Research Article

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Evaluation of diamide insecticides co-applied with other agrochemicals at various times to manage *Ostrinia nubilalis* in processing snap bean

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Abstract

BACKGROUND: Multiple applications of pyrethroid insecticides are used to manage European corn borer, *Ostrinia nubilalis* Hübner, in snap bean, but new diamide insecticides may reduce application frequency. In a 2 year small-plot study, *O. nubilalis* control was evaluated by applying cyantraniliprole (diamide) and bifenthrin (pyrethroid) insecticides at one of three phenological stages (bud, bloom and pod formation) of snap bean development. Co-application of these insecticides with either herbicides or fungicides was also examined as a way to reduce the total number of sprays during a season.

RESULTS: Cyantraniliprole applications timed either during bloom or during pod formation controlled *O. nubilalis* better than similar timings of bifenthrin. Co-applications of insecticides with fungicides controlled *O. nubilalis* as well as insecticide applications alone. Insecticides applied either alone or with herbicides during bud stage did not control this pest.

CONCLUSION: Diamides are an alternative to pyrethroids for the management of *O. nubilalis* in snap bean. Adoption of diamides by snap bean growers could improve the efficiency of production by reducing the number of sprays required each season.

Supporting information may be found in the online version of this article.

Keywords: chlorantraniliprole; cyantraniliprole; European corn borer; *Phaseolus vulgaris*; pyrethroid alternative; tank-mix

1 INTRODUCTION

European corn borer, *Ostrinia nubilalis* Hübner (Lepidoptera: Crambidae), is an economically important pest of succulent snap bean, *Phaseolus vulgaris* L., in the Great Lakes region of the United States. In temperate, snap bean production regions, *O. nubilalis* has one or two generations each season and will sporadically infest snap bean crops.[1–3] *Ostrinia nubilalis* larvae initially feed on foliage, but then bore into developing bean pods, which results in either direct contamination or reduced quality of processed bean products (i.e. secondary pathogen infections following feeding damage). Larvae also attack stems of snap bean plants, reducing plant health by limiting water and nutrient movement.[4] In addition to reduced plant health, neonate larvae that attack small lateral bean stems have been shown to shift feeding activity to pods in later instars before completing development.[2] This relationship between plant and pod damage has been the basis for recommendations to protect snap bean crops prior to pod formation under high infestation pressure.[2]

Historically, tolerance for pod damage by snap bean processors has been very low, and field rejections have been documented at a threshold of one *O. nubilalis* larva per 1000 pods.[2] In New York State, Eckenrode *et al.*[1] reported field rejections of processing snap bean and economic losses for processors even under low adult *O. nubilalis* pressure. As a preventive measure against *O. nubilalis* contamination, snap bean processors in the Great Lakes region have recommended that growers apply a series of prophylactic insecticide sprays during vulnerable periods of crop development, a practice that has been in use for the past four decades.[1–4] Although the grower community has successfully used these scheduled insecticide sprays to minimize contamination, interest among consumers for more sustainably grown snap beans has motivated a reduction of all production inputs (e.g. herbicides, insecticides, fungicides, nutrients and fuel). Consumer demand has motivated an evaluation of newer insecticides for *O. nubilalis* management that could decrease the environmental footprint of the crop, and also improve product safety by limiting pesticide residues and minimize cost of production for the grower.

In the Great Lakes region, insecticide application decisions for *O. nubilalis* control are based on the expected vulnerability of

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plant growth stages to infestation and the anticipated contamination of the processed product.[5,6] Insecticide applications begin at either bloom or early pod formation (R6–R7 growth stage) to prevent *O. nubilalis* larval infestation of bean pods.[2,3] Programs use a sequence of two or three foliar-applied pyrethroids separated by 5–7 days.[6] The transition to pyrethroid insecticides from older, broad-spectrum organophosphate insecticides has reduced the environmental footprint of pest management in snap bean production systems;[6] however, pyrethroids have limited residual activity and often require several applications to protect the crop during vulnerable pod formation stages, which may last 14–18 days. Transition from pyrethroid insecticides to newer insecticides with longer residual activity could result in fewer pesticide applications and reduce the amount of fossil fuel required to produce the crop, thereby improving the economic and environmental sustainability of the snap bean production system. Moreover, insecticides that are compatible in tank mixes with other common agrochemicals (e.g. fungicides and herbicides) could be co-applied at earlier crop development stages, further reducing the application frequency in the crop.

Cyantraniliprole is an anthranilic diamide insecticide that has excellent activity on several chewing pests and selected piercing-sucking insects.[7,8] Cyantraniliprole is anticipated to be the newest diamide registered in the United States on snap bean for control of *O. nubilalis*, and the third diamide insecticide to be registered on snap bean, after chlorantraniliprole and flubendiamide.[9,10] When applied to foliage, cyantraniliprole moves into local leaf tissues at the site of application, but also moves to other vegetative structures through the plant xylem.[7,8] The combination of translaminar and systemic plant protection is a desirable property for crops like snap bean that have both piercing-sucking pests (e.g. aphids and leafhoppers) and chewing pests, such as *O. nubilalis*. Systemic movement into the developing pod is very limited, however, and damaging larval stages often encounter the insecticides only in the foliage.

