Research Article

Received: 29 May 2018 Revised: 27 June 2018 Accepted article published: 26 July 2018 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/ps.5150

Grower adoption of insecticide resistance management practices increase with extension-based program

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Abstract

BACKGROUND: Insecticide resistance management (IRM) practices that improve the sustainability of agricultural production systems are developed, but few studies address the challenges with their implementation and success rates of adoption. This study examined the effectiveness of a voluntary, extension-based program to increase grower adoption of IRM practices for onion thrips (*Thrips tabaci*) in onion. The program sought to increase the use of two important IRM practices: rotating classes of insecticides during the growing season and applying insecticides following an action threshold.

RESULTS: Onion growers ($n = 17$) increased their adoption of both IRM practices over the 3-year study. Growers increased use of insecticide class rotation from 76% to 100% and use of the action threshold for determining whether to apply insecticides from 57% to 82%. Growers who always used action thresholds successfully controlled onion thrips infestations, applied significantly fewer insecticide applications (one to four fewer applications) and spent \$148/ha less on insecticides compared with growers who rarely used the action threshold. Growers who regularly used action thresholds and rotated insecticide classes did so because they were primarily concerned about insecticide resistance development in thrips populations.

CONCLUSION: Implementation of the IRM education program was successful, as adoption rates of both practices increased within 3 years. Growers were surprisingly most receptive to adopting these practices to mitigate insecticide resistance as opposed to saving money. Developing extension-based programs that involve regular and interactive meetings with growers may significantly increase the adoption of IRM and related integrated pest management tactics.

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

Keywords: insecticide resistance; management; extension; adoption; onion thrips

1 INTRODUCTION

The development of insecticide resistance is a threat to many agricultural production systems where insecticides are applied. Over 500 insect species have developed resistance to one or more insecticides,[1] which has contributed to a global yield loss of 1.5 billion dollars (USD) annually.[2] This loss can be further exacerbated by the lack of new, readily available insecticides. New active ingredients are costly to develop and can take between 10 and 15 years until they are commercially available.[3] Thus, insecticide resistance management (IRM) tactics, including chemical class rotation, using thresholds, and other non-chemical control measures are needed to maintain the profitability and stability of agricultural systems. Numerous research efforts have identified IRM and related integrated pest management (IPM) tactics to slow the onset of insecticide resistance in a variety of agricultural production systems.[4–8] While the efficacy and application of IRM is dependent on the specific pest biology and agricultural production system, the goal of these techniques is to reduce the selection pressure of a given active ingredient on an insect pest, thus prolonging the active ingredient's efficacy.[9]

The effectiveness of IRM and related IPM practices to delay the onset of insecticide resistance is largely predicated on grower decision and compliance.[10,11] However, our understanding of the implementation and adoption of IRM and related IPM practices is relatively limited.[12] Previous studies and surveys on general IPM practices reveal that rates of grower adoption vary from 30% to 99% depending on region and commodity.[13–17] Currently, the USDA estimates that 70% of US cropland is managed using some level of IPM[18]; however, the use of IRM tactics is unknown. Growers tend to adopt practices that are not risky, easy to implement, and save money,[13,19,20] which can put some IRM and related practices at a disadvantage because many are complicated and time-consuming to implement. Consequently, the adoption of some IPM practices have been slow to progress as compared with other agricultural technologies.[21,22] Adoption of IPM practices has been associated with many factors including farm size and age of grower,[23,24] but grower education and inexperience remain some

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of the greatest impediments for IPM and IRM practice adoption.[13] Many studies have evaluated the effect of different educational programs on grower's knowledge[25–27] and adoption of IPM.[28–30] Nevertheless, further research is needed to identify those methodologies that can successfully increase adoption of IRM and related IPM tactics to mitigate the onset of insecticide resistance.

Poor insecticide resistance management has resulted in pest control failures worldwide. In onion production systems, insecticide resistance in onion thrips (*Thrips tabaci*) populations has led to significant yield losses. Onion thrips has developed resistance to pyrethroids, organophosphates, and carbamates.[31–35] Previous research has identified two pest management practices that should mitigate insecticide resistance and control onion thrips populations; using an action threshold[36,37] and following an insecticide sequence that rotates insecticide classes.[38] The use of thresholds is an important component to insecticide resistance management programs.[9] In onion production in the Great Lakes region, an action threshold of one thrips per leaf has been effective in controlling thrips populations without reducing yield.[36,39] Implementing an action threshold to control thrips in onion production can reduce the frequency of insecticide applications between 30% and 50%, thereby reducing exposure of insecticides to onion thrips populations.[36,39] Recent research also has identified effective thrips management using season-long rotation sequences of insecticides belonging to different classes.[37,38,40,41] Onion thrips typically complete a generation in approximately 14 days on onion,[42] thus no more than two consecutive sprays of the same mode of action is recommended. As such, proposed insecticide sequences include multiple products with different modes of action applied twice 7–10 days apart.[38,40,41] This approach should reduce exposure of an insecticide to multiple generations of onion thrips and slow the potential onset of insecticide resistance.[43–45] Recent onion grower survey results in New York revealed that only 52% of growers rotated insecticide classes, and even fewer (40%) used an action threshold to determine when to make an insecticide application (Nault BA, unpublished). Therefore, an opportunity existed to help onion growers improve their adoption of action thresholds and rotation of insecticide classes following research-based IRM tactics, while maintaining acceptable levels of onion thrips control.

