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Residual activity of diamide insecticides for *Ostrinia nubilalis* control in processing snap bean

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ABSTRACT

The processing snap bean industry views European corn borer, *Ostrinia nubilalis* (Hübner), larvae as contaminates in beans and has established a near zero tolerance. Currently, growers in New York (USA) apply 1–2 pyrethroid insecticide treatments for *O. nubilalis* control in snap bean. The objective of this study was to compare the residual efficacy of diamide and traditional pyrethroid insecticides at various foliar application timings against *O. nubilalis*. Insecticides were tested at four different timings (1, 7, 10, and 14 days before snap bean pod formation) in field trials performed in western New York in 2015 and 2016. Treatments were evaluated for *O. nubilalis* plant and pod damage and yield. Bioassays using snap bean leaves collected from the treated field plots were used to assess larval mortality. All materials exhibited excellent control of *O. nubilalis* when applied 1 day before pod formation, reducing pod and plant damage to ~0%. However, for applications 14 days before pod formation, chlorantraniliprole and chlorantraniliprole + lambda-cyhalothrin consistently had lower pod and plant damage and higher larval mortality compared with the other materials. Chlorantraniliprole applied at 7, 10, and 14 days before pod formation also resulted in higher yields than the untreated control in 2015. Our results indicate that chlorantraniliprole-containing insecticides could be applied only once per season, eliminating the need for multiple applications, and could also be co-applied with fungicides or herbicides, which are applied earlier than standard pyrethroid insecticides. These results indicate that the anthranilic diamides, especially chlorantraniliprole, exhibit longer-term efficacy than pyrethroids, increasing the flexibility of spray timing by growers.

1. Introduction

The European corn borer (*Ostrinia nubilalis* (Hübner)) (Lepidoptera: Crambidae) is an important pest of several crops in the United States, primarily field corn and sweet corn, but also many other crops including snap bean, potato, pepper, wheat, and cotton (Hudon et al., 1989; Kennedy and Storer, 2000). The majority of field corn varieties planted include those that have been genetically modified to include one or more *Bt* genes (Fernandez-Cornejo et al., 2014), which provide effective *O. nubilalis* control. However, organic field corn, processing sweet corn, and all other crops (except cotton) attacked by *O. nubilalis* do not contain the *Bt* trait. In these crops, growers rely on insecticides, typically pyrethroids, to prevent damage caused by *O. nubilalis* and other lepidopteran pests.

Ostrinia nubilalis larvae initially feed on snap bean foliage after hatching, then quickly move into pods or plant stems (Dively and McCully, 1979; Sanborn et al., 1982). Individuals feeding inside pods during harvest often remain within the pods during processing and contaminate the finished product. To mitigate this contamination risk, insecticides are an important tool for *O. nubilalis* management. In the processing snap bean industry in New York (USA), growers make 1–2 prophylactic applications of pyrethroid insecticides (typically bifenthrin) per season at bloom or early-pod formation (additional sprays follow if necessary) to protect the crop from *O. nubilalis* infestations (Schmidt-Jeffris et al., 2016). This management strategy has continued for decades despite the lack of preference for, and poor performance of, *O. nubilalis* on snap bean (Cranshaw and Radcliffe, 1984; Dively and McCully, 1979; Eckenrode and Webb, 1989; Webb et al., 1987). Moreover, *O. nubilalis* populations have been declining throughout the United States over the last >10 years (Bohnenblust et al., 2014; Hutchison et al., 2010), including those near New York snap bean fields during the period when the crop is vulnerable (Schmidt-

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Jeffris et al., 2016).

Although pyrethroids have been highly effective in preventing pod infestation by *O. nubilalis*, they pose several problems. Pyrethroids can be harmful to insect pollinators and natural enemies (Croft, 1990; Desneux et al., 2007; Hull and Starner, 1983; Theiling and Croft, 1988), and other wildlife, including aquatic invertebrates and fish (Anderson, 1982; Antwi and Reddy, 2015; Haya, 1989). Relying heavily on one mode of action also increases the likelihood of resistance development. Many insects such as silverleaf whitefly, corn earworm, diamondback moth, and onion thrips have developed resistance to pyrethroids (Houndété et al., 2010; Jacobson et al., 2009; Kranthi et al., 2001; Liu et al., 1981; Shelton et al., 2003). Although pyrethroid resistance in *O. nubilalis* has not yet been documented in the United States, lambda-cyhalothrin resistance has been reported in France (Siegwart et al., 2012), demonstrating the potential for similar occurrences in other locations. Although pyrethroids are an inexpensive tool for managing *O. nubilalis* in snap bean, alternative materials that are more selective, like the diamides, should be identified. Alternative insecticides with known efficacy can serve as replacements in the event that pyrethroid resistance develops or registration is lost due to environmental concerns. Replacing broad-spectrum pesticides with diamides would reduce environmental impact and worker safety concerns. Diamides are known for their selectivity, in terms of both beneficial arthropod toxicity (Brugger et al., 2010; Dinter et al., 2008; Dinter et al., 2009, 2012; Dinter and Samel, 2015; Gradish et al., 2010; Larson et al., 2012; Whalen et al., 2016) and human safety (Cordova et al., 2006; Lahm et al., 2007).