In addition to insect pests, snap bean producers routinely apply herbicides and fungicides during well-defined phenological stages of snap bean. Co-application of cyantraniliprole with other agrochemicals at these times could reduce the total number of applications needed and may increase the flexibility in timing of *O. nubilalis* management tactics. Importantly, previous studies in other crops have shown antagonistic effects of certain fungicides on the activity of insecticides when co-applied to crops.[11–13] Determining whether similar antagonistic effects occur during the co-application of a diamide is important information for the design of new pest management recommendations in snap bean.

The objective of this study was to examine the potential for improving control of *O. nubilalis* in processing snap bean with diamide insecticides. Specifically, we (1) compared *O. nubilalis* control with chlorantraniliprole, cyantraniliprole and bifenthrin at three different phenological stages of snap bean development (i.e. bud, bloom and pod formation) to determine the duration of residual activity for each insecticide under field conditions in snap bean, and (2) co-applied cyantraniliprole and bifenthrin insecticides with either herbicides or fungicides at similar crop stages to determine whether co-applications of either cyantraniliprole or bifenthrin with common agrochemicals would reduce *O. nubilalis* control. As Wiles *et al.*[7] documented translaminar and systemic movement of cyantraniliprole in plants, we hypothesized that the control of *O. nubilalis* with a single cyantraniliprole application would be significantly better than a pyrethroid application timed during early reproductive stages (e.g. bud and bloom). Additionally, we hypothesized that the co-application of insecticides with other agrochemicals would not result in increased loss of *O. nubilalis* control.

2 METHODS

2.1 Small-plot insecticide timing and co-application studies

2.1.1 *Experimental site and design*

Experiments were conducted at Cornell University's NYSAES Fruit and Vegetable Research Farm near Geneva, New York, in 2012, 2013 and 2014 (42.866664° N, −77.029784° W). The cultivar 'Huntington' was chosen as one common processing snap bean cultivar grown in the Great Lakes region. Experiments were planted on 31 May 2012, 5 June 2013 and 3 June 2014. For each experiment, a 0.6 ha field was machine planted at a density of 23 seeds m^{-1} using a tractor-mounted planter (Monosem NG Plus; Monosem Inc., Edwardsville, KS). Individual plots consisted of two rows of 3.1 m length, and rows were spaced 0.8 m apart. Plots were arranged in a randomized complete block design with five replications. Each plot was flanked by two untreated rows and 1.5 m of bare soil between experimental blocks. Best management practices for weed, irrigation and nutrient management for processing snap bean were used.[14]

All seeds received a vendor-applied seed treatment of thiamethoxam, mefenoxam and fludioxonil (CruiserMaxx™; Syngenta, Greensboro, NC) to protect seedlings early in the season against seedcorn maggot (*Delia platura* Meigen), potato leafhopper (*Empoasca fabae* Harris) and diseases. Moreover, thiamethoxam seed treatment is not considered to be an effective material for managing *O. nubilalis.*

2.1.2 *Insecticide timing experiments*

In 2012, insecticide treatments of chlorantraniliprole, cyantraniliprole and bifenthrin were selected as two diamide insecticides and an industry standard insecticide for *O. nubilalis* control respectively. Each insecticide was tested at a single application rate (Table 1). In 2013 and 2014, cyantraniliprole was tested at two different application rates and compared with a single rate of bifenthrin for *O. nubilalis* control (Table 1). Because cyantraniliprole has better control of piercing-sucking pests than chlorantraniliprole, it will control the key pests of snap bean and will be an important material for pest management in processing bean. For this reason, we chose to include only cyantraniliprole in 2013 and 2014.

In each study year, cyantraniliprole treatments were applied with a penetrating adjuvant surfactant as suggested by the manufacturer label (0.25% v/v methylated seed oil; DuPont Crop Protection, Wilmington, DE). All crop protection products used in this study were commercially formulated and applied at several rates to examine the efficacy against *O. nubilalis* larvae (Table 1). Each insecticide at each rate in the small-plot timing study was tested individually at three different phenological stages of snap bean development. Bud stage applications occurred prior to the crop flowering, approximately 30 days after planting (R5 stage bean).[15] The second application occurred at the bloom phase (R6 stage) of bean growth. The final application occurred at pod formation phase (R7 stage).

2.1.3 *Co-application of insecticides with other agrochemicals*

In addition to insecticide-only treatments applied at the three plant stages, insecticides were also paired with common bud

Table 1. Details on agrochemicals evaluated in field experiments

Type	Study years[a]	Application timing[b]	Trade name	Active ingredient (AI)	Chemical group	Manufacturer	Rate ha^{-1}	g (AI) ha^{-1}
Insecticides[c]	2012, 2013, 2014	Bud (R5), bloom (R6), pod formation (R7)	Brigade® 2EC	Bifenthrin	Pyrethroid	FMC Corporation, Agricultural Products Group, Philadelphia, PA	0.2 L	47.9
	2012	Bud (R5), bloom (R6), pod formation (R7)	Coragen®	Chlorantraniliprole	Diamide	E. I. du Pont De Nemours and Co., Wilmington, DE	0.3 L[d]	51.2
	2013, 2014	Bud (R5), bloom (R6), pod formation (R7)	Exirel™	Cyantraniliprole	Diamide	E.I. du Pont De Nemours and Co., Wilmington, DE	1.0 L[d]	100.0
	2012, 2013, 2014	Bud (R5), bloom (R6), pod formation (R7)	Exirel™	Cyantraniliprole	Diamide	E.I. du Pont De Nemours and Co., Wilmington, DE	1.5 L[d]	150.0
Herbicides	2013, 2014	Bud (R5)	Basagran®	Bentazon	Benzothiadiazinone	Arysta LifeScience North America, LLC, Cary, NC	0.9 L	431.4
	2013, 2014	Bud (R5)	Reflex®	Fomesafen	Diphenyl ether	Syngenta Crop Protection, LLC, Greensboro, NC	0.9 L	216.0
Fungicides	2013, 2014	Bloom (R6)	Topsin® M WSB	Thiophanate-methyl	Thiophanate	United Phosphorus, Inc., King of Prussia, PA	2241.6 g	1569.1
	2013, 2014	Pod formation (R7)	Bravo Weather Stik®	Chlorothalonil	Chloronitrile	Syngenta Crop Protection, LLC, Greensboro, NC	2.3 L	1656.0