The purpose of this study was to improve the adoption of research-based IRM tactics for onion thrips in onion. We developed an extension program entitled, 'IRM adoption program' to increase onion grower adoption of (1) an action threshold to make decisions about insecticide use, and (2) a rotation of insecticide classes in a season-long sequence that adhered to resistance management principles. We hypothesized that the use of action thresholds and rotation of insecticide classes would increase over the 3-year program, and conservatively estimated that growers would collectively increase their use of both tactics by 10% annually. Furthermore, we anticipated that growers who adopted these tactics would positively benefit by applying fewer insecticide applications, reducing total insecticide cost, while successfully managing onion thrips infestations.

2 MATERIALS AND METHODS

2.1 Thrips management approaches prior to the IRM adoption program

2.1.1 Grower participants

Onion growers from four of the major onion-producing counties in New York participated in this program, and all were familiar with Cornell Entomology and Cornell Cooperative Extension. Invitations to participate in the scouting program were sent to all known commercial onion growers from each county ($n = 22$). Those growers who responded to the invitations were selected as participants for the 'IRM adoption program'. The counties included Orleans, Wayne, Orange, and Oswego. In 2015, 15 growers participated in the program. In 2016, two additional growers joined the program for a total of 17, and in 2017, 14 growers continued to participate in the program (Fig. S1).

2.1.2 Farm demographics and onion thrips management practices

Prior to initiating the IRM program, a survey was given to all participating growers to obtain baseline information about their farm demographics as well as the tactics they used for managing onion thrips (Table S1 and Fig. S2). All growers who participated in the IRM adoption program were commercial vegetable producers and farmed between 22 and 2023 ha of onions annually. Growers who participated in this study collectively managed 45–60% of the total onion hectarage in New York from 2015 to 2017 and represented 28% of the commercial onion growers in the state. The average grower participant operated a 51-ha farm (Fig. S2).

Most growers responded that they implemented IPM tactics on their farm to control onion thrips populations (Table S1). Approximately 76% of growers stated that they implemented a cultural pest management tactic, but none used either biological or physical controls to reduce onion thrips infestations. Approximately 88% of growers either scouted their own onion fields or had a professional crop consultant scout their fields. Many growers (65%) claimed to use an action threshold to determine when to apply an insecticide. However, most growers made between seven and eight insecticide applications each season specifically targeting onion thrips, which typically follows a standard or weekly insecticide program.[37] Most growers (94%) claimed to effectively rotate insecticides in an effective season-long sequence, and only made two sequential applications of one mode of action before rotating to a new insecticide.

2.2 IRM adoption program

All growers who participated in this program received free, weekly scouting information from personnel affiliated with either Cornell Cooperative Extension or the Department of Entomology. All scouts had previous experience scouting agricultural crops for insect pests and had been properly trained to correctly identify and count onion thrips on onion prior to program initiation. Each scout was assigned a location within the state (Fig. S1) where he or she would work with a sub-set of onion growers from that county. Each grower selected one onion field ranging from 4 to 8 ha that was scouted weekly for the entire onion growing season. Initiation and conclusion of scouting depended on the phenology of the crop, not on previous history of thrips infestations in that field. Scouting typically began in early to mid-June and concluded in late August for a total of approximately 10–13 weeks.

Scouts randomly sampled onion plants within fields and visually assessed plants for onion thrips adults and larvae.[46] Within 24 h of sampling fields, scouts sent a report to each onion grower documenting the infestation level of onion thrips in their field, whether the population exceeded an action threshold of one thrips per leaf (including both adults and larvae), and if so, what insecticide product and rate to use. In most cases, growers and scouts met and discussed this scouting information and recommendation. All scouts were unified in providing the same advice throughout the season.

A minimum of 1 week between applications was recommended. Insecticide products, rates and the sequence for applying these products were as follows: (1) Movento® at 5 fl oz. per acre (350 g/ha) (spirotetramat) (Bayer CropScience, Research Triangle Park, NC, USA), (2) Agri-mek SC® at 3.5 fl oz. per acre (245 g/ha) (abamectin) (Syngenta, Greensboro, NC, USA), (3) a co-application of Lannate® LV at 48 fl oz. per acre (3360 g/ha) (methomyl) (DuPont Crop Protection, Wilmington, DE, USA) and Warrior® at 1.9 fl oz. acre (140 g/ha) (lambda-cyhalothrin) (Syngenta, Greensboro, NC, USA), and (4) Radiant® SC at 8–10 fl oz. per acre (560–700 g/ha) (spinetoram) (Dow AgroSciences, Inc., Indianapolis, IN, USA). In 2016, Exirel® (cyantraniliprole) (DuPont Crop Protection, Wilmington, DE, USA) also was recommended at 13.5 fl oz. per acre (945 g/ha) as a substitution for the Lannate® LV and Warrior® combination. In 2017, Minecto™ Pro (premix formulation of cyantraniliprole and abamectin) was registered in New York for controlling onion thrips on onion and was consequently included as an insecticide option provided to growers. Minecto™ Pro was recommended at 7–10 fl oz. per acre (490–700 g/ha) (abamectin and cyantraniliprole) (Syngenta, Greensboro, NC, USA). Movento® (spirotetramat), Radiant® SC (spinetoram), Exirel® (cyantraniliprole), and Minecto™ Pro (premix formulation of cyantraniliprole and abamectin) provide excellent control of onion thrips larvae. Agri-mek® SC, Lannate® LV, and Warrior® are less effective insecticides; however, they often provide suppression or limited control, and thus are still recommended at specific times throughout the season. Agri-mek (abamectin) offers only thrips suppression. While onion thrips populations in New York have developed resistance to both methomyl and lambda-cyhalothrin, the mixture of the two insecticides has been shown to provide better thrips control than the level of control provided by either product alone.[46] Growers were encouraged, but not required, to follow the action threshold recommendations and insecticide sequences provided by the scouts.