Diamide insecticides show promise for selective control of *O. nubilalis* in snap bean. In previous studies, cyantraniliprole and chlorantraniliprole performed as well as pyrethroids when applied as foliar sprays during pod formation (Huseth et al., 2015; Schmidt-Jeffris and Nault, 2016). These diamides also have shown potential as at-plant treatments, including seed treatments, in-furrow applications, and fertilizer pre-mixes (Groves et al., 2013a, 2013b; Schmidt-Jeffris and Nault, 2016). Huseth et al. (2015) compared the performance of different application timings (at bud, bloom, or pod stages) of chlorantraniliprole and cyantraniliprole with those of bifenthrin and found similar reductions in plant and pod damage. Although not statistically different, the two diamide treatments had lower damage than the bifenthrin treatment at the two earlier timings (bud and bloom stages).

Cyantraniliprole is compatible with fungicides and herbicides; co-applications of these pesticides resulted in no loss of efficacy against *O. nubilalis* in snap bean (Huseth et al., 2015). The long residuals of the diamides and their likely compatibility with other agrochemicals indicates that these materials could increase the flexibility of pesticide applications for *O. nubilalis* control. This is in contrast to the pyrethroids, which have been documented to lose efficacy when mixed with other agrochemicals like chlorothalonil (Al-Dosari et al., 1996; Sherrod et al., 1983). Diamides could be applied much earlier to the snap bean crop (well before pod formation) to coincide with other crop protectants (herbicide or fungicide applications) to save labor and fuel costs. Additionally, a single, early-season diamide application could replace multiple pyrethroid applications.

The objective of these studies was to compare the residual field efficacy of various diamide-containing insecticides with each other, and with the current industry standard (bifenthrin), for managing *O. nubilalis* in processing snap bean. Additionally, we sought to supplement results from our field studies with those obtained in laboratory bioassays that assessed *O. nubilalis* larval mortality after exposure to the same insecticide treatments. Evaluating the efficacy of these materials at multiple application timings is important because growers will need to know which materials may perform best when co-applied with other pesticides during the crop's production. Such information could become especially critical if older materials, like the pyrethroids, are eliminated due to regulatory or resistance issues.

2. Materials and methods

2.1. Field locations and planting

Studies were conducted on a research farm at the New York State Agricultural Experiment Station (NYSAES) near Geneva, NY (42.865500°, −77.029667°) in 2015 and 2016. The experimental design was identical in both years. All fields were planted with cv. 'Huntington' using a tractor-mounted, precision vacuum planter (Monosem Inc., Edwardsville, KS) at 23 seeds per m. The planting dates were 25 June 2015 and 6 June 2016. All seeds (including the untreated control) were treated with thiamethoxam (Cruiser 5FS, Syngenta Crop Protection, Greensboro, NC) and mefenoxam and fludioxonil (ApronMaxx, Syngenta Crop Protection, Greensboro, NC) to protect seedlings against seed corn maggot (*Delia platura* (Meigen)) (Diptera: Anthomyiidae), early infestations of potato leafhopper (*Empoasca faba*e (Harris)) (Hempitera: Cicadellidae) and seedling diseases. None of these seed treatments affect *O. nubilalis*. Plots consisted of two 3.0 m long rows spaced 0.76 m apart and were flanked by one or two adjacent, untreated barrier rows. Within a row, plots were separated by a 1.5 m section of bare ground.

The experimental design was a two-way factorial arranged as a randomized complete block design (RCBD) consisting of five insecticides (Table 1) applied once per plot at four different timings (1, 7, 10, and 14 days before pod formation (DBP)) and an untreated control (total of 21 treatment combinations). Each treatment was replicated five times.

2.2. Pesticide applications

Four diamide-containing insecticides (Table 1) were compared with an industry standard pyrethroid (bifenthrin) and an untreated control. Insecticide applications were made using a CO_2-pressurized, backpack sprayer calibrated to deliver 185 L/ha at 276 kPa through four flat fan nozzles (TJ 8002VS, Spraying Systems) in which the nozzles were evenly spaced across 1.5 m (two rows) for even broadcast application over the canopy. The non-ionic adjuvant Induce (Helena Chemical Company, Collierville, TN) was added to all materials, except Brigade 2EC (bifenthrin), at a rate of 0.125% V:V. The spray timings (1, 7, 10, 14 DBP) corresponded with 6 August, 31 July, 28 July and 24 July in 2015 and 24 July, 17 July, 14 July and 10 July in 2016.