[a] Chlorantraniliprole was only included in the 2012 study. Co-applications were only tested in 2013 and 2014.
[b] Applications were timed at specific phenological stages of bean maturation. Growth stages when treatments were applied are given in parentheses.
[c] Preparations were based on 183.3 L (48.4 gal) ha^{-1} in 2012, 171.2 L (45.2 gal) ha^{-1} in 2013 and 187.1 L (49.4 gal) ha^{-1} in 2014.
[d] Applications of cyantraniliprole were all paired with 0.25% v/v methylated seed oil.

stage herbicides, bloom stage fungicides and pod formation stage fungicides (Table 1 and supporting information Table S1). Each insecticide at each rate was co-applied with either weed or disease management tools at specific phenological stages defined in Section 2.1.2. Individual insecticide treatments and co-applications were tested to determine whether *O. nubilalis* control was compromised by the herbicides and fungicides. Bud stage insecticide applications were paired with fomesafen and bentazon herbicides which are used in combination to control annual broadleaves (Table 1).[14] Bloom stage insecticide applications were paired with thiophanate-methyl fungicide used to control white mold [*Sclerotinia sclerotiorum* (Lib.) de Bary].[14] Pod formation stage insecticide applications were paired with chlorothalonil fungicide used to control gray mold (*Botrytis cinera* Pers.: Fr.).[14] Preliminary tests revealed no physical incompatibility of insecticides with these herbicides and fungicides.

2.1.4 *Pesticide applications*

Plots were designated to receive a foliar insecticide treatment during one of the three phenological crop stages described above. Bud treatments were applied on 2 July 2012, 6 July 2013 and 5 July 2014. Bloom stage treatments were applied on 10 July 2012, 13 July 2013 and 15 July 2014. Pod formation treatments were applied on 16 July 2012, 19 July 2013 and 22 July 2014. Pesticides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 183 L ha^{-1} at 276 kPa. In 2012, sprays were delivered through three hollow-cone nozzles (TeeJet TXA8001VK; Spraying Systems, Wheaton, IL) in which the center nozzle was directed over the top of the row and the others were on drop pipes directed into the side of the canopy. In 2013 and 2014, sprays were delivered through four flat-fan nozzle tips (TeeJet TR8002VS; Spraying Systems) evenly spaced across 1.5 m for an even broadcast application over two adjacent rows of plant canopy.

2.1.5 *Infestation and evaluation*

Natural *O. nubilalis* pressure in small-plot experiments is rarely sufficient for effective evaluation of insecticide treatments on snap bean. To increase *O. nubilalis* pressure during the typical infestation period, a single row was infested with neonate larvae during late bloom to early pod formation stage. *Ostrinia nubilalis* egg masses were obtained from a laboratory-reared colony (French Agricultural Research, Inc.; Lamberton, MN). Egg masses were maintained until hatching in an environmental chamber at 24 °C. In 2012, one row in each plot was infested with approximately 1000 neonates on 15 July, and a second release of 1000 neonates per plot on 17 July. In 2013, one row in each plot was infested with approximately 1000 neonates on 16 July, a second release of 1000 neonates on 17 July and a third release of 500 neonates per plot on 18 July. In 2014, one row in each plot was infested with approximately 1000 neonates on 21 July and a second release of 1000 neonates on 22 July. Distribution of infestation events over several consecutive days decreased the likelihood that acute environmental conditions (e.g. low humidity, high air temperatures and direct sun) would adversely affect larval survivorship.[3] An untreated control treatment was included to confirm success of *O. nubilalis* establishment and damage.

All plants within the infested row were harvested on 1 August 2012, 6–7 August 2013 and 5–6 August 2014. Each snap bean plant and marketable pod was inspected for *O. nubilalis* damage, and numbers of plants and market-sized pods damaged and not damaged by *O. nubilalis* larvae were recorded from each plot.

2.2 Statistical analysis

To determine the effect of different insecticides and delivery timings on *O. nubilalis* damage to snap bean, we reported the average number of damaged plants and pods at harvest. Study year and location were analyzed independently because agronomic and climatic conditions differed annually. To determine whether co-application of insecticides with other agrochemicals reduced efficacy against *O. nubilalis* plant or pod damage, we conducted a series of independent tests on paired combinations. Because different co-application partners (i.e. herbicides and fungicides) were used at different time points, the study design was not balanced. We analyzed each insecticide and insecticide co-applied with other pesticides independently to determine whether blends of specific agrochemicals had adverse effects on *O. nubilalis* efficacy. Preliminary analyses indicated that bifenthrin at bud stage had the least efficacy on *O. nubilalis.* We chose to use bifenthrin at bud stage as the reference contrast in all full models examining insecticide timing. All data manipulation and statistical analyses were conducted in R,[16] using the base distribution package.

