Research Article

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Consequences of co-applying insecticides and fungicides for managing *Thrips tabaci* (Thysanoptera: Thripidae) on onion

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Abstract

BACKGROUND: Insecticides and fungicides are commonly co-applied in a tank mix to protect onions from onion thrips, *Thrips tabaci* Lindeman, and foliar pathogens. Co-applications reduce production costs, but past research shows that an insecticide's performance can be reduced when co-applied with a fungicide. An evaluation was made of the effects of co-applying spinetoram, abamectin and spirotetramat with commonly used fungicides, with and without the addition of a penetrating surfactant, on onion thrips control in onion fields.

RESULTS: Co-applications of insecticides with chlorothalonil fungicides reduced thrips control by 25–48% compared with control levels provided by the insecticides alone in three of five trials. Inclusion of a penetrating surfactant at recommended rates with the insecticide and chlorothalonil fungicide did not consistently overcome this problem. Co-applications of insecticides with other fungicides did not interfere with thrips control.

CONCLUSION: Co-applications of pesticides targeting multiple organisms should be examined closely to ensure that control of each organism is not compromised. To manage onion thrips in onion most effectively, insecticides should be applied with a penetrating surfactant, and should be applied separately from chlorothalonil fungicides.

Keywords: *Allium cepa*; onion thrips; abamectin; spinetoram; spirotetramat; chlorothalonil

1 INTRODUCTION

Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), is a key pest of onion and related *Allium* spp. worldwide, and its control is vital to the production and profitability of these crops.[1] Damage caused by *T. tabaci* can reduce onion bulb yields by >30–50%.[2,3] Losses can be compounded when *T. tabaci* infect the crop with *Iris yellow spot virus* (Bunyaviridae: Tospovirus), a virus that can substantially reduce bulb yield.[4] Insecticides are the most important tool for *T. tabaci* control in onion, but there are no insecticides that provide long-term effective and consistent control over the 1–2 months when onion fields need to be protected from thrips. In addition, *T. tabaci* is notorious for developing resistance to insecticides.[5–10] The absence of products demonstrating season-long efficacy, combined with label restrictions to manage insecticide resistance, means multiple applications of different insecticides are needed to control infestations.

Spinetoram, one of the most effective new insecticides for managing *T. tabaci* infestations in onion,[11–13] belongs to a novel class of chemistry called the spinosyns. The mode of action targets the insect's nervous system and causes involuntary muscle contractions, paralysis and ultimately death. Spinetoram has local systemic action and becomes translaminar in the plant tissue, and it has both contact and ingestion activity.[14] To ensure that spinetoram penetrates the waxy leaf surface of the onion leaves, the label recommends applying it with either a methylated crop oil or non-ionic penetrating surfactant.

Abamectin is another product recently registered for use on onion in the United States that is effective against *T tabaci*.[11,12] Abamectin belongs to a novel class of chemistry called the avermectins, which attack the nervous system and cause irreversible paralysis. It has limited systemic activity, but can move into leaf tissue to provide residual control like spinetoram. Abamectin is active primarily through ingestion, but there is some contact activity.[15] Similarly to spinetoram, the manufacturer of abamectin recommends addition of a methylated crop oil or non-ionic penetrating surfactant to improve efficacy.

Spirotetramat is one of the newest products for thrips control in onion, but is still under regulatory review. Spirotetramat belongs to a novel class of chemistry called the tetramic acids, which inhibit lipid biosynthesis, causing acute poisoning and finally death.[16] Spirotetramat is a systemic insecticide that must penetrate the leaf surface to become systemic, and is active through ingestion. For maximum efficacy, spirotetramat must be

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mixed with an adjuvant that has both spreading and penetrating properties.[17]

Insecticides and fungicides are routinely co-applied as foliar sprays. Co-application of insecticides and fungicides is cost effective, enabling growers to treat the field once instead of twice, saving them both time and money. One of the most commonly used fungicides on onion is chlorothalonil,[18] which is formulated to include a spreader-sticker surfactant for improving coverage of the fungicide on the leaf surface. Past research has shown that pyrethroid insecticides were less effective against *T. tabaci* populations in onion fields when they were co-applied with chlorothalonil than when the insecticides were applied alone.[19] The cause or mechanism responsible for the reduction in insecticide efficacy was not determined. One possible mechanism is an interaction between the spreader sticker in the fungicide formulation and the insecticide. Co-applying fungicides with spreader stickers could reduce the performance of the insecticides if the spreader sticker in the fungicide formulation interferes with the ability of the insecticide to penetrate the leaf surface.

To the authors' knowledge, no studies have compared the efficacy of new insecticides when co-applied with penetrating surfactants and fungicides that include spreader-sticker surfactants. A series of experiments was conducted to evaluate the efficacy of spinetoram, abamectin and spirotetramat, in combination with different classes of penetrating surfactants and in combination with different classes of fungicides, on *T. tabaci* control in onion. The present studies were focused on the impacts of these combinations on *T. tabaci* control; the efficacy of the fungicide in the fungicide and insecticide mixtures was not investigated, nor were the mechanisms responsible for reductions in thrips control when fungicides were co-applied with insecticides identified.

2 MATERIALS AND METHODS

2.1 Study sites

Field experiments were conducted in commercial dry bulb onion fields in the Elba Muck region (GPS coordinates: 43.125090, −78.109328) in Genesee County, New York, from 2009 to 2012, and in the Potter Muck region (GPS coordinates: 42.711563, −77.194898) in Yates County, New York, in 2010. Most plots consisted of a single row, 4.6–6.1 m long. Row spacing was 38 cm. Plots were flanked by at least one untreated row and 0.9 m of bare ground within rows. Weeds were controlled using a number of herbicides recommended for onion production in New York.[20] No insecticides or fungicides were applied to plots during these experiments other than the present treatments.