2.3. Ostrinia nubilalis damage assessment

Natural *O. nubilalis* pressure in snap bean at the research location is typically insufficient to evaluate insecticide treatments. Therefore, the right-hand row of each plot was infested with ~1700 *O. nubilalis* neonates obtained from French Agricultural Research Inc. (Lamberton, MN). Neonates were released by holding wax paper sheets containing emerging larvae over the plants and tapping the sheets evenly over the row. Releases were timed to coincide with pod formation (7–9 August 2015 and 24–25 July 2016).

Harvest occurred on 25–27 August 2015 and 9–10 August 2016. The numbers of damaged and undamaged snap bean plants and market-sized pods were recorded from the infested section of each plot at harvest. Plants were removed from the infested row of each plot and plants and pods were individually inspected for damage. *Ostrinia nubilalis* damage was recorded if an entry hole with feeding

Table 1
Insecticides used in field experiments and bioassays.

Active Ingredient (AI)	Trade name	Rate (L/ha)	g AI/ha
flubendiamide	Belt SC[a]	0.1	70.1
chlorantraniliprole	Coragen SC[b]	0.3	51.2
cyantraniliprole	Exirel[b]	1.0	98.1
chlorantraniliprole + lambda-cyhalothrin	Besiege[c]	0.4	43.9 + 20.0
bifenthrin	Brigade EC[d]	0.2	52.5

[a] Bayer CropScience LP, Research Triangle Park, NC.
[b] E. I. du Pont De Nemours and Co., Wilmington, DE.
[c] Syngenta, Greensboro, NC.
[d] FMC Corporation, Agricultural Products Group, Philadelphia, PA.

damage was observed; in most cases the larva was also present.

2.4. Bioassays to determine residual activity against O. nubilalis larvae

Each year a laboratory bioassay was conducted in which the efficacy of the same treatments used in field trials was evaluated for *O. nubilalis* neonate mortality. Bioassays were initiated on 7 Aug 2015 and 25 Jul 2016 (one day after the 1 DBP spray). Therefore, larvae were exposed to residues that were 1, 7, 10, or 14 d old, corresponding with each spray timing. Three trifoliates were randomly collected from the left-hand row of each plot (the uninfested row). A single leaflet from each trifoliate was placed abaxial side upward into a 10.2 cm diameter Petri dish (Fisher Scientific, Waltham, MA) lined with moistened filter paper. Fifteen *O. nubilalis* neonates were transferred onto each leaflet. As with the field studies, the experimental design was RCBD and each treatment was replicated five times, with three sub-replicates (individual Petri dishes with leaflets) per replicate. Petri dishes were maintained in an environmental chamber at 24 °C and 60% relative humidity. After 96 h, the number of live and dead larvae was recorded.

2.5. Data analyses

Initially, the main effects of "insecticide" and "timing" and their interaction (insecticide × timing) were modeled as fixed effects. Replicate was treated as a random effect. Data for each year were analyzed separately using a generalized linear mixed model (SAS PROC GLIMMIX, SAS Institute, 2016, Cary, NC), specifying a binomial distribution for damage data (damaged plants/total plants and damaged pods/total pods) and mortality data (dead/total) and a normal distribution for yield data. Initial analysis indicated that for all response variables the interaction between "insecticide" and "timing" was significant (except "yield" in 2016, where no effect was significant). Therefore, for the final analysis reported in the results, all 21 treatments ("insecticide" and "timing" combinations and the untreated control) were compared with each other. For all analyses, treatment means were compared using least-squared means at $P < 0.05$.

3. Results

3.1. Weather conditions

Weather conditions in 2015 were very different from those in 2016. In 2015, the month preceding the trial had 21 cm of rainfall and the period during the trial had 24 cm of rainfall. These wet conditions delayed planting by nearly three weeks; however, planting occurred well within the typical processing snap bean planting period in New York. In 2016, the month preceding the trial had 3.4 cm of rainfall and the period during the trial had 6.6 cm of rainfall. The mean (±SE) daily high temperature during the trial in 2015 was 24.9 ± 0.4 °C and in 2016 it was 27.0 ± 0.5 °C.

3.2. Plant damage (Fig. 1A and B)

Plant damage by *O. nubilalis* in 2015 was higher than in 2016. This was exemplified by levels of damage in the untreated control, which was 73% and 32% in 2015 and 2016, respectively. The effect of treatment on plant damage was significant in 2015 ($F_{20,80} = 42.22$; $P < 0.0001$) and 2016 ($F_{20,80} = 16.90$; $P < 0.0001$). Efficacy of all materials declined as residue age (timing of application DBP) increased. In both years, all treatments applied at 1 DBP were equally effective against *O. nubilalis* (~0–1% damage).

In 2015 and 2016, flubendiamide and bifenthrin applied at 7 DBP were less effective at protecting plants against *O. nubilalis* than applications at 1 DBP, and these materials also had significantly higher percentages of damaged plants (4–20%) than other materials applied at 7 DBP. Percent damaged plants treated with chlorantraniliprole, cyantraniliprole, and chlorantraniliprole + lambda-cyhalothrin at 7 DBP remained low (~0–2%).