Preliminary analyses of the full study design confirmed that untreated controls had significantly greater plant and pod damage than insecticide treatments. Because comparisons of interest were between the standard insecticide used by the processing snap bean industry (i.e. bifenthrin) and the novel diamide insecticide (i.e. cyantraniliprole) delivered at different times, untreated control plots were omitted from further analyses, but were included in tables for comparison purposes. Moreover, because numbers of neonates used to infest plots differed between years, a comparison between untreated controls was made as a single estimate of infestation efficiency using ANOVA in R ($\alpha = 0.05$; functions *lm* and *anova*). All count data were converted to percentages because the number of plants and pods between plots differed. Data on the proportion of damaged bean pods and damaged bean plants were analyzed using ANOVA in R (functions *lm* and *anova*), with timing, insecticide and their interaction as independent variables. The interaction between timing of application and insecticide active ingredient was one primary hypothesis tested, so we chose to retain this interaction term and associated main effects in the final model for comparison purposes. Treatment means from the final models were compared using Tukey's honestly significant difference test ($\alpha = 0.05$).

In a second analysis, the effect of co-application of insecticides and other crop protectants on *O. nubilalis* pod damage was determined. Independent comparisons between each insecticide and paired bud stage herbicides, bloom stage fungicides and pod stage fungicides were completed with Welch *t*-tests for unequal variances in R ($\alpha = 0.05$; function *t.test*). A one-sided *t*-test was used to determine whether the percentage of *O. nubilalis* damage was greater than damage in insecticide treatments alone (i.e. antagonistic effect). Because paired insecticides and all co-application treatments were not tested at every application time point, multiple comparisons of efficacy through time for each insecticide were not conducted. To meet assumptions of normality, percentages derived from counts were transformed using an arcsine square root transformation {i.e. arcsin[sqrt(damaged plants/total plants)]}. However, non-transformed means and standard deviations are presented for graphical and tabular comparison.

3 RESULTS

3.1 Insecticide timing

The percentage of marketable pods damaged by *O. nubilalis* varied significantly by insecticide treatment and application timing main effects in 2013 ($F = 6.44$; df = 12, 32; $P < 0.01$), but only the application timing main effect was significant in 2012 ($F = 2.37$; df = 12, 32; $P = 0.03$) and 2014 ($F = 2.72$; df = 12, 32; $P = 0.01$) (Table 2). Greater *O. nubilalis* damage to bean pods was observed for insecticides sprayed at the bud formation application time than bloom or pod formation application timings (Tables 3 and 4, Fig. 1). As insecticide and timing main effects were both only significant in 2013, mean separations of individual treatments were completed for that study year only (Fig. 2). However, average proportion damaged pod summary statistics are presented for comparison purposes (Tables 3 and 4). There was no significant insecticide treatment × timing interaction effect on percentage of damaged bean pods in 2012, 2013 or 2014.

Evaluation of the percentage of plants damaged by *O. nubilalis* also varied significantly by treatment and timing main effects in 2013 ($F = 5.08$; df = 12, 32; $P < 0.01$), but only the timing main effect was significant in 2012 ($F = 2.87$; df = 12, 32; $P < 0.01$) and 2014

Table 2. ANOVA results for main effects and interactions for *O. nubilalis* infestation of pods and plants

		Plant damage			Pod damage		
Year	Source	df[a]	*F*	*P*	df[a]	*F*	*P*
2012	Block	4	2.9	0.03	4	1.0	0.42
	Timing	2	7.7	<0.01	2	6.8	<0.01
	Insecticide	2	1.9	0.17	2	2.3	0.12
	Timing × insecticide	4	0.8	0.52	4	1.5	0.22
2013	Block	4	1.6	0.2	4	5.0	<0.01
	Timing	2	19.1	<0.01	2	18.4	<0.01
	Insecticide	2	5.6	<0.01	2	8.7	<0.01
	Timing × insecticide	4	1.2	0.31	4	0.8	0.52
2014	Block	4	0.6	0.7	4	0.9	0.46
	Timing	2	12.9	<0.01	2	11.3	<0.01
	Insecticide	2	0.4	0.67	2	0.1	0.91
	Timing × insecticide	4	0.9	0.46	4	0.9	0.48

[a] Total df = 32 for plant and pod damage tests.

Table 3. Average *O. nubilalis* infestation (mean percentage ± SE) of snap bean pods and plants treated at three phenological plant stages with chlorantraniliprole, cyantraniliprole and bifenthrin in 2012

Phenological stage	Insecticide	Plant damage	Pod damage
Untreated[a]	–	18.5 ± 5.2	8.7 ± 2.5
Bud[b]	Bifenthrin	9.0 ± 6.4	2.6 ± 1.2
	Chlorantraniliprole (51.2 g AI ha^{-1})	4.1 ± 3.3	1.9 ± 1.1
	Cyantraniliprole (150 g AI ha^{-1})	1.0 ± 0.7	0.7 ± 0.3
Bloom	Bifenthrin	0.7 ± 0.4	1.4 ± 0.4
	Chlorantraniliprole (51.2 g AI ha^{-1})	0.0 ± 0.0	0.0 ± 0.0
	Cyantraniliprole (150 g AI ha^{-1})	0.0 ± 0.0	0.2 ± 0.1
Pod formation	Bifenthrin	0.0 ± 0.0	0.0 ± 0.0
	Chlorantraniliprole (51.2 g AI ha^{-1})	0.0 ± 0.0	0.3 ± 0.1
	Cyantraniliprole (150 g AI ha^{-1})	0.0 ± 0.0	0.0 ± 0.0

[a] Untreated controls were not included in analyses, but have been provided for comparison.
[b] Timing main effects were significant (Table 2); the insecticide main effect and insecticide by timing interaction were not significant.