2.2 Insecticides, surfactants, fungicides and application technique

Three insecticide active ingredients were evaluated in this study: spinetoram (Radiant® SC; Dow AgroSciences, Indianapolis, IN), two formulations of abamectin (Agri-Mek 0.15EC® and Agri-Mek SC®; Syngenta, Greensboro, NC) and spirotetramat (Movento®; Bayer CropScience, Research Triangle Park, NC). Three distinct classes of penetrating surfactants were evaluated, including: a non-ionic surfactant (NIS), which included a blend of alkyl aryl polyoxylkane ethers, free fatty acids and dimethyl polysiloxane (Induce®); a modified vegetable oil (crop oil), which included a mix of methylated vegetable oils and nonylphenol ethoxylate [methylated spray oil concentrate (MSO)]; an organosilicone, which included a polyalkyleneoxide-modified heptamethyltrisiloxane (Silwet® L-77 surfactant). All three penetrating surfactants are made by the Helena Chemical Company (Collierville, TN).

Five classes of fungicides, all of which included a spreader-sticker surfactant in their formulations, were evaluated, including: azoxystrobin (Quadris® flowable fungicide; Syngenta, Greensboro, NC); two formulations of chlorothalonil (Bravo Weather Stik® and Chloronil® 720; Syngenta, Greensboro, NC); iprodione (Rovral® brand 4 flowable fungicide; Bayer CropScience, Research Triangle Park, NC); mancozeb (Dithane® F-45 Rainshield; Dow AgroSciences, Indianapolis, IN); pyrimethanil (Scala™ SC; Bayer CropScience, Research Triangle Park, NC). In addition, a stand-alone, spreader-sticker surfactant, consisting of alcohol ethoxylate, 1,2-propanediol and synthetic latex (Bond Max®; Loveland Products, Inc., Greeley, CO) and not combined with a fungicide, was evaluated.

In 2009, applications were made using a CO_2-pressurized backpack sprayer equipped with a boom containing four flat-fan nozzles (8003), with each nozzle spaced 38.1 cm apart. The sprayer was calibrated to deliver 355 L ha^{-1} at 276 kPa. In 2010–2012, the same CO_2-pressurized backpack sprayer was used, but with a single-row boom and a single, twin flat-fan nozzle (TJ60-8004VS). This sprayer was calibrated to deliver 393 L ha^{-1} at 276 kPa.

2.3 Sampling thrips

T. tabaci is the only thrips species that damages onion fields in New York. The total number of thrips larvae per plant was counted visually from 10–15 randomly selected plants within each plot approximately 1 week after each application. Adults were not recorded because they move between plots and their presence does not always reflect the efficacy of the treatments. *T. tabaci* voucher specimens are located in the Department of Entomology at the New York State Agricultural Experiment Station in Geneva, New York.

2.4 Impact of chlorothalonil on efficacy of abamectin for thrips control

2.4.1 2009 field experiment

This experiment was conducted on the Elba muck in a field of 'Milestone' onions that were transplanted on 20 April 2009. The purpose of this study was to determine whether chlorothalonil (Bravo Weather Stik®) would reduce the efficacy of thrips control when co-applied with abamectin (Agri-Mek® 0.15 EC). The non-ionic penetrating surfactant (NIS) Induce® was included with the insecticide. Three treatments were evaluated, including: abamectin + NIS; abamectin + NIS + chlorothalonil; an untreated control. Abamectin and chlorothalonil were applied at rates of 0.02 and 2.5 kg AI ha^{-1} respectively, and the NIS was applied at a rate of 0.25% v:v (Table 1). Treatments were replicated 5 times and arranged in a randomized complete block design (15 plots total; $n = 5$). Plots were 1.5 m wide and 5 m long and contained five rows of onions spaced evenly apart. Spray applications were made on 29 June and on 6, 13 and 20 July. *T. tabaci* were counted on 6, 13, 20 and 27 July.

2.4.2 2010 field experiment

This experiment was conducted on the Potter muck in a field of 'Nicolet' onions that were seeded on 22 April 2010. Similarly to the field experiment described in Section 2.4.1, the purpose of this study was to test the impact of chlorothalonil (Bravo Weather Stik®) on the efficacy of abamectin, but using the new Agri-Mek® SC formulation and two different penetrating surfactants: an NIS

Table 1. Pesticides, penetrating surfactants and applications rates for each experiment described in Section 2

Category	Active ingredient	Trade name	Application rates used for each product				
			2.4.1[a]	2.4.2	2.5.1	2.5.2	2.6
Insecticide	Abamectin	Agri-Mek 0.15EC®	0.02 kg AI ha^{-1}				
	Abamectin	Agri-Mek SC®		0.016 kg AI ha^{-1}	0.02 kg AI ha^{-1}	0.02 kg AI ha^{-1}	
	Spinetoram	Radiant® SC			0.05 kg AI ha^{-1}		
	Spirotetramat	Movento®			0.09 kg AI ha^{-1}	0.09 kg AI ha^{-1}	0.09 kg AI ha^{-1}
Penetrating surfactant	Non-ionic (NIS)[b]	Induce®	0.25% v:v	0.5% v:v	0.5% v:v	0.5% v:v	0.05-0.5% v:v
	Crop oil[c]	MSO		0.5% v:v	0.6% v:v		
	organosilicone[d]	Silwet® L-77			0.25% v:v		
Fungicide with spreader sticker	Azoxystrobin	Quadris® F				0.22 kg AI ha^{-1}	
	Chlorothalonil	Bravo Weather Stik®	2.5 kg AI ha^{-1}	1.26 kg AI ha^{-1}			
	Chlorothalonil	Chloronil® 720			2.5 kg AI ha^{-1}	2.5 kg AI ha^{-1}	2.5 kg AI ha^{-1}
	Iprodione	Rovral® brand 4 F				0.84 kg AI ha^{-1}	
	Mancozeb	Dithane® F-45 RainShield				2.7 kg AI ha^{-1}	
	Pyrimethanil	Scala® SC				0.79 kg AI ha^{-1}	
Spreader-sticker surfactant	Alcohol ethoxylate and synthetic latex	Bond Max®			0.25% v:v		

[a] Number of the subsection in Section 2 that provides a detailed description of each experiment.
[b] Active ingredient included a blend of alkyl aryl polyoxylkane ethers, free fatty acids and dimethyl polysiloxane.
[c] Active ingredient included a modified vegetable oil consisting of a mix of methylated vegetable oils and nonylphenol ethoxylate.
[d] Active ingredient included a polyalkyleneoxide-modified heptamethyltrisiloxane.