Cyantraniliprole applied at 10 DBP began to lose efficacy against *O. nubilalis*, resulting in the highest (34%, 2015) and second highest (12%, 2016) percentage of damaged plants compared to other materials applied at 10 DBP. In 2016, bifenthrin applied at 10 DBP had a significantly higher proportion of *O. nubilalis*-damaged plants (19%) than cyantraniliprole; in 2015 *O. nubilalis*-plant damage did not differ when these insecticides were applied at 10 DBP. Also in 2015, the two chlorantraniliprole-containing materials applied at 1, 7, 10 DBP provided statistically equivalent levels of *O. nubilalis* control (all ~0% damage). Similarly, in 2016, the chlorantraniliprole-only treatment applied at those times did not differ in efficacy (0–1%) for any of those residue ages. However, in 2016, chlorantraniliprole + lambda-cyhalothrin applied at 10 DBP was slightly less effective in preventing plant damage (3%) than when it was applied at 1 and 7 DBP (~1%).

In 2015, the flubendiamide treatment applied at 14 DBP failed to control *O. nubilalis*, as plant damage (68%) did not differ from damage in the untreated control (73%). In contrast, in 2016, flubendiamide applied at 14 DBP had significantly lower damage (16%) than the control (32%). In both years of the study, the highest percentage of *O. nubilalis*-damaged plants occurred in plots applied with flubendiamide at 14 DBP. The second highest level of plant damage occurred in plots treated with bifenthrin at 14 DBP (2015: 59%, 2016: 13%), but levels were not significantly different from those treated with flubendiamide at the same time (2015: 68%, 2016: 16%). Treatments containing chlorantraniliprole had the least amount of *O. nubilalis*-plant damage compared with other products applied at 14 DBP (2015: 15%, 2016: 7%). In 2015, *O. nubilalis*-plant damage was intermediate for the cyantraniliprole treatment applied at 14 DBP (48%), whereas in 2016 plant damage was equal to the chlorantraniliprole-containing treatments (8%). Overall,