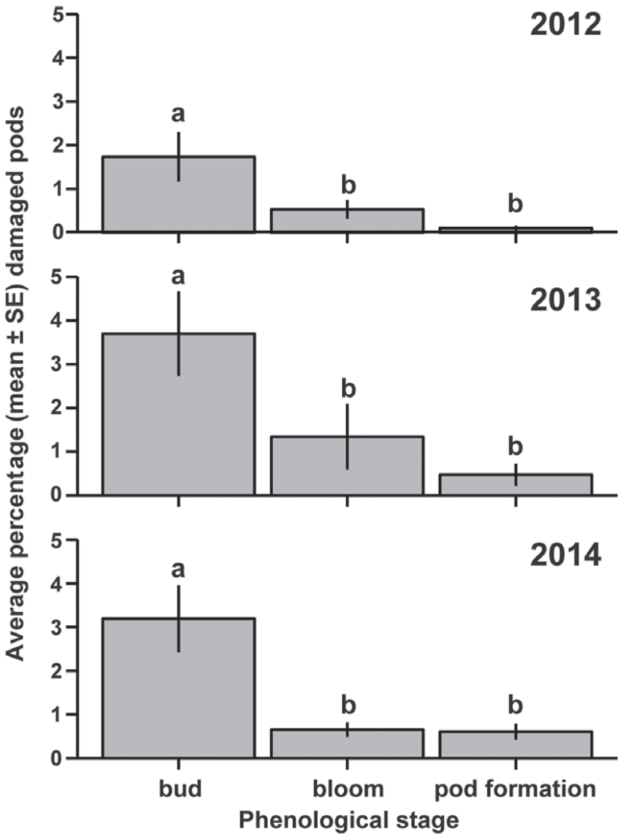

Figure 1. Average (mean percentage ± SE) *O. nubilalis* snap bean pod damage within each phenological application timing in 2012, 2013 and 2014. Means followed by the same lower-case letter do not differ significantly (Tukey's HSD test at $P = 0.05$; overall test statistics are given in Table 2).

($F = 2.49$; df = 12, 32; $P = 0.02$) (Table 2). *Ostrinia nubilalis* damage to bean plants for insecticides sprayed at the bud formation application time was greater than damage in treatments applied during the bloom or pod formation application times (Tables 3 and 4). Similarly to results observed for pod damage, timing and insecticide main effects were both significant in 2013 only, and means separations are only presented for that year (Fig. 2). Furthermore, there was no significant treatment × timing interaction effect on the percentage of damaged bean plants in 2012, 2013 or 2014.

Average percentages of damaged pods and plants differed across years (Tables 3 and 4). Comparison of untreated control plots between years showed a significant effect of year for plant damage ($F = 15.28$; df = 2, 12; $P < 0.01$), but no significant difference in pod damage ($F = 2.01$; df = 5.49; $P = 0.17$). Control of *O. nubilalis* damage to snap bean plants and pods was equal for chlorantraniliprole and a high rate of cyantraniliprole (150 g ha^{-1}) in 2012 (Table 3). Comparison of insecticides alone and insecticides paired with either fungicides or herbicides revealed no significant reduction in *O. nubilalis* control for any combination in either 2013

Table 4. Average *O. nubilalis* infestation (mean percentage ± SE) of snap bean pods and plants treated at three phenological plant stages with cyantraniliprole and bifenthrin in 2013 and 2014

		Plant damage		Pod damage	
Phenological stage	Insecticide	2013[b]	2014	2013	2014
Untreated[a]	–	63.5 ± 9.8	13.3 ± 3.8	14.8 ± 4.6	6.0 ± 1.4
Bud	Bifenthrin	22.1 ± 10.1	11.3 ± 3.5	5.0 ± 2.7	4.4 ± 1.5
	Cyantraniliprole (100 g AI ha^{-1})	19.4 ± 7.5	6.9 ± 2.2	3.7 ± 1.2	2.8 ± 1.0
	Cyantraniliprole (150 g AI ha^{-1})	20.5 ± 2.0	9.6 ± 6.4	2.4 ± 0.5	2.4 ± 1.5
Bloom	Bifenthrin	12.5 ± 3.9	1.2 ± 1.2	3.7 ± 2.0	0.4 ± 0.2
	Cyantraniliprole (100 g AI ha^{-1})	1.5 ± 1.1	1.4 ± 0.7	0.2 ± 0.1	0.8 ± 0.4
	Cyantraniliprole (150 g AI ha^{-1})	1.7 ± 1.3	1.0 ± 0.7	0.1 ± 0.1	0.8 ± 0.3
Pod formation	Bifenthrin	7.7 ± 3.4	0.0 ± 0.0	1.2 ± 0.7	0.7 ± 0.5
	Cyantraniliprole (100 g AI ha^{-1})	0.8 ± 0.8	3.8 ± 2.2	0.2 ± 0.1	0.6 ± 0.3
	Cyantraniliprole (150 g AI ha^{-1})	0.5 ± 0.5	1.1 ± 1.1	0.0 ± 0.0	0.5 ± 0.2

[a] Untreated controls were not included in analyses, but have been provided for comparison.
[b] Timing main effects were significant in both years (Table 2); in 2013, insecticide main effects were also significant (mean separations are presented in Fig. 2).