(Induce®) and a crop oil (MSO). Four treatments were evaluated, including: abamectin + NIS; abamectin + NIS + chlorothalonil; abamectin + crop oil + chlorothalonil; an untreated control. Abamectin and chlorothalonil were applied at rates of 0.016 and 1.26 kg AI ha^{-1} respectively. The NIS and crop oil were applied at a rate of 0.5% v:v (Table 1). Treatments were replicated 4 times and arranged in a randomized complete block design (16 plots total; $n = 4$). Plots were one row wide and 6.1 m long. Spray applications were made on 23 June, on 2, 8, 15, 22 and 30 July and on 6 and 11 August. *T. tabaci* were counted on 1, 8, 15, 22 and 28 July and on 6, 11 and 19 August.

2.5 Effects of fungicides, penetrating surfactants and insecticides on thrips control

2.5.1 2010 field experiment

This experiment was conducted on the Elba muck in a field of 'Red Bull' onions that were transplanted on 22 April 2010. This study expanded on the results of the experiments described in Section 2.4. The purpose was to evaluate thrips control using different combinations of insecticides and chlorothalonil (Chloronil® 720). Because the spreader sticker in Chloronil® 720 is proprietary and not available for public research, the authors attempted to assess whether the fungicide or the spreader-sticker surfactant was affecting the efficacy of the insecticide by evaluating the impact of a generic spreader sticker, Bond Max®, which lacked penetrating properties, on thrips control when co-applied with an insecticide. It is recognized that the formulation and concentration of the Bond Max® spreader sticker may differ from the spreader sticker in the Chloronil® 720 formulation.

A total of 37 treatments were evaluated in this study, composed of all possible combinations of three insecticides (abamectin, spinetoram and spirotetramat), four penetrating surfactant treatments (no penetrating surfactant, NIS, crop oil and organosilicone), three fungicide/spreader-sticker surfactant treatments (no fungicide/spreader sticker, chlorothalonil and synthetic latex) and an untreated control (three insecticides × four penetrating surfactant treatments × three fungicide/spreader-sticker treatments + one untreated control = 37 treatments). Abamectin (Agri-Mek® SC), spinetoram and spirotetramat were evaluated at labeled recommended rates of 0.02, 0.05 and 0.09 kg AI ha^{-1} respectively. The NIS, crop oil and organosilicone were evaluated at high rates of 0.5, 0.6 and 0.25% v:v respectively. Chlorothalonil was evaluated at the high recommended rate of 2.5 kg AI ha^{-1}, and the synthetic latex was evaluated at a moderate recommended rate of 0.25% v:v (Table 1).

Treatments were replicated 4 times and arranged in a randomized complete block design (148 plots total; $n = 4$). Plots were a single row wide, 6.1 m long and flanked by untreated rows. Spray applications were made on 22 June, when plants had an average of 21.1 larvae per plant (2.3 per leaf), and on 30 June. *T. tabaci* were counted on 29 June and on 7 and 12 July.

2.5.2 2011 and 2012 field experiments

These experiments were conducted on the Elba muck in a field of 'Red Bull' onions that were transplanted on 30 April 2011, and in a field of 'Highlander' onions that were transplanted on 10 April 2012. The main purpose of this study was to evaluate co-applications of insecticides and five commonly used fungicides on the control of *T. tabaci*.

A total of 25 treatments were evaluated. The treatments included all possible combinations of two insecticides (abamectin and spirotetramat), six fungicide treatments (no fungicide, chlorothalonil, mancozeb, azoxystrobin, iprodione and pyrimethanil), two penetrating surfactant treatments (no penetrating surfactant or NIS) and an untreated control (two insecticides × two penetrating surfactant treatments × six fungicide treatments + one untreated control = 25 treatments). Abamectin (Agri-Mek® SC) and spirotetramat were evaluated at the same rates as those used in the field experiment described in Section 2.5.1. The NIS (Induce®) was evaluated at 0.5% v:v. Chlorothalonil (Chloronil® 720) was evaluated at a rate of 2.5 kg AI ha^{-1}, mancozeb at a rate of 2.7 kg AI ha^{-1}, azozystrobin at a rate of 0.22 kg AI ha^{-1}, iprodione at a rate of 0.84 kg AI ha^{-1} and pyrimethanil at a rate of 0.79 kg AI ha^{-1} (Table 1).

All treatments were replicated 4 times and arranged in a randomized complete block design (100 plots total; $n = 4$). Plots were a single row wide, 4.6 m long and flanked by untreated rows. In 2011, spray applications were made on 19 July, when plants had an average of 78 larvae per plant (7.8 larvae per leaf), and on 27 July. *T. tabaci* were counted on 26 July and 3 August. In 2012, spray applications were made on 14 June, when plants had an average of 20.3 larvae per plant (2.4 larvae per leaf), and on 22 June. *T. tabaci* were counted on 21 and 29 June.

2.6 Effects of an NIS penetrating surfactant rate on thrips densities using co-applications of spirotetramat and chlorothalonil

This experiment was conducted on the Elba muck in a field of 'Hendrix' onions that were seeded on 11 May 2011. The purpose of this study was to determine whether thrips control could be improved by manipulating the rate of the NIS (Induce®) in co-applications of spirotetramat and chlorothalonil. Co-applications of spirotetramat and chlorothalonil were evaluated using five rates of NIS: 0, 0.05, 0.1, 0.25 and 0.5% v:v. Additionally, treatments included chlorothalonil + NIS at 0.5% v:v and chlorothalonil alone for a total of seven treatments. Spirotetramat was applied at 0.09 kg AI ha^{-1} and chlorothalonil (Chloronil® 720) was applied at a rate of 2.5 kg AI ha^{-1}. All treatments were replicated 5 times and arranged in a randomized complete block design (35 plots total; $n = 5$). Plots were a single row wide, 6.1 m long and flanked by untreated rows. Spray applications were made on 10 August, when plants had an average of 36.4 larvae per plant (4.5 larvae per leaf), and again on 17 August. *T. tabaci* were counted on 17 and 23 August.

2.7 Statistical analyses

The mean density of *T. tabaci* larvae per plant was calculated for each date and summed over all sampling dates for each treatment. The cumulative mean density was considered to be the dependent variable and was transformed using a $\log_{10}(x + 1)$ function before analysis. All figures show non-transformed cumulative mean densities of *T. tabaci* per plant.