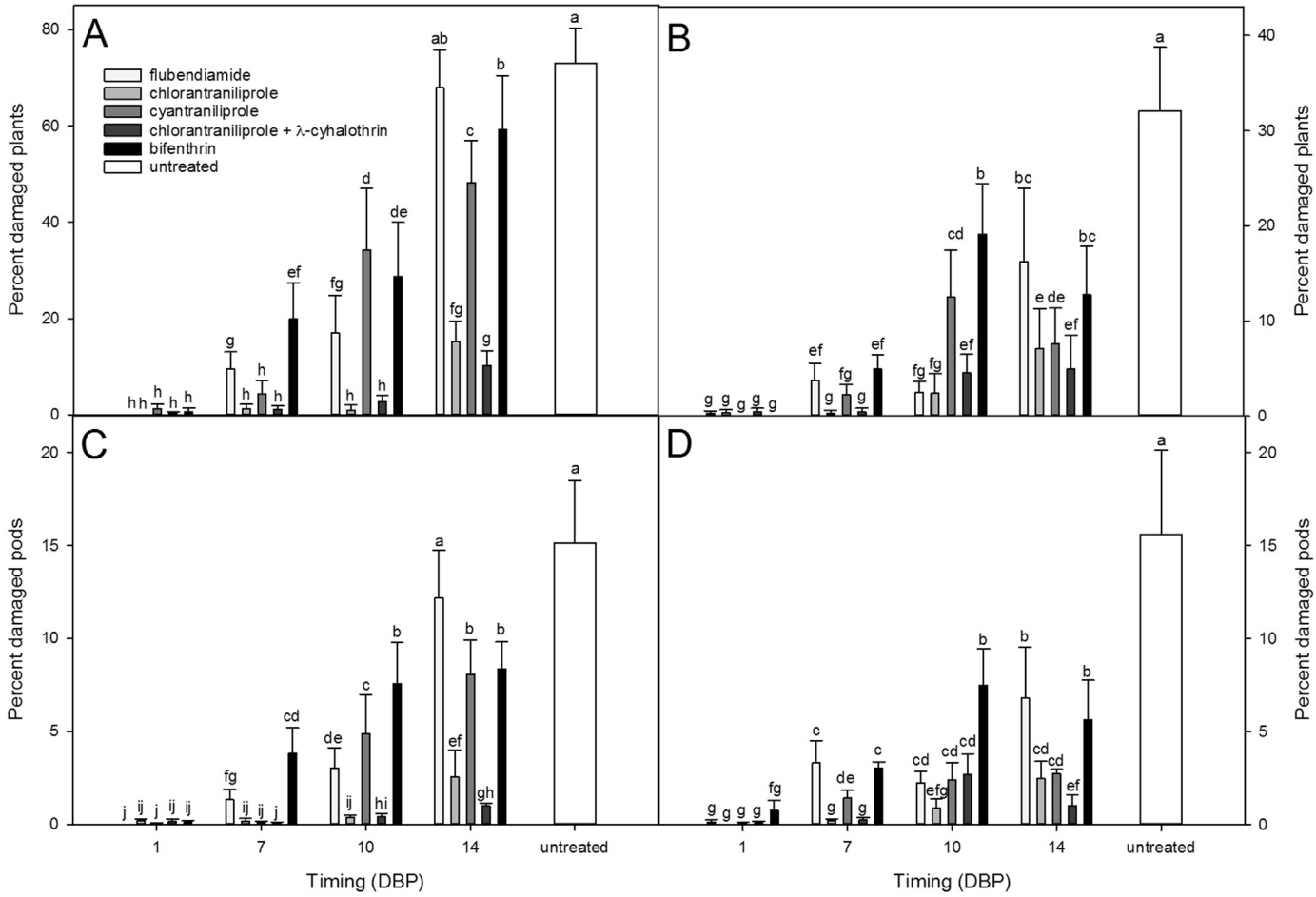

Fig. 1. Percentage of insecticide-treated plants damaged by *O. nubilalis* in A) 2015 and B) 2016 and percentage of damaged pods in C) 2015 and D) 2016. Means followed by the same letter are not statistically different (least-squared means, $P < 0.05$).

flubendiamide and bifenthrin applied at 7 to 14 DBP tended to have the highest percent of *O. nubilalis* plant damage, while treatments containing chlorantraniliprole applied at the same times tended to have the least amount of plant damage.

3.3. Pod damage (Fig. 1C and D)

Pod damage by *O. nubilalis* in the untreated controls was similar in 2015 and 2016 (~15%). The effect of treatment on pod damage was significant in 2015 ($F_{20,80} = 39.93$; $P < 0.0001$) and 2016 ($F_{20,80} = 30.86$; $P < 0.0001$). Damage to pods by *O. nubilalis* for a given treatment followed similar patterns as the damage to plants. In both years, all insecticides applied at 1 DBP performed equally well in controlling *O. nubilalis* (<1% pod damage).

In 2015, bifenthrin (4%) and flubendiamide (1%) applied at 7 DBP had significantly higher *O. nubilalis*-damage than the other pesticides (~0%) applied at the same time. The two chlorantraniliprole-containing treatments and cyantraniliprole applied at 1 and 7 DBP had equivalent levels of *O. nubilalis*-damage (~0%). In 2016, a similar performance difference occurred, except that *O. nubilalis*-pod damage in the cyantraniliprole treatment applied at 7 DBP (1%) was intermediate to damage in the bifenthrin and flubendiamide treatments (3%) and the two chlorantraniliprole treatments (0%) applied at the same time.

In both years, *O. nubilalis*-pod damage in the chlorantraniliprole treatment applied at 10 DPB was at the same level as those applied at 1 and 7 DPB (<1%). In 2015, *O. nubilalis*-pod damage in the chlorantraniliprole + lambda-cyhalothrin treatment applied at 10 DPB was equal to the chlorantraniliprole treatment applied at the same time (both ~0%), but it was higher in 2016 (2% vs. 1%). In 2016, flubendiamide, cyantraniliprole, and chlorantraniliprole + lambda-cyhalothrin applied at 10 DPB had equivalent amounts of *O. nubilalis*-pod damage (2–3%), whereas bifenthrin applied at the same time had the highest damage (8%) and chlorantraniliprole-alone treatment had the lowest damage (<1%).

For both years of the study, flubendiamide applied at 14 DBP had the highest amount of pod damage (2015: 12%, 2016: 7%); it had the same percentage of damaged pods as the untreated control in 2015, but in 2016 it had lower pod damage. In both years, chlorantraniliprole + lambda-cyhalothrin had the lowest percentage of *O. nubilalis*-damaged pods of all the 14 DBP treatments (1%), followed by chlorantraniliprole-only in 2015 (3%), and chlorantraniliprole and cyantraniliprole (2–3%) in 2016.

3.4. Yield (Table 2)

Overall, yields were much higher in 2015 than 2016. The difference in precipitation was the probable cause of the higher yield in 2015 (plots were not irrigated in either year). The effect of treatment on yield was significant in 2015 ($F_{20,80} = 1.93$; $P = 0.0212$), but not in 2016 ($F_{20,80} = 1.34$; $P = 0.1776$). In 2015, only yield in the chlorantraniliprole-only treatments applied at 7, 10, and 14 DBP (~3 kg) was significantly higher than yield in the untreated control (~2 kg).

Table 2
Mean yield (±SE) of snap beans harvested from field plots that received insecticide treatments at various times before pod formation in 2015 and 2016. Means followed by the same letter are not statistically different (least-squared means, $P < 0.05$).