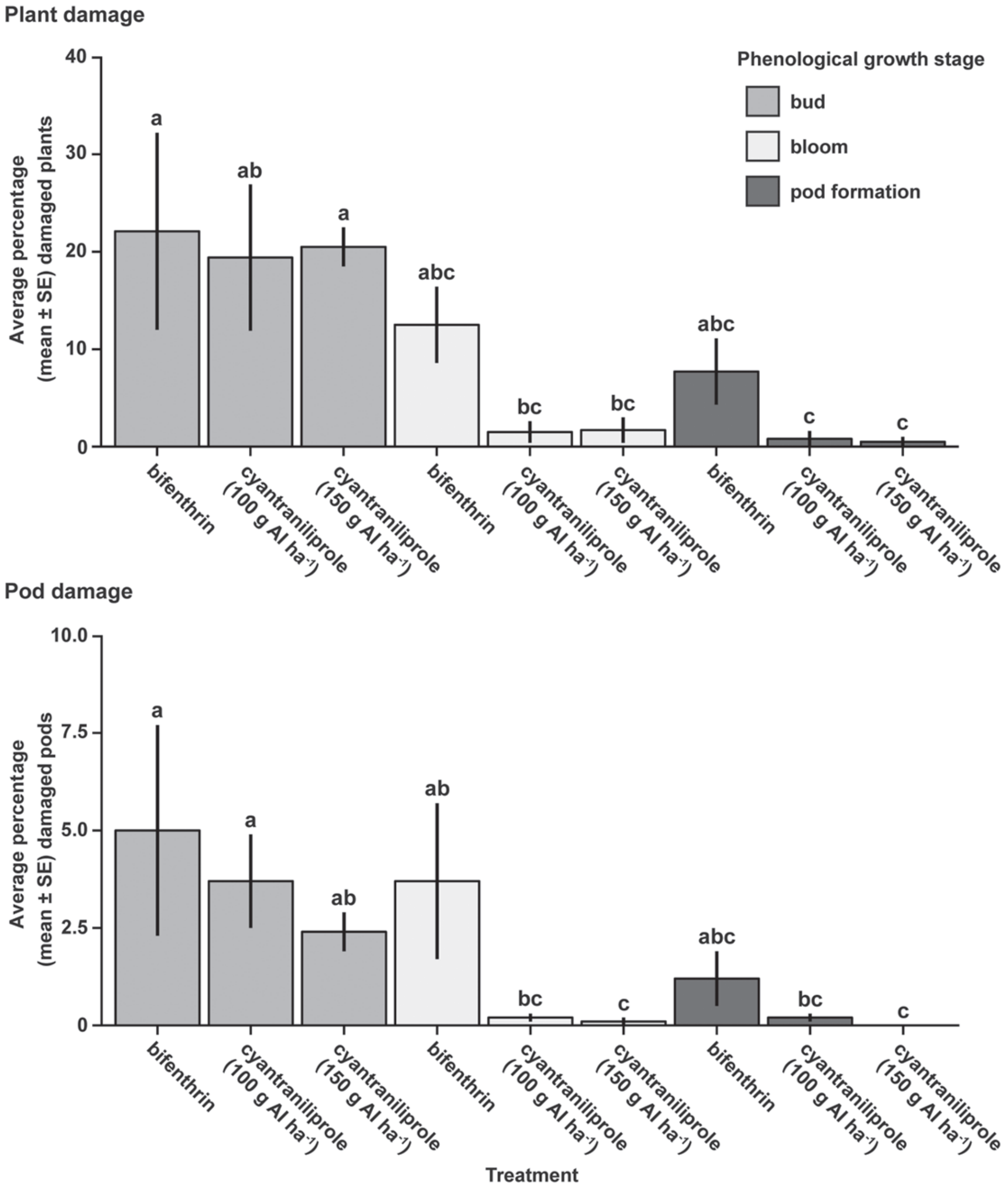

Figure 2. Average (mean percentage ± SE) *O. nubilalis* snap bean plant and pod damage within each phenological application timing in 2013. Means followed by the same lower-case letter do not differ significantly within individual snap bean damage group (Tukey's HSD test at $P = 0.05$; overall test statistics are given in Table 2).

or 2014, indicating no antagonistic effects of co-application with these insecticides and other agrochemicals.