All analyses were done using mixed-model regression (PROC MIXED) in SAS v.9.3.[21] For all experiments, insecticide, penetrating surfactant and fungicide/spreader-sticker surfactant treatments were considered to be fixed main treatment effects in the models, whereas replication was considered to be random in the models. Where applicable, all two-way interactions were tested, but not three-way interactions.

For the 2009 and 2010 experiments in Section 2.4 and for the 2011 experiment in Section 2.6, untreated and treated plots were analyzed together, and treatment means were compared using a Fisher's protected LSD at $P < 0.05$.[21]

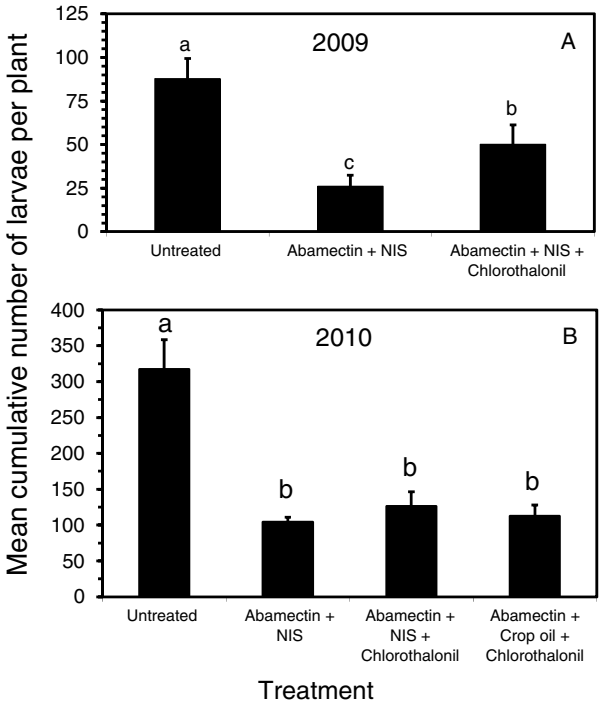

Figure 1. Mean (± SE) cumulative number of *Thrips tabaci* larvae per onion plant in plots treated with abamectin and a penetrating surfactant with or without the fungicide chlorothalonil in June 2009 (A) and in July and August 2010 (B). Numbers of larvae per plant 1 week after each application were summed over four consecutive weeks in 2009 and eight consecutive weeks in 2010. Means followed by a different letter within a panel were significantly different [$P < 0.05$, Fisher's protected LSD (A: df = 2, 8; B: df = 3, 9), $n = 4$ for both studies].

For the 2010, 2011 and 2012 experiments in Section 2.5, untreated means were only included in the analysis comparing untreated plots with plots that received insecticides. All other regression analyses testing the different combinations of insecticides, surfactants and fungicides and their interactions on thrips control did not include the untreated control plots. In 2010, main effects were defined as insecticide (abamectin, spinetoram and spirotetramat), penetrating surfactant (no surfactant, NIS, crop oil and organosilicone) and fungicide/sticker (no fungicide, chlorothalonil and synthetic latex). In 2011 and 2012, main effects were defined as insecticide (abamectin and spirotetramat), penetrating surfactant (no surfactant and NIS) and fungicide (no fungicide, chlorothalonil, mancozeb, azoxystrobin, iprodione and pyrimethanil). All pairwise mean comparisons of treatments for these experiments were made using Tukey–Kramer at $P < 0.05$.

3 RESULTS

3.1 Impact of chlorothalonil on efficacy of abamectin

3.1.1 2009 field experiment

Mean cumulative densities of *T. tabaci* larvae in plots treated with abamectin with and without chlorothalonil were significantly lower (43–70%) compared with densities in the untreated control ($F = 13.5$; df = 2, 8; $P = 0.0027$) (Fig. 1A). Larval densities in plots treated with abamectin + NIS were significantly lower than densities in plots sprayed with abamectin + NIS + chlorothalonil (Fig. 1A).

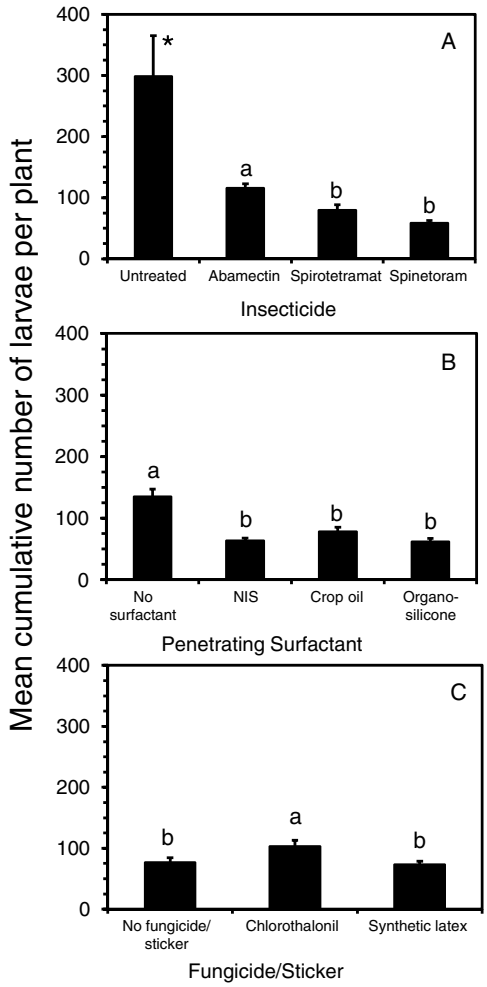

Figure 2. Mean (± SE) cumulative number of *Thrips tabaci* larvae per onion plant in all insecticide treatments (A), penetrating surfactant treatments (B) and fungicide/sticker treatments (C) in 2010. The asterisk in (A) signifies significantly lower densities of thrips larvae in insecticide-treated plots compared with untreated plots ($P < 0.05$, *F*-test, df = 1, 146). Treatment means followed by a different letter within a panel were significantly different [$P < 0.05$, Tukey–Kramer (A: df = 2, 36; B: df = 3, 36; C: df = 2, 84), $n = 4$].