Pesticide	Timing[a]	Yield (kg)	
		2015	2016
untreated	–	1.59 ± 0.37cde	0.87 ± 0.05
flubendiamide	14	1.86 ± 0.12a-e	1.19 ± 0.16
chlorantraniliprole		2.51 ± 0.42a	1.03 ± 0.12
cyantraniliprole		1.48 ± 0.28de	1.21 ± 0.11
chlorantraniliprole + lambda-cyhalothrin		2.03 ± 0.38a-e	0.98 ± 0.03
bifenthrin		1.98 ± 0.13a-e	1.17 ± 0.07
flubendiamide	10	2.11 ± 0.25a-d	1.19 ± 0.11
chlorantraniliprole		2.63 ± 0.26a	0.98 ± 0.09
cyantraniliprole		1.51 ± 0.26de	0.96 ± 0.14
chlorantraniliprole + lambda-cyhalothrin		1.56 ± 0.36cde	1.11 ± 0.09
bifenthrin		1.98 ± 0.44a-e	1.17 ± 0.12
flubendiamide	7	2.35 ± 0.40abc	1.19 ± 0.07
chlorantraniliprole		2.62 ± 0.39a	1.03 ± 0.04
cyantraniliprole		1.67 ± 0.28b-e	1.06 ± 0.18
chlorantraniliprole + lambda-cyhalothrin		1.95 ± 0.14a-e	0.94 ± 0.08
bifenthrin		1.26 ± 0.11e	1.00 ± 0.08
flubendiamide	1	1.66 ± 0.37cde	1.04 ± 0.09
chlorantraniliprole		2.07 ± 0.29a-d	1.10 ± 0.10
cyantraniliprole		2.34 ± 0.20abc	1.02 ± 0.13
chlorantraniliprole + lambda-cyhalothrin		2.46 ± 0.22ab	1.36 ± 0.12
bifenthrin		2.19 ± 0.24a-d	0.95 ± 0.11
$F(20,80)$		1.93	1.34
P		0.0212	0.1776

[a] Days before pod formation.

3.5. Bioassays (Fig. 2)

The effect of treatment on mortality was significant in 2015 ($F_{20,290} = 35.36$; $P < 0.0001$) and 2016 ($F_{20,286} = 28.13$; $P < 0.0001$). All materials caused 99–100% mortality of neonates exposed to residues applied at 1 DBP, except flubendiamide in 2015 (89%). In 2015, chlorantraniliprole, chlorantraniliprole + lambda-cyhalothrin, and bifenthrin applied at 7 DBP caused the same high level of mortality as when applied at 1 DBP, whereas cyantraniliprole applied at 7 DBP lost efficacy (95%). Mortality in the flubendiamide treatment remained lower than other materials at 7 DBP (88%). In 2016, efficacy of bifenthrin (75%) and flubendiamide (90%) treatments applied at 7 DBP was reduced compared with applications at 1 DBP. Mortality of *O. nubilalis* was the same among cyantraniliprole and chlorantraniliprole-containing treatments applied at 7 DBP and 1 DBP (~100%).

In both years, the two chlorantraniliprole-containing treatments caused higher levels of mortality (88–94%) than other materials applied at 10 DBP, but mortality was significantly reduced compared with mortality after applications made at 1 and 7 DBP. The other three materials (flubendiamide, cyantraniliprole, and bifenthrin) applied at 10 DBP also caused less mortality compared with when they were applied at 7 DBP. In 2015, *O. nubilalis* mortality in the flubendiamide treatment applied at 10 DPB (42%) was lower than all other 10 DPB treatments (64–91%), while in 2016 flubendiamide (61%) and bifenthrin (54%) had the lowest and statistically similar levels of mortality among the 10 DPB applications.

In 2015, chlorantraniliprole-alone caused the highest mortality (78%) of the 14 DBP treatments, followed by chlorantraniliprole + lambda-cyhalothrin (50%), then the other three treatments (35%). In 2016, chlorantraniliprole (61%) and chlorantraniliprole + lambda-cyhalothrin (64%) applied at 14 DBP caused equal levels of mortality, followed by bifenthrin (47%) and cyantraniliprole (48%), then flubendiamide (24%). Percent mortality in flubendiamide applied at 14 DBP was statistically equal to percent mortality in the untreated control (21%).