4 DISCUSSION

Incorporating newer, reduced-risk insecticides into commercial agriculture pest management programs requires activity on target pests, minimal impact on non-target organisms and compatibility with large-scale production systems. In high-value processing crops, highly mobile or ephemeral insect pest infestations (e.g. *O. nubilalis* and *Helicoverpa zea* Boddie) are often controlled with successive, prophylactic insecticide applications at specific plant growth stages.[6,17,18] Over the past four decades, processing snap bean producers have relied on prophylactic pyrethroid insecticide applications based on vulnerable, phenological stages to manage *O. nubilalis* infestations.[6,17] Integration of diamide insecticides could further improve sustainability of snap bean production by limiting non-target impacts while reducing the total number of sprays. However, integration of these new insecticides into the current snap bean production system requires a better understanding of residual activity, or the period over which these products remain active following an application. Moreover, compatibility with other common agrochemicals may reduce the number of applications required to manage key insect pests, diseases and weeds in the crop. This study demonstrated that diamide insecticides could be (1) successfully applied at earlier phenological stages of snap bean development than currently recommended, (2) co-applied with other fungicides as this provided equivalent control of *O. nubilalis* to insecticides applied alone and (3) applied a single time in commercial fields to provide an equivalent level of protection plus yield and quality to those treated with pyrethroid insecticides.

Cyantraniliprole was an effective tool to reduce *O. nubilalis* infestation when applied at bloom and pod formation stages, but did not provide acceptable control when applied at bud stage. Cyantraniliprole control of *O. nubilalis* was equal to control provided by chlorantraniliprole applications when applied at bloom and pod formation stages (Table 3). When compared directly with bifenthrin, cyantraniliprole control of *O. nubilalis* resulted in less damage to pod or plant structures in 2013. This trend was not observed in 2012 or 2014, when insecticides were not statistically different and only the timing effect remained significant (Table 2, Fig. 1). Cyantraniliprole was significantly better than bifenthrin in controlling *O. nubilalis* infestations in 2013, which was the year when the infestation was greatest (~2500 neonates plot^{-1} in 2013 and ~2000 neonates plot^{-1} in 2012 and 2014). If true, this result suggests that cyantraniliprole may perform better than bifenthrin under higher *O. nubilalis* pressure. Furthermore, infestations that occur over a protracted period of time better represent the variability of adult flights into the crop,[1] and support the use of newer materials that have longer residual activity and thereby provide extended protection, while minimizing the possibility for mistimed applications that could result in *O. nubilalis* damage.

Co-application of insecticides with fungicides was equally as effective in controlling *O. nubilalis* as insecticides alone. Damage in stand-alone bifenthrin and cyantraniliprole treatments was not significantly different from co-application treatments made at the same phenological stage (e.g. cyantraniliprole alone versus cyantraniliprole + thiophanate-methyl at bloom) (Table S1). In a previous study, Nault *et al.*[13] found that reduced-risk insecticides with either translaminar or systemic movement had reduced insecticidal activity on *Thrips tabaci* Lindeman in onion when materials were paired with the fungicide chlorothalonil. Here, we did not observe any antagonistic effect of chlorothalonil on control of *O. nubilalis*. These findings demonstrate that co-application of common fungicides could be a valuable adjustment to the current pest management program in processing snap bean production. Reducing applications in processing snap bean has clear benefits for the producer by limiting fuel use and emissions, soil compaction, spray drift from multiple applications and operator fees.

Chlorantraniliprole and cyantraniliprole provided excellent control of *O. nubilalis* when applied at either bloom or pod formation stages, which were separated by 7 days in 2012. We observed the same trend for cyantraniliprole control of *O. nubilalis* in 2013 and 2014, which were separated by 7 and 8 days respectively. In fruit production systems, diamide insecticides have shown superior residual activity against a variety of lepidopteran pest species when compared with other common insecticides.[19–21] This increase in residual activity could be an important improvement for commercial processing snap bean systems where logistics of spraying fields at very specific times becomes a challenge for larger producers. Moreover, increased flexibility of application timing and a reduced number of sprays are advantageous for producers who currently spray pyrethroids at bloom and pod formation stages when compared with a revised program where diamide insecticides could be applied only once at bloom or later if adverse weather conditions occur during bloom. This additional flexibility in treatment timing is highly advantageous for large snap bean producers that are constrained by their ability efficiently to spray large areas entering vulnerable stages of crop development simultaneously.

Although direct comparisons of efficiency savings for novel and standard insecticides were not estimated, the ability to co-apply insecticides does provide a baseline for broader measures of pest management improvement. These application cost estimates show how a small adjustment to one component in the production system could have a strong effect at regional or national scales. The 2012 National Agriculture Statistics Service census estimated that New York state producers grew 11 302 ha of processing snap beans in 2012. Moreover, the broader Great Lakes agricultural region (i.e. Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania and Wisconsin), produced 50 663 ha of processing snap beans in 2012, a sum that equates to approximately 73% of the 69 821 ha of domestic production.[22] Elimination of one or more insecticide applications for the control of *O. nubilalis* at the state or regional scale would result in considerable economic gain for producers and processors, a reduction in the environmental footprint of pest management practices used on the crop and an increase in the overall sustainability of the processing snap bean system.

5 CONCLUSIONS

This study reports the feasibility of applying new diamide insecticides to control *O. nubilalis* in processing snap bean. We found that diamides could be co-applied with fungicides with no antagonistic effects and sprayed earlier (bloom) than current recommendations suggest for other insecticides (pod formation). The findings of this study suggest that future economic analyses of snap bean production should examine the value of improved efficacy, application flexibility and diamide insecticides. These estimates integrated with other environmental impact and sociological effects of pest management practice would be meaningful additions to a more comprehensive analytical framework to help processors make more informed decisions about specific crop protection components that will improve the system-wide sustainability of processing snap bean production.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

REFERENCES

1 Eckenrode CJ, Robbins PS and Andaloro JT, Variations in flight patterns of European corn borer (Lepidoptera: Pyralidae) infestation in snap beans. *J Econ Entomol* **12**:393–396 (1983).