At the end of each growing season, every grower supplied pesticide application records for fields sampled by the scout (i.e. products, rates, dates of application). Pesticide application records were compared with weekly thrips density data to determine whether the grower complied with the IRM guidelines (i.e. following the action threshold and/or the insecticide sequence that rotated chemical classes). Additionally, annual post-season meetings between scouts and all growers within each county were held, where scouts discussed all insecticide records with the group. All 17 participating growers, who collectively represent between 45% and 60% of the onion acreage in New York, completed a survey describing their experience participating in the program (Fig. S3).

2.3 Measurement of IRM adoption and definitions of associated metrics

Every insecticide application made by participating onion growers was analyzed based on its compliance with the action threshold and an insecticide rotation sequence. An insecticide application complied with the action threshold if applied when onion thrips densities exceeded the action threshold of one thrips per leaf. Applications were noncompliant if applied below the action threshold. Insecticide applications complied with insecticide rotation requirements if no more than two consecutive insecticide applications of a single mode of action or insecticide group was applied. Conversely, an insecticide application was considered noncompliant if more than two insecticide applications of a given class were applied and if the same insecticide was not applied consecutively. For each participating grower, the number of compliant insecticide applications from either IRM tactic was compared with the total number of insecticide applications made in every year to determine overall adoption success of each tactic.

In response to recent research (Nault BA, unpublished), all growers were recommended to apply two sequential applications of Movento® (spirotetramat) early in the growing season either before onions were bulbing (4–6 leaves) or when onion thrips densities reached 0.5 thrips per leaf. Therefore, an application of Movento® (spirotetramat) at this lower density was considered as compliant in 2017; no other times or for no other insecticides was this lower threshold compliant. Total insecticide cost per hectare was estimated using prices obtained from local agrichemical dealers. The costs of surfactants and other spray adjuvants were not included in overall cost estimates because they are routinely used and similarly priced. Insecticides were characterized as either inexpensive (<\$24 (USD)/hectare) or expensive (>\$72 (USD)/hectare). Movento® (spirotetramat), Radiant® SC (spinetoram), and Exirel® (cyantraniliprole) insecticide applications were considered expensive, whereas Warrior® (lambda-cyhalothrin) and Agri-mek® SC (abamectin) insecticide applications were considered inexpensive. Insecticides priced between \$24 and \$72/ha ((Lannate® (methomyl) mixed with Warrior® (lambda-cyhalothrin) and Minecto™ Pro (Minecto™ Pro (premix formulation of cyantraniliprole and abamectin)) were infrequently used and excluded from this analysis. All insecticides were characterized based on chemical class and the number of applications from each insecticide class was counted for every grower in each year.

2.4 Statistical analysis

2.4.1 *Adoption analysis*

Data were fit using generalized linear mixed effect models (GLMER, LMER) using the R library lme4 package.[47] Adoption data (i.e. percentage of insecticide applications made when thrips density exceeded the action threshold of the total applied; percentage of insecticide applications that were rotated properly of the total applied) were analyzed with the lme4 package and function glmer() for binomial regression. Years in program (participating years) was treated as a fixed effect and grower within county as a random effect. The 'IRM adoption program' was initiated in 2015; however, the number of participating growers differed between years, which affected the number of years a grower participated in the program. This was accounted for by generating a new variable (participating years) that was used in the analysis rather than calendar year (e.g. 2015, 2016, 2017). Differences in adoption data between years were determined using ANOVA, and differences separated using Tukey's HSD ($P < 0.05$).

2.4.2 *Post-hoc analysis of metrics associated with IRM adoption*

Analyses were conducted to determine if adoption of either IRM tactic (independent variable) significantly affected seasonal onion thrips densities, number of insecticide applications, and costs and types of insecticides (expensive or inexpensive) used. These metrics were analyzed using adoption data (same as mentioned previously) as fixed effects. Growers within county were treated as a random effect. Seasonal onion thrips densities, number of insecticide applications, and costs of insecticides data were normally distributed, and analyzed using function lmer() for linear regression. Numbers of products and counts of expensive and inexpensive insecticides were analyzed using a Poisson distribution with function glmer(). Additional analysis identified the relative thrips abundance over the 3-year period, which was analyzed using function lmer() with participating year as a fixed effect and growers

Table 1. Thrips density (thrips/leaf), insecticide use and cost, and adoption of insecticide resistance management (IRM) tactics by onion growers in four major onion growing counties in New York over 3 years

County	Year participating in program	*n*	Onion thrips density (thrips/leaf)	Number of insecticide applications	Insecticide cost per acre (USD)[a]	Percent (%) of insecticide applications made in accordance to the action threshold	Percent (%) of insecticide applications made in accordance to insecticide rotation restrictions
Orange	1	3	0.7 ± 0.1	5.3 ± 1.2	190 ± 5	68 ± 26	73 ± 20
	2	3	0.6 ± 0.3	6.3 ± 1.3	158 ± 23	48 ± 29	75 ± 16
	3	0	n/a	n/a	n/a	n/a	n/a
Wayne	1	4	0.5 ± 0.3	3.5 ± 0.3	122 ± 13	50 ± 22	85 ± 9
	2	4	0.4 ± 0.1	5 ± 0.4	134 ± 24	57 ± 17	78 ± 16
	3	4	0.4 ± 0.1	2 ± 0.5	65 ± 13	100	100
Orleans	1	5	1.3 ± 0.4	5.6 ± 0.7	162 ± 28	80 ± 20	87 ± 6
	2	5	1.5 ± 0.6	6 ± 0.7	163 ± 24	85 ± 15	94 ± 4
	3	4	0.8 ± 0.1	4.8 ± 1	107 ± 13	96 ± 4	100
Oswego	1	5	0.4 ± 0.1	7.2 ± 0.5	163 ± 15	38 ± 15	60 ± 8
	2	5	0.6 ± 0.3	5.4 ± 1	154 ± 27	65 ± 15	89 ± 5
	3	4	0.1 ± 0.02	4.3 ± 1	109 ± 45	49 ± 12	100