4. Discussion

Weather conditions were very different in the two years of our study. The spring of 2015 was characterized by heavy rainfall, whereas 2016 was hot and dry. The wetter conditions during the 2015 field trial may have been responsible for increased establishment (and resulting damage) of *O. nubilalis* after infestation; plant damage in the untreated control was >2 times higher in 2015 than in 2016. This species is known to perform better in higher humidity conditions. Despite the difference in plant damage, pod damage in the untreated control in both years was very similar (~15–16%). A similar trend was seen in the Huseth et al. (2015) study (which also examined artificially infested plots) which reported very high plant damage in one year (~64%) and lower levels (13–19%) for the other two years, but similar levels of pod damage in all three years (6–15%). While the differences in plant damage in those years were attributed to higher infestation rates (2500 neonates per plot in the "high damage" year, 2000 in the "lower damage" years), our study used the same release rate both years and still obtained different levels of plant damage. Indeed, the release rate in the present study (1700 neonates per plot) was lower than that used in any year of the Huseth et al. (2015) study, yet the

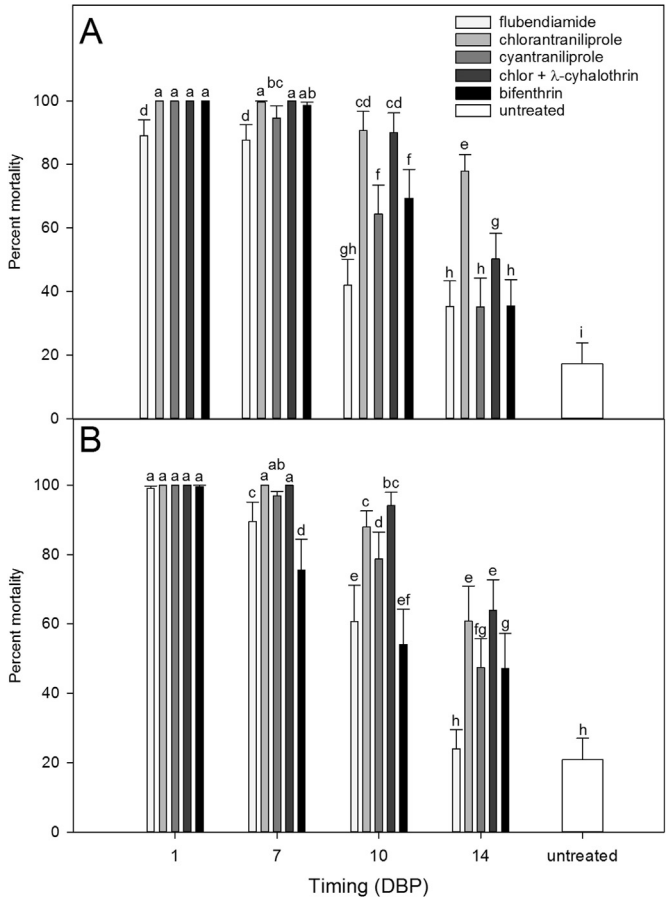

Fig. 2. Percent mortality of *O. nubilalis* neonates exposed to pesticide residues on snap bean leaves in A) 2015 and B) 2016). Means followed by the same letter are not statistically different (least-squared means, $P < 0.05$).

plant and pod damage levels in both 2015 and 2016 were much higher than the two "lower pressure" years in the Huseth et al. (2015) study. Taken together, these results emphasize the likely important role that weather and other abiotic factors have on *O. nubilalis* establishment and subsequent damage in the field.

Despite the contrasting weather conditions in our two-year study, performance of the materials evaluated to control *O. nubilalis* was similar. All materials were highly effective (in terms of plant/pod damage, bioassay mortality) when applied at pod formation (1 DPB timing). However, as the age of residues increased, efficacy decreased. The decline in efficacy was more severe (and occurred earlier) for some materials compared to others. This was most apparent in 2015, when *O. nubilalis* damage was higher.

In the field trials and bioassays, the materials containing chlorantraniliprole (chlorantraniliprole only and chlorantraniliprole + lambda-cyhalothrin) had the highest levels of efficacy at earlier timings, compared with other materials at similar timings. This active ingredient has the potential to provide season-long protection against *O. nubilalis* when applied as a foliar spray even as early as 14 DBP. Other studies also have shown chlorantraniliprole to be an effective material for *O. nubilalis* control. Huseth et al. (2015) achieved an acceptable level of control with chlorantraniliprole applied at pod stage (similar to 1 DBP) and bloom (similar to 7 DBP). Although Huseth et al. (2015) considered the level of control provided by chlorantraniliprole when it was applied at bud stage (similar to 14 DBP) to be unacceptable, this may have been due to the high number of neonates used in artificial infestation. Chlorantraniliprole applied at 14 DBP would likely provide excellent control under the much lower *O. nubilalis* pressure that is observed in New York snap bean fields (Schmidt-Jeffris et al., 2016). In trials where *O. nubilalis* pressure was high enough that artificial infestation was not needed, chlorantraniliprole treatments applied in-furrow (at the same rate used in the present study) reduced pod and plant damage to 0% compared with 15% damaged stems and 0.5% damaged pods in the untreated control (Groves et al., 2013b). The equal effectiveness of both chlorantraniliprole alone and chlorantraniliprole + lambda-cyhalothrin indicates that the addition of the pyrethroid is not necessary for achieving high levels of *O. nubilalis* control. However, late-season infestations of another pest, *Empoasca fabae*, are typically controlled by the foliar-applied pyrethroids used for *O. nubilalis* management, while early-season infestations are managed with neonicotinoid seed treatments (Flood and Wyman, 2005; Nault et al., 2004). Cyantraniliprole has not been successful controlling *E. fabae* (in potato) (Groves et al., 2013a) and chlorantraniliprole is not known for its efficacy against sucking pests (Barry et al., 2015). Therefore, growers whose snap bean fields experience high late-season *E. fabae* pressure will need to consider non-diamide-only foliar products.