3.1.2 2010 field experiment

Larval densities in plots treated with abamectin with and without chlorothalonil were significantly lower (60–67%) compared with densities in the untreated control ($F = 17.9$; df = 3, 9; $P = 0.0004$) (Fig. 1B). Larval densities in plots treated with abamectin + NIS were similar to densities in plots treated with abamectin + NIS + chlorothalonil and with abamectin + crop oil + chlorothalonil (Fig. 1B).

3.2 Effects of fungicides, penetrating surfactants and insecticides on thrips control

3.2.1 2010 field experiment

The mean cumulative number of *T. tabaci* larvae in untreated plots at the end of the experiment was 299 ± 67 per plant. There was a significant difference between plots receiving insecticides and the untreated control plots ($F = 48.9$; df = 1, 146; $P < 0.0001$); insecticides reduced thrips densities by 61–81% compared with densities in the untreated control (Fig. 2A). Untreated control plots were not included in subsequent analyses.

The mean cumulative number of *T. tabaci* larvae per plant was significantly affected by all main effect terms in the model: insecticide ($F = 23.6$; df = 2, 36; $P < 0.0001$); penetrating surfactant ($F = 15.4$; df = 3, 36; $P < 0.0001$); fungicide/sticker ($F = 10.4$; df = 2, 84; $P < 0.0001$). Larval densities in plots treated with either spinetoram or spirotetramat were significantly lower than densities in plots treated with abamectin ($P < 0.0001$) (Fig. 2A). Plots sprayed with spinetoram had lower larval densities than plots sprayed with spirotetramat, but this difference was not significant ($P > 0.05$). The addition of a penetrating surfactant significantly lowered larval densities in all plots compared with plots that did not receive a penetrating surfactant ($P < 0.0011$), but there were no significant differences in thrips densities among the three penetrating surfactant treatments ($P > 0.05$) (Fig. 2B). Larval densities in plots treated with chlorothalonil were significantly greater than densities in plots receiving only the synthetic latex spreader-sticker surfactant and densities in plots that did not receive any fungicide/sticker ($P < 0.0012$) (Fig. 2C). There was no difference in thrips densities in plots that received only the synthetic latex spreader sticker and plots that did not receive any fungicide/sticker ($P > 0.05$) (Fig 2C).

Densities of *T. tabaci* larvae were impacted significantly by interactions between insecticides and penetrating surfactants ($F = 4.3$; df = 6, 36; $P = 0.0023$). The interaction between insecticides and penetrating surfactants was due to a significant effect of penetrating surfactant on thrips densities in treatments sprayed with abamectin and spirotetramat, but no effect of penetrating surfactant in treatments sprayed with spinetoram (Fig. 3A). *T. tabaci* densities in plots receiving a penetrating surfactant were numerically lower than densities in plots treated with abamectin alone ($P > 0.05$), and significantly lower than densities in plots treated with spirotetramat alone ($P < 0.0003$). In contrast, larval densities in plots treated with spinetoram were not affected by the presence or absence of a penetrating surfactant ($P > 0.05$). The type of penetrating surfactant did not affect thrips densities for any of the insecticides ($P > 0.05$) (Fig. 3A).

There was no interaction between insecticides and fungicide/sticker treatments on *T. tabaci* densities. Larval densities in plots in which insecticides were co-applied with either the spreader sticker or no fungicide/spreader sticker tended to be lower than densities in plots that included chlorothalonil, but there were no significant differences (Fig. 3B).

T. tabaci densities were affected by a significant interaction between penetrating surfactants and fungicide/sticker ($F = 3.5$; df = 6, 84; $P = 0.0038$) (Fig. 3C). This interaction was caused by differences between *T. tabaci* densities in treatments with no fungicide or spreader-sticker surfactant and treatments that included chlorothalonil, compared with treatments that included the synthetic latex spreader sticker. In the no fungicide/spreader-sticker treatments and the chlorothalonil treatment, larval densities in plots that received a penetrating surfactant were significantly lower than *T. tabaci* densities in plots that received no penetrating surfactant ($P < 0.0108$ and $P < 0.0351$ respectively), but there were no differences in larval densities between the three penetrating surfactants evaluated ($P > 0.05$) (Fig. 3C). In contrast, larval densities in the treatments receiving synthetic latex alone were affected by the organosilicone penetrating surfactant; treatments receiving the synthetic latex spreader sticker and the organosilicone penetrating surfactant had significantly lower thrips densities than treatments that only received the synthetic latex spreader sticker ($P < 0.0008$) (Fig. 3C). There were no significant differences between larval densities in plots receiving

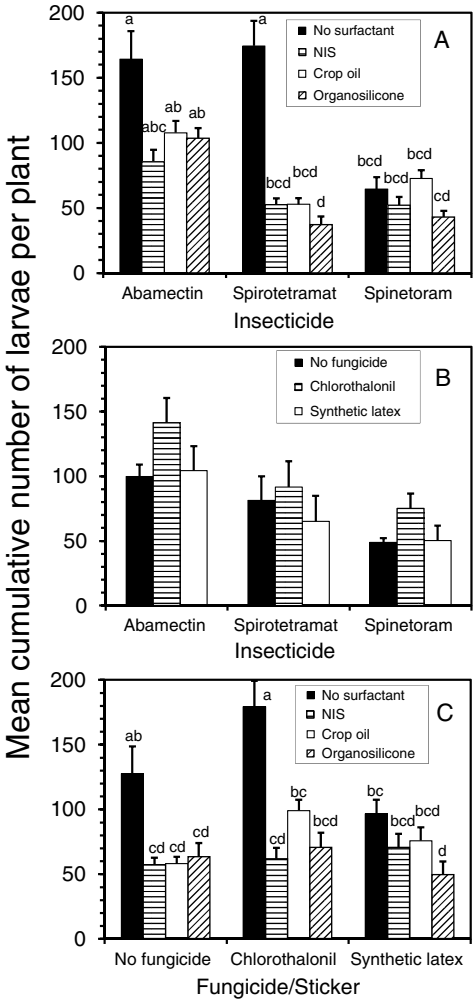

Figure 3. Mean (± SE) cumulative number of *Thrips tabaci* larvae per onion plant in the insecticide + penetrating surfactant treatments (A), insecticide + fungicide/sticker treatments (B) and fungicide/sticker + penetrating surfactant treatments (C) in 2010. Means followed by a different letter within a panel were significantly different [$P < 0.05$, Tukey–Kramer (A: df = 6, 36; C: df = 6, 84), $n = 4$]; however, the insecticide + fungicide/sticker treatment means were not significantly different [$P > 0.05$, Tukey–Kramer (B: df = 4, 84), $n = 4$].