[a] Costs of insecticides were estimated based on prices provided by commercial pesticide dealers in New York from 2015 to 2017.

within county as a random effect. Differences in treatments (seasonal onion thrips densities, number of insecticide applications or products, and costs of insecticides, etc.) were determined using ANOVA, and differences separated using Tukey's HSD ($P < 0.05$). Marginal and conditional R-squared values were determined using package, MuMIn, and function r.squaredGLMM().[48]

3 RESULTS

3.1 Onion thrips pressure

Onion thrips densities were slightly higher in years 1 and 2 compared to year 3, but this difference was only marginally significant ($P = 0.059$, $F_{2,39} = 5.64$). In years 1 and 2, seasonal densities of onion thrips were 0.6 ± 0.1 and 0.8 ± 0.2 thrips per onion leaf, respectively, which was greater than densities in year 3, 0.4 ± 0.1 thrips per leaf. Onion thrips densities in onion fields were significantly different across counties (Table 1). Across all years, onion fields in Orleans County tended to have the greatest average number of thrips per leaf (1.1 ± 0.2), which was significantly greater than densities in Oswego (0.3 ± 0.1), but not Wayne (0.4 ± 0.1) or Orange (0.6 ± 0.1) counties ($P = 0.003$, $F_{3,39} = 13.5$).

No growers reported reduced onion bulb yields from onion thrips damage in this study using either the action threshold or rotating insecticide classes. Most growers stated that they effectively controlled thrips in all 3 years. Growers who regularly used the action threshold did not express lower satisfaction with their thrips control and did not report any 'poor' or 'failed' control of thrips in any year of the program. In year 1, approximately 94% (16/17) of growers stated that they had 'good' or 'excellent' control of onion thrips. Similarly, in year 2, most (88%, 15/17) growers said that they had 'good' or 'excellent' control of thrips. Some growers reported having slightly reduced onion thrips control in year 2, as 12% said that they had 'average' control of thrips, as compared with year 1 when only 6% (1/17) of growers reported having had 'average' control of thrips. In year 3, growers across the state experienced high levels of thrips control, with most growers (83%, 10/12) having excellent control, 17% (2/12) having 'good' control, and none (0/12) having 'average' control.

3.2 Adoption of the action threshold

3.2.1 *Adoption frequency of the action threshold*

Growers significantly increased their use of the action threshold over the 3-year program (Fig. 1(a)) ($P = 0.006$, $F_{2,41} = 9.98$). More insecticide applications were applied following an action threshold in year 3 as compared with year 1 (82% and 57%, respectively) (Fig. 1(a)). Specifically, there were large increases in complete adoption of the action threshold (100% of insecticide applications made in accordance to the action threshold) by individual growers from year 1 to 3. Only 23% (4/17) of growers used the action threshold for every insecticide application in year 1, but in year 3, 58% (7/12) of growers used the action threshold for every insecticide application.

Growers in Orleans County tended to have the highest, consistent rates of action threshold adoption, whereas growers in Oswego County tended to have the lowest (Table 1); however, these differences were not significant ($P = 0.158$) (Table 1). Growers increased adoption of thresholds in all counties in years 2 and 3 compared to year 1, except Orange County whose growers only participated in the program for the first 2 years.

3.2.2 *Onion thrips populations*

Overall, seasonal mean onion thrips densities were greater in fields that used the action threshold more frequently (Fig. 2). This relationship was consistent in years 1 and 2, but not year 3 (Table S2). On average, growers who always used the action threshold (100% compliance) had between three and nine times more thrips per leaf as compared with growers who did not use the action threshold (less than 15% compliance) (Fig. 2). While populations of thrips were higher in fields with greater adoption of the action threshold, all growers successfully controlled onion thrips. Over all 3 years, 97% (46/47) of the onion fields had mean

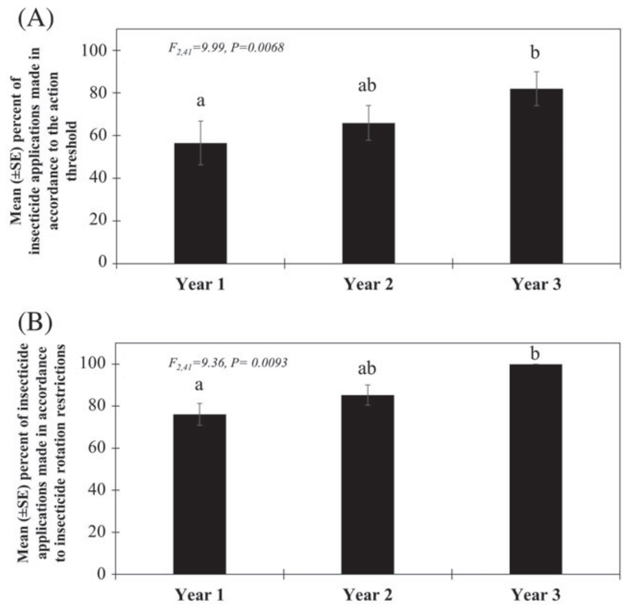

Figure 1. Adoption of insecticide resistance management tactics to manage onion thrips for growers who participated in our program over 3 years in New York. The average percentage of insecticide applications made using the action threshold of one thrips per leaf (A), and the percentage of insecticide applications rotating between insecticide classes (B). The scouting program was voluntary, and growers could choose whether or not to follow the scouting recommendation of using the action threshold and rotating between insecticide classes.

season densities below the economic threshold of 2.2 thrips per leaf (Fournier *et al.*, 1995) (Fig. 2).

