after 4 DAT (Table 3, Fig. 1). Differences in flonicamid concentrations were observed across sampling dates ($F = 9.6$; $df = 3, 7$; $p < 0.01$). Concentrations of flonicamid persisted out to 14 DAT and generally decreased over time. Thiamethoxam concentrations were detected in all sampling dates ($F = 6.3$; $df = 3, 7$; $p < 0.01$) and were significantly greater at 4 DAT compared to 7, 10, and 14 DAT. Dicrotophos concentrations were present out to 14 DAT ($F = 16.7$; $df = 3, 5.4$; $p < 0.01$) and were significantly higher at 4 DAT compared to all other sampling dates. Differences in acephate concentrations were observed across sampling dates ($F = 6.3$; $df = 3, 7$; $p < 0.03$) with significantly higher concentrations detected at 4 and 7 DAT compared to 14 DAT. Novaluron was detected at all sampling dates. Similar to other insecticides, concentration of novaluron decreased over time, but these differences were not significant. Sulfoxaflor concentrations were detected at 4, 7, and 10 DAT but not at 14 DAT. Concentrations of sulfoxaflor were higher at 4 DAT compared to 7 and 10 DAT ($F = 14.4$; $df = 3, 6$; $p < 0.01$).

Table 2. Impact of selected insecticides on mean (SEM) number of tarnished plant bug nymphs per 3.048 row m and mean (SEM) cotton lint in the mid-south from 2017 to 2021[z]

Treatment	4 DAT[y]	7 DAT	10 DAT	Yield[x]
	Mean (± S.E.)			
Untreated	19.8 (1.4) a[w]	19.8 (1.3) a	15.1 (1.9) a	933 (66.5) e
Imidacloprid	11.9 (1.0) b	14.5 (0.9) b	15.3 (1.9) a	1,017 (68.4) d
Flonicamid	11.3 (0.9) bc	12.4 (0.9) c	9.6 (1.3) b	1,062 (69.3) bcd
Thiamethoxam	10.5 (0.9) bc	10.3 (0.8) d	9.3 (1.2) b	1,051 (69.2) cd
Novaluron	8.3 (0.5) ed	7.5 (0.5) ef	5.9 (0.8) c	1,169 (66.0) a
Oxamyl	9.4 (0.9) cd	10.7 (1.0) cd	9.7 (1.1) b	1,124 (66.4) ab
Dicrotophos	7.7 (0.7) ef	8.4 (0.6) e	10.4 (1.4) b	1,107 (65.8) abc
Acephate	6.9 (0.6) ef	7.6 (0.5) ef	6.9 (0.8) c	1,172 (67.9) a
Sulfoxaflor	5.8 (0.5) f	6.4 (0.5) f	5.4 (0.6) c	1,171 (68.4) a
F	39.6	51.1	17.1	11.1
d.f	8, 890	8, 968	8, 420	8, 422
p > F	<0.01	<0.01	<0.01	<0.01

[z] Tarnished plant bug threshold is 6 per 3.048 row m.

[y] Days after treatment.

[x] Yield expressed in kg ha^{-1} of lint based on 40% lint turnout.

[w] Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$).

Table 3. Mean (SEM) of concentrations in parts per billion of selected tarnished plant bug insecticides in cotton leaf tissue to determine residual activity in 2021 study conducted at the Delta Research and Extension Center in Stoneville, MS

Treatment	4 DAT[z]	7 DAT	10 DAT	14 DAT			
	Mean Concentrations, PPB (± S.E.)				F	d.f.	*p* > F
Imidacloprid	19.3 (10.3) a[y]	0.0 a	0.0 a	0.0 a	3.4	3, 7	0.08
Flonicamid	7,687.3 (3663.0) a	2,176.7 (1576.0) ab	323.5 (144.9) bc	615.6 (1.2) c	9.6	3, 7	0.01
Thiamethoxam	193.2 (86.6) a	29.6 (15.4) b	12.1 (1.1) b	15.7 (1.3) b	6.3	3, 7	0.03
Novaluron	2,350.8 (1181.1) a	829.2 (575.5) a	144.9 (64.2) a	137.5 (92.4) a	1.3	3, 6	0.3
Oxamyl	200.7 (133.2) a	0.0 a	0.0 a	0.0 a	4.0	3, 8	0.06
Dicrotophos	22,445.0 (11,894.0) a	3,341.7 (2900.0) b	253.1 (117.4) bc	44.9 (1.8) c	16.7	3, 5.4	<0.01
Acephate	35,407.0 (17,520.4) a	13,419.8 (6996.0) ab	535.0 (176.6) bc	338.0 (74.5) c	6.3	3, 7	0.03
Sulfoxaflor	1,279.5 (655.6) a	150.3 (104.0) b	19.1 (1.1) bc	0.0c	14.4	3, 6	<0.01

[z] Days after treatment.

[y] Means within a row followed by the same letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$). Letters were assigned based on log transformation of the data.

Trace amounts of acephate, novaluron, and thiamethoxam were detected in untreated controls.