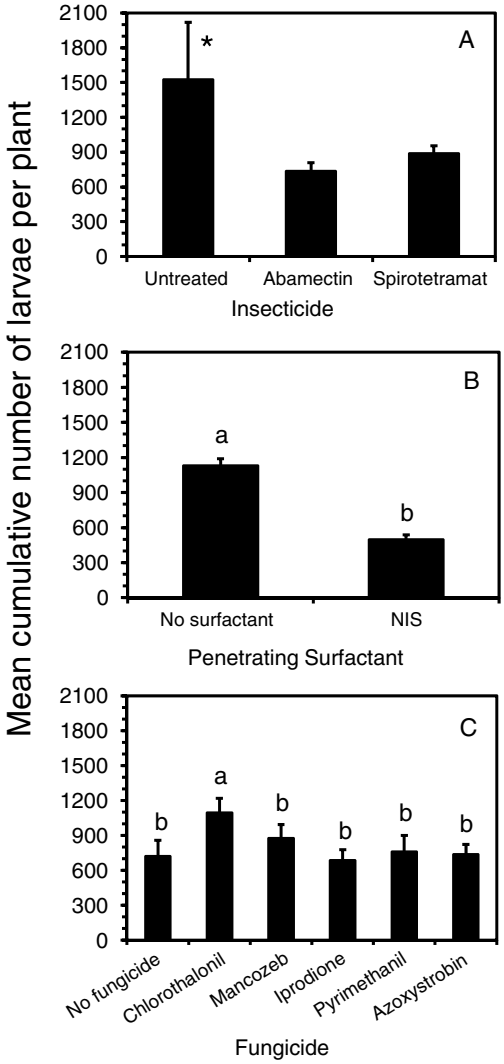

Figure 4. Mean (± SE) cumulative number of *Thrips tabaci* larvae per onion plant in both insecticide treatments (A), penetrating surfactant treatments (B) and fungicide treatments (C) in 2011. The asterisk in (A) signifies significantly lower densities of thrips larvae in insecticide-treated plots compared with untreated plots ($P < 0.05$, F-test, df = 1, 98). Insecticide treatment means were similar [$P > 0.05$, Tukey–Kramer (A: df = 1, 12), $n = 4$]. Other treatment means followed by a different letter within a panel were significantly different [$P < 0.05$, Tukey–Kramer (B: df = 1, 12; C: df = 5, 65), $n = 4$].

synthetic latex alone and the other two penetrating surfactants ($P > 0.05$) (Fig. 3C).

3.2.2 2011 field experiment

The infestation of *T. tabaci* was extremely high in this experiment. The mean cumulative number of *T. tabaci* larvae in untreated plots at the end of the experiment was 1524 ± 495 per plant. There was a significant difference between plots receiving insecticides and the untreated control plots ($F = 7.5$; df = 1, 98; $P = 0.0074$); insecticides reduced thrips densities by 42–52% compared with densities in the untreated control (Fig. 4A). Untreated control plots were not included in subsequent analyses.

The mean cumulative number of larvae per plant was significantly affected by two of the three main effect terms in the model: penetrating surfactant ($F = 29.5$; df = 1, 12; $P = 0.0002$) and fungicide ($F = 7.1$; df = 5, 65; $P < 0.0001$). In the insecticide treatments, larval densities in the abamectin treatment were lower than densities in the spirotetramat treatment, but the difference was not significant ($P > 0.05$) (Fig. 4A). There were no significant interactions between the main effects ($P > 0.05$).

Adding an NIS penetrating surfactant significantly reduced larval densities by 56% compared with *T. tabaci* densities in plots that received insecticides but no penetrating surfactant ($P = 0.0002$) (Fig. 4B). Larval densities in plots treated with an insecticide + fungicide were similar to densities in plots treated with an insecticide and no fungicide, except for plots treated with chlorothalonil. Plots treated with chlorothalonil had significantly higher *T. tabaci* densities than all other insecticide/fungicide combination treatments ($P < 0.05$) (Fig. 4C). Plots that received insecticides + chlorothalonil had 52% more thrips larvae compared with plots that received insecticides and no fungicide (Fig. 4C). There were no significant differences among larval densities in the other fungicide treatments ($P > 0.05$) (Fig. 4C).

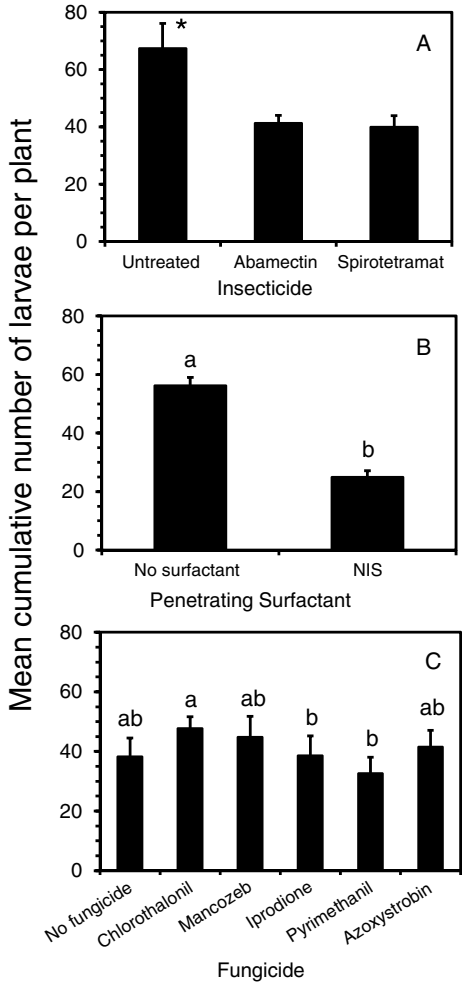

Figure 5. Mean (± SE) cumulative number of *Thrips tabaci* larvae per onion plant in both insecticide treatments (A), penetrating surfactant treatments (B) and fungicide treatments (C) in 2012. The asterisk in (A) signifies significantly lower densities of thrips larvae in insecticide-treated plots compared with untreated plots ($P < 0.05$, *F*-test, df = 1, 98). Larval densities between insecticide treatments did not differ [$P > 0.05$, Tukey–Kramer (A: df = 1, 12), $n = 4$]. Other treatment means followed by a different letter within a panel were significantly different [$P < 0.05$, Tukey–Kramer (B: df = 1, 12; C: df = 5, 65), $n = 4$].