3.2.3 *Insecticide applications*

Overall, growers who used the action threshold more often made significantly fewer insecticide applications (Fig. 3(a)) ($P = 0.00014$, $F_{1,40} = 14.81$). This trend occurred consistently in years 2 and 3, but not in year 1 (Table S2). Growers who always used action thresholds (100% compliance) made between one and four fewer insecticide applications per season compared with growers who did not follow the action threshold (less than 15% compliance) (Fig. 3(a)). Overall, most growers (59%, 10/17) reduced the number of insecticide applications in years 2 and 3 as compared with year 1, 29% (5/17) applied the same number of applications and 12% (2/17) increased the number of applications. The total number of products applied throughout the growing season was not significantly related to action threshold use.

3.2.4 *Insecticide cost*

Insecticide costs decreased with increased use of the action threshold (Fig. 4). However, the statistical significance of this relationship differed between years (Table S2). Growers who used the action threshold for every insecticide application (100% compliance) saved approximately $148/ha as compared with those growers who rarely used the action threshold (less than 15% of their insecticide applications) ($P = 0.016$, $F_{1,22} = 5.7$). The use of inexpensive insecticides was negatively correlated with action threshold use ($P = 0.034$, $F_{1,40} = 4.49$) (Fig. 5), suggesting that growers who rarely followed the action threshold were making more applications with inexpensive products. Specifically, greater numbers of applications of lambda-cyhalothrin were negatively associated with action threshold use ($P = 0.02$, $F_{1,40} = 5.31$) (Fig. S4(a)). There were no significant relationships between the use of expensive insecticide products and adoption of the action threshold.

3.3 Adoption of insecticide class rotation

3.3.1 *Adoption frequency of insecticide (mode of action) rotation*

Over the 3-year program, there was a significant increase in the percentage of insecticide applications that successfully rotated insecticide classes ($P = 0.009$, $F_{2,41} = 9.35$) (Fig. 1(b)). Adoption of insecticide class rotation was relatively high across all years but increased 31% from year 1 to 3. A total of 44 insecticide applications did not comply with proper insecticide rotation recommendations over the 3-year program; 29 of the non-compliant applications (66%) included more than two insecticide applications of a given insecticide class. The remaining 34% (15/44) of non-compliant insecticide applications involved an insecticide that was not applied consecutively, thereby exposing more than one onion thrips generation to a given insecticide class.

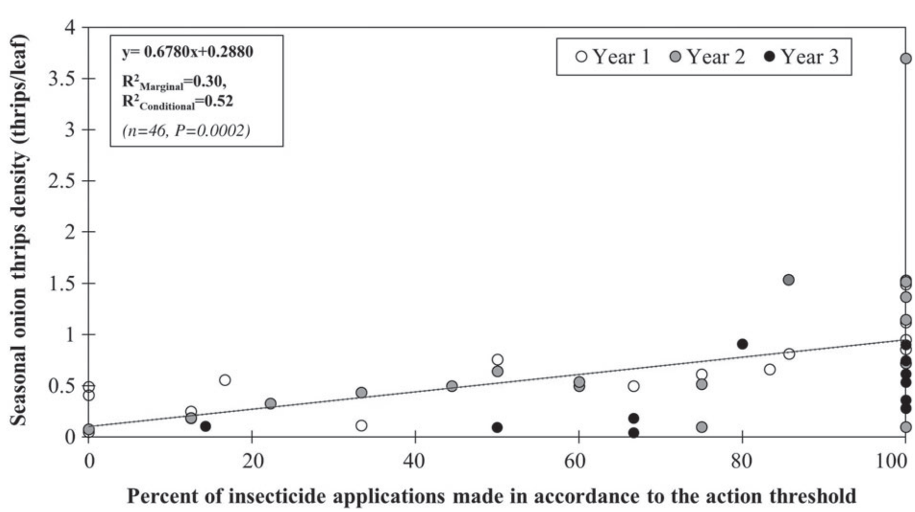

Figure 2. Relationship between use of the action threshold (1 thrips/leaf) and seasonal onion thrips densities over the 3-year period that the IRM adoption program was implemented. Each point represents one onion field that was scouted for thrips and managed by an onion grower in our program. Points with various colors correspond to a particular year.