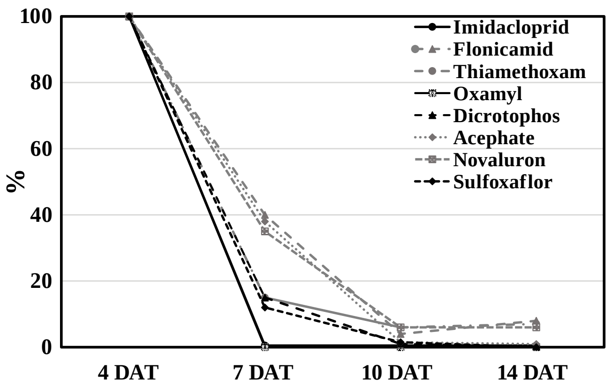

Figure 1. Mean percentage of insecticide residues on cotton leaves at the different time (days) intervals after a foliar application during bloom. Percentages are relative to the insecticide residuals detected 4 days after application (Table 3).

DISCUSSION

Management of tarnished plant bug is essential in all cotton producing states in the Mid-South. The number of insecticide applications needed to control this pest has increased considerably over the last two decades, ultimately resulting in higher total cost of control (Gore et al., 2014). In Mississippi, from 2000 to 2004, an average of 2.44 insecticide applications per season were needed to control tarnished plant bugs, increasing to 5.08 average applications in 2010 to 2014 (Cook and Threet, 2021). Few highly effective insecticides are available to control this pest, and residual control is often short. Sequential applications might be needed every four to five days to control heavy tarnished plant bug densities (Cook and Threet, 2021; Crow et al., 2021). In these studies, all insecticides generally reduced tarnished plant bug nymph populations out to 10 DAT, although imidacloprid provided no control at 10 DAT. Single applications of imidacloprid generally proved to be insufficient, but subsequent applications made within 10 d of the initial spray provided good control of tarnished plant bugs in a study in Arkansas (Steckel et al., 2018; Taillon et al., 2019). Due to its low cost, imidacloprid is used frequently prior to bloom, but multiple imidacloprid applications are needed to control sustained infestations. Results from the chemical analysis supports imidacloprid's poor residual activity because no concentrations were detected after 4 DAT. Overall, thiamethoxam, flonicamid, and dicrotophos provided some control of nymphs across sampling dates, but control was less than 38% at 10 DAT. Dicrotophos resulted in moderate control at 4 and 7 DAT, 61 and 56%, respectively. Oxamyl provided similar control at 10 DAT to thiamethoxam, flonicamid, and dicrotophos, but no residues were detected by 7 DAT. Although organophosphate resistant populations of tarnished plant bugs have been documented (Snodgrass, 1996), acephate provided 54% control of nymphs at 10 DAT and low concentrations persisted out to 14 DAT. This is contradictory to bioassay results of Barrett et al. (2021), where acephate provided poor control of tarnished plant bugs after a rainfall event and suggested control was variable and highly dependent on rainfall and the level of organophosphate resistance in the local tarnished plant bug population. In addition to acephate, novaluron and sulfoxaflor provided 60 to 64% residual control of tarnished plant bug nymphs at 10 DAT. Similarly, studies by Gore et al. (2018) demonstrated suppression of nymphs for more than two weeks when novaluron was applied. Siebert et al. (2012) found that a single application of sulfoxaflor at 50 g ai ha^{-1} reduced populations below the threshold of greater than 69%, whereas Taillon et al. (2019) reported good control of tarnished plant bugs out to 11 DAT with sulfoxaflor. However, at 14 DAT, residues of sulfoxaflor were not detected. Yield results were variable in these trials, but all insecticide treatments resulted in greater yield compared to the untreated control. Acephate, novaluron, and sulfoxaflor resulted in higher yields than imidacloprid, flonicamid, and thiamethoxam.

Although chemical concentrations immediately after application were not measured in this study, a study by Lawson et al. (2020) determined that insecticide residue levels in cotton were likely to decrease by more than 80% within the first 24 hours after application, including acephate and imidacloprid. They also determined that concentrations of all insecticides and fungicides that were evaluated decreased 95% or more by 9 DAT (Lawson et al., 2020). The sample intervals taken in our study were somewhat different than in Lawson et al. (2020) but suggest a similar rate in the reduction of insecticide residues. It did not appear that insecticide treatments in this study persisted substantially longer than other insecticides. Indeed, there was a substantial and generally similar drop in insecticide concentrations between 4 and 7 DAT (Fig. 1). Thus, perceived residual control appears to be more a function of initial efficacy combined with relatively low levels of reinfestation.

With the rapid reduction of insecticide concentrations, mortality by most insecticides included within this study were likely a result of exposure within the first few days after application. Most of the insecticides in the study applied as single applications only provide control for a few days. By 10 DAT, all insecticides had concentrations of 0 to 6% of concentration detected at the 4 DAT sample; therefore, the rainfall event that occurred 11 DAT likely had little impact on the insecticide concentrations at 14 DAT (Table 3). Rainfall events occurring closer to the initial application would likely have an impact on both insect control and detected concentrations.

In these studies, across the Mid-South, control of tarnished plant bug nymphs never reached 75%, no matter the insecticide or sampling date. The moderate efficacy and short residual shown in these studies explain why multiple insecticide applications within short intervals are needed and recommended to manage heavy tarnished plant bug populations, especially under conditions of sustained field immigration (Crow et al., 2021). Continued resistance monitoring and insecticide screening trials are important to optimize management of this pest. Rotating and tank-mixing insecticides with differing modes of actions are recommended to provide effective control of tarnished plant bug and limit resistance development (Crow et al., 2021). Cultural control methods such as planting early (Adams et al., 2013), removal of host plants (Abel et al., 2007), and proper fertility (Samples, 2014) also should be incorporated into overall integrated pest management plans so there is not a complete reliance on insecticides for management of tarnished plant bugs in the midsouthern U.S.

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