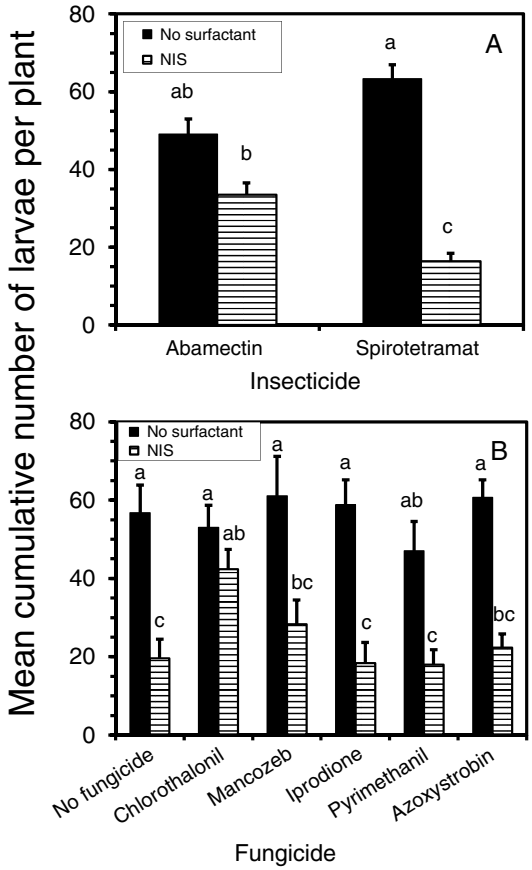

Figure 6. Mean (± SE) cumulative number of *Thrips tabaci* larvae per onion plant in the insecticide + penetrating surfactant treatments (A) and the fungicide/sticker + penetrating surfactant treatments (B) in 2012. Treatment means followed by a different letter within a panel were significantly different [$P < 0.05$, Tukey–Kramer (A: df = 1, 12; B: df = 5, 65), $n = 4$].

3.2.3 *2012 field experiment*

The mean cumulative number of *T. tabaci* larvae in untreated plots at the end of the experiment was 67 ± 9 per plant. There was a significant difference between plots receiving insecticides and the untreated control plots ($F = 5.0$; df = 1, 98; $P = 0.0284$): insecticides reduced thrips densities by 39–41% compared with densities in the untreated control (Fig. 5A). Untreated control plots were not included in subsequent analyses.

Similarly to results in 2011, the mean cumulative number of larvae per plant was significantly affected by two of the three main effect terms in the model: penetrating surfactant ($F = 60.6$; df = 1, 12; $P < 0.0001$) and fungicide ($F = 3.4$; df = 5, 65; $P = 0.0081$), and there were no significant differences in larval densities between the two insecticide treatments (insecticide main effect, $P > 0.05$) (Fig. 5A). There were significant interactions between insecticide treatments and penetrating surfactants ($F = 17.1$; df = 1, 12; $P = 0.0014$) and between fungicides and penetrating surfactants ($F = 3.1$; df = 5, 65; $P = 0.0139$).

Including an NIS penetrating surfactant to plots that received insecticides significantly reduced larval densities by 56% compared with *T. tabaci* densities in plots that received insecticides but no penetrating surfactant ($P < 0.0001$) (Fig. 5B). Densities of larvae in plots treated with an insecticide + fungicide were similar to those treated with an insecticide and no fungicide. However, plots treated with an insecticide + chlorothalonil had significantly higher *T. tabaci* densities ($P < 0.05$) than those treated with an insecticide + iprodione and an insecticide + pyrimethanil (Fig. 5C).

Densities of *T. tabaci* larvae were impacted significantly by an interaction between insecticides and penetrating surfactants. The interaction between insecticides and penetrating surfactants was due to a significant effect of penetrating surfactant on thrips densities in treatments sprayed with spirotetramat, but no effect of penetrating surfactant in treatments sprayed with abamectin (Fig. 6A). *T. tabaci* densities in plots receiving spirotetratmat + NIS were significantly lower than densities in plots treated with spirotetramat alone ($P < 0.0001$), whereas plots receiving abamectin + NIS had numerically lower thrips densities than plots treated with abamectin alone ($P > 0.05$) (Fig. 6A). The lowest densities of *T. tabaci* larvae were recorded in plots treated with spirotetramat + NIS.

T. tabaci densities were also affected by a significant interaction between fungicides and penetrating surfactant, primarily as a result of the differences between *T. tabaci* densities in

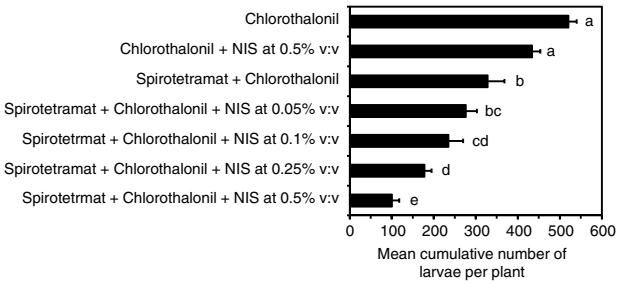

Figure 7. Mean (± SE) cumulative number of *Thrips tabaci* larvae per onion plant in plots treated with spirotetramat and chlorothalonil with various rates of a non-ionic penetrating surfactant. Means followed by a different letter were significantly different [$P < 0.05$, Fisher's protected LSD (df = 6, 18), $n = 4$].

chlorothalonil-treated plots compared with all other treatments. *T. tabaci* densities were significantly lower in all treatments that included the penetrating surfactant, except plots treated with chlorothalonil (range: $P = 0.05$ to $P < 0.0001$). In chlorothalonil-treated plots, larval densities were numerically lower in the chlorothanolil + NIS treatments compared with the chlorothalonil alone treatments, but the difference was not significant ($P > 0.05$) (Fig. 6B).