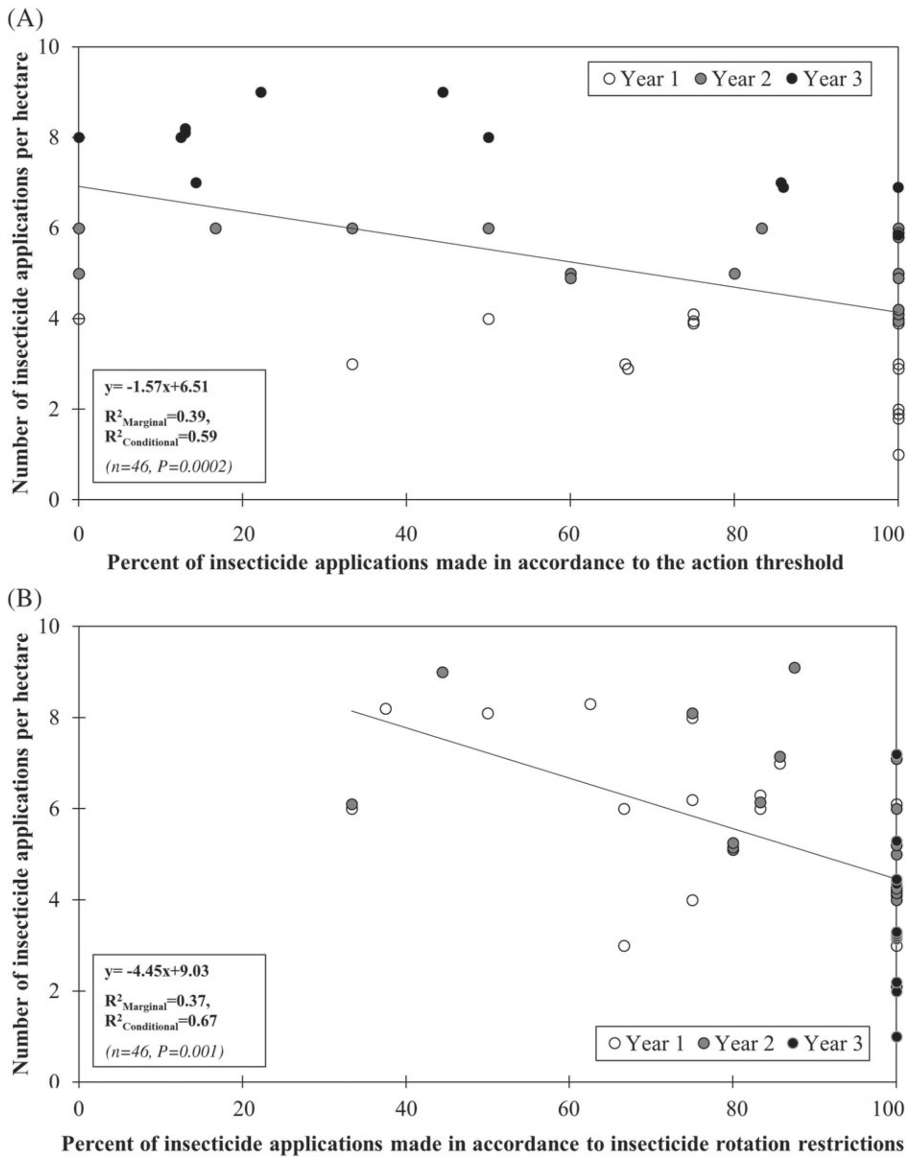

Figure 3. Relationship between use of the action threshold (1 thrips/leaf) and number of insecticide applications per acre over the 3-year period that the IRM adoption program was implemented (A). Relationship between insecticide rotation and number of insecticide application per hectare over the 3-year period the IRM adoption program was implemented (B). Each point represents one onion field that was scouted for thrips and managed by an onion grower in our program. Points with various colors correspond to a particular year.

There were no significant differences between counties and insecticide class rotation ($P = 0.192$); however, rates of adoption differed numerically among years (Table 1). In years 1 and 2, at least 60% of growers from all counties adopted the insecticide rotation recommendations and Orleans County growers tended to have the highest levels of adoption (Table 1). In year 3, 100% of growers in all counties followed the insecticide rotation recommendation.

3.3.2 *Onion thrips populations*

Onion thrips populations did not differ based on insecticide class rotation ($P = 0.546$) (Table S2). Numerically, growers who did not rotate insecticide classes appropriately tended to have slightly lower thrips densities than those that consistently rotated between insecticide classes. Overall, growers who properly rotated insecticide classes for every application (100% of insecticide properly rotated) had 0.6 thrips/leaf, whereas the growers with lowest rates of insecticide class rotation (33% of insecticide properly rotated) averaged 0.4 thrips/leaf.

3.3.3 *Insecticide applications*

Overall, growers who rotated insecticide classes more frequently made significantly fewer insecticide applications (Fig. 3(b)) ($P = 0.00014$, $F_{1,40} = 14.45$). Growers with the lowest levels of insecticide class rotation (33% of insecticide properly rotated) made one to three more insecticide applications as compared with those growers who properly rotated every insecticide application. A variety of products were used to control onion thrips populations (Table 2). On average, growers applied between two and four different insecticide products each season, but some growers used as many as five products and others as little as one product to control onion thrips. There was no significant relationship between the number of different products used throughout

Table 2. Percentage and use of different insecticide classes to control thrips over the 3-year IRM adoption program

Insecticide use	Year	Insecticide classes: Tetronic and tetramic acid derivatives	Avermectins	Pyrethroids	Carbamates	Diamides	Spinosyns
Total percent applied	1	28.8%	23.1%	17.3%	5.8%	1.9%	23.1%
	2	33.7%	21.8%	14.9%	3.0%	4.0%	22.8%
	3	57.5%	30.0%	2.5%	0.0%	0.0%	10.0%
	All years	35.5%	23.7%	13.9%	3.7%	2.4%	20.8%
Average number applications (±SE)	1	1.8 ± 0.1	1.4 ± 0.2	1.0 ± 0.3	0.3 ± 0.1	0.1 ± 0.1	1.2 ± 0.1
	2	2 ± 0.1	1.4 ± 0.2	0.9 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	1.4 ± 0.2
	3	1.9 ± 0.1	1.0 ± 0.2	0.08 ± 0.008	0 ± 0	0 ± 0	0.3 ± 0.1
	All years	1.9 ± 0.1	1.3 ± 0.1	0.7 ± 01	0.1 ± 0.1	0.1 ± 0.1	1.1 ± 0.1