2 Dively GP and McCully JE, Nature and distribution of European corn borer feeding injury on snap beans. *J Econ Entomol* **72**:152–154 (1979).

3 Sanborn SM, Wyman JA and Chapman RK, Studies on the European corn borer in relation to its management on snap beans. *J Econ Entomol* **75**:551–555 (1982).

4 Cranshaw WS and Radcliffe EB, Influence of cultivar and plant age on European corn borer (Lepidoptera: Pyralidae) infestation in snap bean. *J Econ Entomol* **77**:374–376 (1984).

5 Webb DR, Eckenrode CJ and Dickson MH, Variation among green and wax beans in survival of larvae of a bivoltine-*E* race of the European corn borer (Lepidoptera: Pyralidae). *J Econ Entomol* **80**:521–524 (1987).

6 Wyman JA and Flood BR, Beans, in *Vegetable Insect Management*, ed. by Foster R and Flood BR. Meister Media Worldwide, Willoughby, pp. 65–80 (2005).

7 Wiles JA, Annan IB, Portillo HE, Rison JL, Dinter A and Frost NM, Cyantraniliprole (DuPont^{TM} Cyazypyr^{TM}) – a novel, substituted anthranilic diamide insecticide for cross-sprectrum control of sucking and chewing pests, in *Les Cochenilles: Ravageur Principal ou Secondaire. 9ème Conférence Internationale sur les Ravageurs en Agriculture, SupAgro, 25–27 October 2011*. Association Française de Protection des Plantes (AFPP), Montpellier, France, pp. 698–705 (2011).

8 Barry JD, Portillo HE, Annan IB, Cameron RA, Clagg DG, Dietrich RF *et al.*, Movement of cyantraniliprole in plants after foliar applications and its impact on the control of sucking and chewing insects. *Pest Manag Sci* DOI:10.1002/ps.3816 (2014).

9 *Advanced Product Search.* [Online]. Agrian Inc. Available: http://www.agrian.com/labelcenter/results.cfm [24 July 2014].

10 *Resistance: Mechanisms and Management.* [Online]. Insecticide Resistance Action Committee. Available: http://www.irac-online.org/about/resistance/ [24 July 2014].

11 Dougherty DE and Schuster DJ, Compatibility of fungicide–insecticide combinations for disease and pickleworm control on honeydew melon. *Proc Fla State Hort Soc* **97**:205–208 (1994).

12 Sherrod DW, Linduska JJ and Hofmaster RN, Interaction of synthetic pyrethroid insecticide–foliar fungicide combinations for Colorado potato beetle control in tomato and Irish potato. *J Ga Entomol Soc* **18**:419–424 (1983).

13 Nault BA, Hsu CL and Hoepting CA, Consequences of co-applying insecticides and fungicides for managing *Thrips tabaci* (Thysanoptera: Thripidae) on onion. *Pest Manag Sci* **69**:841–849 (2013).

14 Reiners S and Petzoldt CH, *Integrated Crop and Pest Management Guidelines for Commercial Vegetable Production*. Cornell Cooperative Extension, pp. 78–103 (2013).

15 Michaels TE, The bean plant, in *Compendium of Bean Diseases*, ed. by Hall R. APS Press, St Paul, pp. 1–5 (1994).

16 *R: a Language and Environment for Statistical Computing. Version 3.1.0.* [Online]. R-Core Development Team, R Foundation for Statistical Computing, Vienna, Austria (2014). Available: http://cran.r-project.org/ [15 August 2014].

17 Hutchison WD, Flood B and Wyman JA, Advances in United States sweet corn and snap bean insect pest management, in *Insect Pest Management*, ed. by Horowitz AR and Ishaaya I. Springer, Berlin, pp. 247–278 (2004).

18 Shelton AM, Olmstead DL, Burkness EC, Hutchison WD, Dively G, Welty C *et al.*, Multi-state trials of *Bt* sweet corn varieties for control of the corn earworm (Lepidoptera: Noctuidae). *J Econ Entomol* **106**:2151–2159 (2013).

19 Ioriatti C, Anfora G, Angeli G, Mazzoni V and Trona F, Effects of chlorantraniliprole on eggs and larvae of *Lobesia botrana* (Denis & Schiffermüller) (Lepidoptera: Torticidae). *Pest Manag Sci* **65**:717–722 (2009).

20 Sial AA and Brunner JF, Toxicity and residual efficacy of chlorantraniliprole, spinetoram and emamectin benzoate to obliquebanded leafroller (Lepidoptera: Torticidae). *J Econ Entomol* **103**:1277–1285 (2010).

21 Magalhaes LC and Walgenbach JF, Life stage toxicity and residual activity of insecticides to codling moth and oriental fruit moth (Lepidoptera: Torticidae). *J Econ Entomol* **104**:1950–1959 (2011).

22 2012 census of agriculture – state level data, in *The 2012 Census Full Report.* [Online]. USDA National Agricultural Statistics Service (2012). Available: http://www.agcensus.usda.gov/Publications/2012/ [1 September 2014].