Past work with cyantraniliprole has also demonstrated its high efficacy against *O. nubilalis* when applied up to 7 DBP (bloom) (Huseth et al., 2015). In our study, cyantraniliprole also typically did as well as chlorantraniliprole when applied at this phenological stage. In the one year that Huseth et al. (2015) compared chlorantraniliprole to cyantraniliprole, cyantraniliprole tended to outperform chlorantraniliprole in terms of both pod and plant damage (but the difference was not statistically significant). However, that study also used a higher rate of cyantraniliprole than the rate in our study (150 g AI/ha as opposed to 98 g AI/ha). Chlorantraniliprole and cyantraniliprole performed similarly in a field trial where natural *O. nubilalis* pressure was used (Groves et al., 2013b). In the present study, the chlorantraniliprole treatments consistently outperformed cyantraniliprole (in terms of both larval mortality and damage) with differences becoming particularly apparent at 10 and 14 DBP, especially in 2015 (the year with higher pressure). Chlorantraniliprole seemed to outperform cyantraniliprole only when *O. nubilalis* pressure was very high as it was in 2015. In contrast, both products performed equivalently under natural field pressure (Groves et al., 2013b) and lower artificial infestation pressure (Huseth et al., 2015).

By all three measures of efficacy (plant and pod damage, larval mortality), flubendiamide was typically the weakest or second weakest material (usually following bifenthrin) across all application timings, except 1 DBP. To our knowledge, flubendiamide has not been previously evaluated for *O. nubilalis* control in snap bean. One study in sweet corn found that flubendiamide rotated with lambda-cyhalothrin reduced all caterpillar damage (a small percentage of which were *O. nubilalis*) to the same level as other diamide and pyrethroid rotations (Kuhar and Doughty, 2016). However, because a pyrethroid rotation was included, the effect of flubendiamide alone cannot be discerned. Flubendiamide's registration was recently cancelled by the United States Environmental Protection Agency (EPA) due to the determination that flubendiamide use could result in "unreasonable adverse effects on the environment", with specific concerns including soil and water contamination and toxicity to aquatic invertebrates (Environmental Protection Agency, 2016). The lack of flubendiamide's long residual activity coupled with the long residual activity of other diamides, indicates that snap bean growers in our region will not be negatively impacted by the loss of flubendiamide for managing *O. nubilalis*.

Bifenthrin-treated plots consistently had higher damage and

less *O. nubilalis* mortality than chlorantraniliprole- and cyantraniliprole-treated plots at all application timings >1 DBP. These results provide additional support showing that the anthranilic diamides, due to their systemic activity (Barry et al., 2015; Jeanguenat, 2013), have more persistent lepidopteran-active residues than the pyrethroids (Huseth et al., 2015; Schmidt-Jeffris and Nault, 2016). However, as previously mentioned, flubendiamide (a phthalic diamide) also tended to be less effective at earlier application timings (particularly 14 DBP, but also 10 DBP). Clearly, in terms of efficacy, either chlorantraniliprole or cyantraniliprole could replace bifenthrin as an *O. nubilalis* control material in snap bean.

This study and previous work demonstrated the ability of chlorantraniliprole and cyantraniliprole to effectively control *O. nubilalis* in snap bean when applied at multiple timings and via multiple delivery approaches. However, the diamide products remain cost prohibitive compared with pyrethroids for processing snap bean growers. Based on recent estimates from agricultural chemical supply companies in western New York, the diamides Belt SC, Coragen SC, Exirel, and Besiege cost roughly 4×, 7×, 16×and 3×more than Brigade SC (bifenthrin), respectively. Compared with an even more commonly used bifenthrin product (Bifenture; United Phosphorus, King of Prussia, PA), the diamide products cost approximately 9×, 16×, 36×and 7×more, respectively. Until either loss of efficacy due to resistance, loss of registration, or a substantial decrease in the price for diamide insecticides occurs, snap bean growers will likely continue using pyrethroid products for *O. nubilalis* control. Even multiple applications of pyrethroids, with the increased expense of labor and fuel, are still more cost effective than a single diamide application.

5. Conclusions

Although the diamides are not currently a financially viable method for controlling *O. nubilalis* in processing snap bean, it is important to explore new modes of action for pest control. If financial circumstances change in the near future, knowledge of the efficacy of newer materials will allow growers to quickly incorporate these products into their pest management programs. The diamides have demonstrated greater flexibility of application and longer-term efficacy than the industry standard pyrethroid products.

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