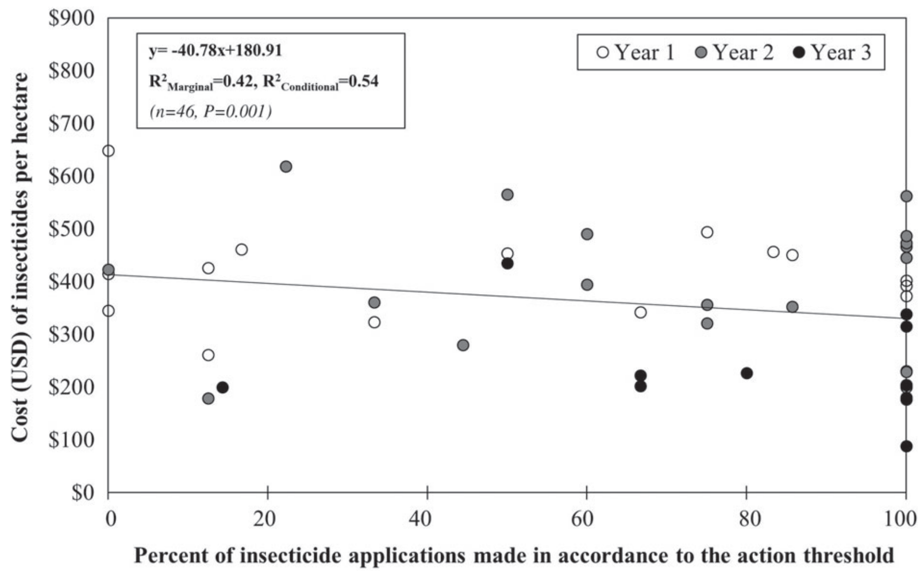

Figure 4. Relationship between use of the action threshold (1 thrips/leaf) and total cost of insecticides per acre over the 3-year period that the IRM adoption program was implemented. Each point represents one onion field that was scouted for thrips and managed by an onion grower in our program. Points with various colors correspond to a particular year.

the growing season and insecticide class rotation ($P = 0.201$). Most growers followed the rotation sequence recommended by the scouts and began their thrips management program with spirotetramat followed in succession by abamectin, co-applications of methomyl and lambda-cyhalothrin or cyantraniliprole, and then spinetoram. Of the 44 insecticide applications that did not comply with the insecticide rotation recommendations, most involved applications of lambda-cyhalothrin. There was a significant negative association between increased lambda-cyhalothrin use and insecticide rotation ($P = 0.001$, $F_{1,40} = 10.14$), indicating that lambda-cyhalothrin tended to be used more frequently by growers who were less likely to follow the insecticide rotation recommendation (Fig. S4(b)).

3.3.4 Insecticide cost

Insecticide class rotation was not significantly associated with total insecticide cost ($P = 0.215$). Regardless of cost, growers created effective season-long sequences of insecticides that successfully rotated classes. While there was no significant relationship between expensive insecticides (>$72/ha) and use of insecticide rotation, there was a significant negative relationship between the use of inexpensive insecticides (<$24/ha) and adoption rates of insecticide rotation ($P = 0.008$, $F_{1,40} = 7.03$) (Fig. 5(b)). The least expensive insecticide applied, lambda-cyhalothrin (at <$7/ha), was commonly used in a non-compliant manner (Fig. S4(b)).

3.4 Grower opinions of the IRM adoption program

All growers surveyed stated that they followed the insecticide sequences provided by the scouts. Growers typically began their onion thrips management program with spirotetramat and concluded with applications of spinetoram with a variety of other products in between. Growers cited a multitude of reasons for not using the action threshold regularly. However, growers most commonly cited that the risk of forgoing a week without an insecticide application was greater than the price of applying an insecticide, despite the thrips population being below the action threshold (Table 3). Secondarily, growers cited that their weekly insecticide program was effective, and therefore did not feel the need to adopt action thresholds. Growers also expressed concern that the action threshold of 1 thrips per leaf was too high and that it didn't adequately accommodate for hot, dry weather conditions. Conversely, those growers who used the action threshold regularly did so because they believed that fewer insecticide applications would slow the onset of insecticide resistance (Table 4). Growers