3.3 Effects of the penetrating surfactant rate on thrips densities using co-applications of spirotetramat and chlorothalonil

Mean cumulative numbers of larvae in plots that received chlorothalonil alone and chlorothalonil + NIS without an insecticide were significantly greater than *T. tabaci* densities in all spirotetramat treatment plots ($P < 0.05$) (Fig. 7). Addition of a penetrating surfactant with co-applications of spirotetramat + chlorothalonil had a profound effect on the level of *T. tabaci* control ($F = 31.0$; df = 6, 18; $P < 0.0001$) (Fig. 7). Densities of larvae significantly decreased as the rate of NIS increased, with the lowest thrips densities occurring when the highest rate of NIS was used, 0.5% v:v ($P < 0.0002$) (Fig. 7).

4 DISCUSSION AND CONCLUSIONS

Management of *T. tabaci* in onion was reduced when the insecticides were co-applied with formulations of the fungicide chlorothalonil (Bravo Weather Stik® and Chloronil® 720), but not when they were co-applied with other commonly used fungicides. The reduction in insecticide efficacy did not appear to be the result of a general interaction between a spreader-sticker surfactant and insecticides, but an interaction specific to the chlorothalonil formulations evaluated in the present studies. The addition of a penetrating surfactant at high rates helped mitigate the negative interactions between at least one of the insecticides, spirotetramat and chlorothalonil.

The three insecticides evaluated in these studies have either translaminar (spinetoram and abamectin) or systemic activity (spirotetramat). Studies testing co-applications of chlorothalonil products and pyrethroid insecticides, which lack translaminar and systemic activity, also found a negative effect on thrips control.[19] In two out of four field studies, co-applications of chlorothalonil (Bravo® 720) at 2.5 kg AI ha^{-1} and pyrethroid insecticides significantly reduced the efficacy of the insecticide on *T. tabaci* control compared with the insecticide alone.[19] Specifically, in the first study, co-applications of chlorothalonil and cypermethrin (Ammo® 2.5E) reduced *T. tabaci* control by only 49%, compared with a 72% reduction when cypermethrin was used alone. In the second study, co-applications of chlorothalonil and lambda-cyhalothrin (Warrior® 1E) reduced thrips control by 66%, whereas thrips control was reduced by 95% when lambda-cyhalothrin was used alone.[19] However, the authors did not observe a reduction in *T. tabaci* control when chlorothalonil and lambda-cyhalothrin were applied sequentially, approximately 90 min apart, compared with lambda-cyhalothrin alone, suggesting that the negative interaction between the two pesticides occurred when the pesticides were mixed in the spray tank. According to the authors, the reduction in insecticide efficacy may have been due to water-soluble insecticides binding to organic materials in the spreader stickers in the fungicide formulation.[19]

Negative effects of co-applications of chlorothalonil and insecticides on insect control have also been documented for other vegetable insect pests. The percentages of honeydew melons, *Cucumis melo* var. *inodorus*, damaged by pickleworm, *Diaphania nitidalis* (Stoll), were significantly greater when chlorothalonil (Bravo® 6 F) was co-applied with either methomyl or *Bacillus thuringiensis* var. *kurstaki* Berliner (Dipel®) by comaprison with damage using insecticides alone.[22] Additionally, the effectiveness of permethrin against the Colorado potato beetle, *Leptinotarsa decemlineata* (Say), in potato, *Solanum tuberosum* L., was diminished when co-applied with a chlorothalonil fungicide.[23]

These results suggest that chlorothalonil, the type and/or quantity of the spreader sticker in the chlorothalonil formulations or a combination of these factors reduced the efficacy of the insecticides. When insecticides were combined with other fungicides or with the synthetic latex spreader sticker without a fungicide, the efficacy of the insecticide against *T. tabaci* was not impaired, suggesting that the decrease in efficacy was not due to the addition of fungicides or spreader-sticker surfactants generally, but to something specific in the chlorothalonil formulations. A decrease in insecticide efficacy when formulations of chlorothalonil are co-applied with newer insecticides may cause onion growers to avoid using the newer insecticide products. In addition, if co-applications with chlorothalonil result in these new insecticides having shorter residual activity, insecticide applications may be needed more frequently, increasing the cost of production and increasing the potential for insecticide resistance.

Onion growers using chlorothalonil fungicides for managing foliar diseases should consider applying these fungicides separately from any insecticides. The present results do not indicate that this strategy is necessary for other fungicides. In New York, chlorothalonil fungicides tend to be used early in the season for control of *Botrytis squamosa* and *B. alii*, which cause Botrytis leaf blight and neck rot respectively. These sprays are often made before insecticides are needed to manage *T. tabaci* infestations. Later in the season, other fungicides are more commonly used for managing *Alternaria porri*, which causes purple blotch, and *Peronospora destructor*, which causes downy mildew. Thus, the greatest probability of co-applying insecticides with chlorothalonil fungicides occurs during the middle 2–4 weeks of the season. During this time, onion growers should consider separating insecticide and chlorothalonil fungicide applications.

Manufacturers have consistently recommended that spinetoram, abamectin and spirotetramat be used in combination with a penetrating surfactant. The present results support this recommendation. In all studies, addition of a penetrating surfactant with the insecticides improved thrips control. In three cases, addition of a penetrating surfactant helped mitigate the

negative effects of co-applying chlorothalonil fungicides with an insecticide (Fig. 3C, Figs 4B and C and Fig. 7), but in one case the addition of a penetrating surfactant did not help reduce the negative effects of co-applying chlorothalonil fungicides with an insecticide (Fig. 6B).

Results from these studies suggest that the performance of pesticides that are co-applied should be examined to ensure that maximum control of the target organism is not compromised, especially in production systems where insecticides are co-applied with chlorothalonil fungicides. In situations where pest or disease control is diminished when pesticides are co-applied, consequences of reduced efficacy of the target organism will need to be weighed against savings in production costs by co-applying the pesticides.

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