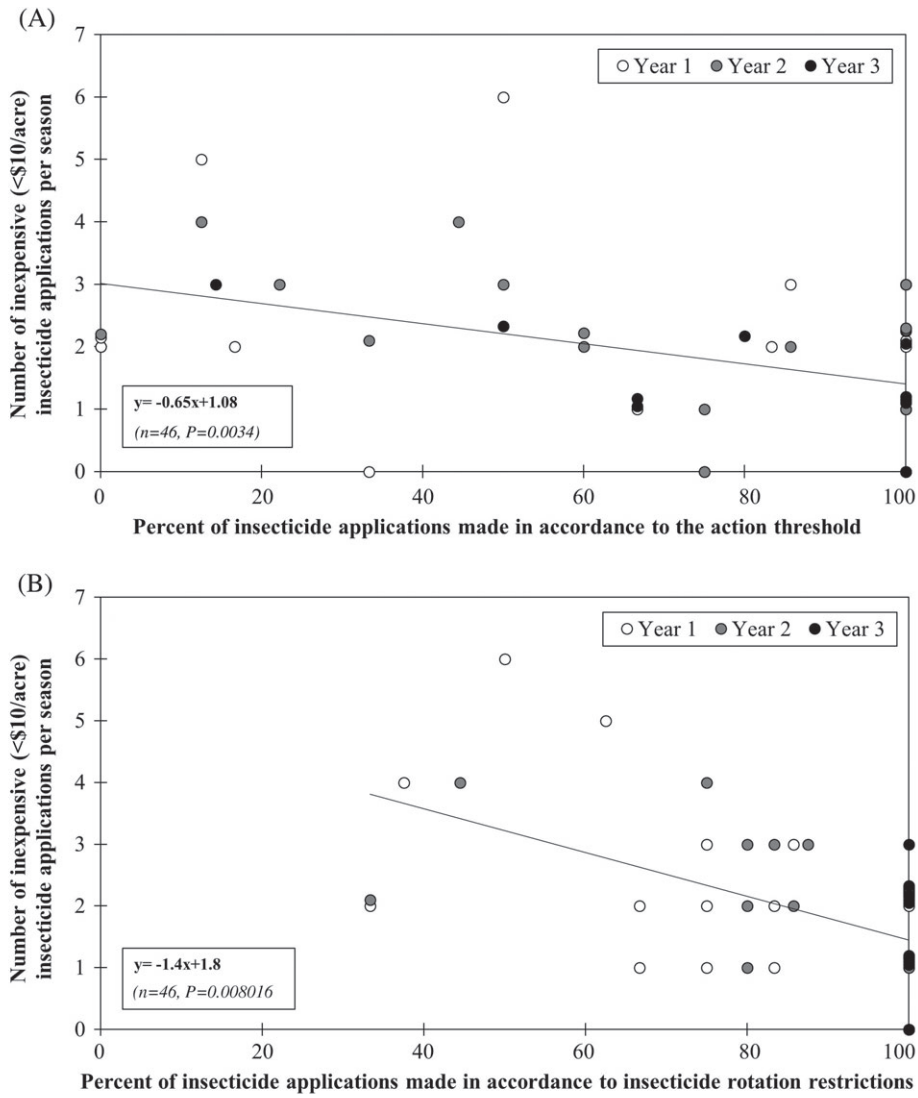

Figure 5. Relationship between use of the action threshold (1 thrips/leaf) and total number of inexpensive insecticide (<$24 (USD)/hectare) applied per acre over the 3-year period that the IRM adoption program was implemented (A). Relationship between insecticide class rotation and total number of inexpensive insecticide (<$24 (USD)/hectare) applied per acre over the 3-year period that the IRM adoption program was implemented (B). Each point represents one onion field that was scouted for thrips and managed by an onion grower in our program. Points with various colors correspond to a particular year.

also attributed their usage of the action threshold to their individual scouts, as 65% of growers said that they trusted their scout, and therefore were likely to value his or her recommendation.

3.5 Value of 'IRM adoption program' to growers

The majority (94%) of onion growers stated that they benefited from the IRM adoption program. Growers reported making between 0 and 5 fewer insecticide applications, with most replying they made two fewer insecticide applications per year from participating in the program. Most growers responded that the scouting program provided a valuable second opinion to their onion thrips management and onion production. Growers described the scouting program as an educational opportunity that provided them with a better understanding of how to implement the action threshold and effectively rotate insecticides on their farm. Growers appreciated the connection they developed with the scout, and many growers followed recommendations because they trusted their scout (Table 4). Growers who participated in the 'IRM adoption program' received all scouting information and recommendations free of cost, but most (94%) stated that they would pay to continue the program. Growers suggested a wide range of prices they would pay to continue the program: between $0 and $123/ha/week. Most growers (65%) stated that they would pay $24/ha/week for a scout to continue to provide IRM recommendations.

4 DISCUSSION

Onion growers increased their use of both IRM tactics over the duration of this study. As hypothesized, there were significant increases in the percentage of insecticide applications made following the action threshold (43%) and in the percentage that successfully rotated insecticide classes (31%). No growers reported a yield loss from adopting either tactic, and 97% of fields had seasonal mean densities of thrips below the regional economic injury

Table 3. Survey results describing why growers who participated in the IRM adoption program used the action threshold to manage onion thrips populations in New York

Reason grower implemented the action threshold	Percent of growers (number responding/total respondents)
• I am concerned about insecticide resistance and want to preserve the useful life of the current insecticides	71% (12/17)
• I trust my Cornell scout and Cornell-based recommendations and value his/her opinion	65% (11/17)
• Using fewer insecticide sprays is less harmful to the environment	47% (8/17)
• The Cornell scout's recommendation to spray or not to spray confirmed what I was going to do anyway	47% (8/17)
• I want to save money on insecticide sprays	33% (5/17)
• Other	12% (2/17)
• Other growers in New York State use the action-threshold based management program and it has been effective for them	6% (1/17)
• Does not apply – I never did	6% (1/17)

Table 4. Survey results describing why growers who participated in the IRM adoption program did not use the action threshold to manage onion thrips populations in New York

Reason grower implemented the action threshold	Percent of growers (number responding/total respondents)
• The cost of an insecticide application is less than the risk of the onion thrips population building when I skip an application	59% (10/17)
• My insecticide program is effective, and I did not want to change it	24% (4/17)
• Other	24% (4/17)
• I have had years where I have trouble controlling thrips, and I don't want to experience that again	18% (3/17)
• Does not apply – I always followed the Cornell scout's recommendations	12% (2/17)
• I did not have time to consult with a scout or read scouting reports for thrips every week	0% (0/17)
• I trust my chemical company representative recommendations for making insecticide applications more than the Cornell scout's recommendations	0% (0/17)
• I did not trust the Cornell scouting recommendations	0% (0/17)

level of 2.2 thrips per leaf.[49] Growers who increased usage of the action threshold made 12–50% fewer insecticide applications in year 3 as compared with year 1. Furthermore, growers who regularly used the action threshold saved approximately $148/ha as compared with growers who did not use the threshold. Therefore, this extension-based program effectively increased IRM education and practice and provided measured benefits to participating growers. Undoubtedly, sustainability of the 'IRM adoption program' will depend on growers who value the program and will make thrips control decisions based on scouting information. Survey data from 2014 revealed that many onion growers (80%) in New York scout or pay for a scouting service and receive weekly information on onion thrips densities (Nault BA, unpublished). Therefore, the resources needed to successfully continue this program are already in place. Nevertheless, ongoing communication between extension educators, crop consultants and growers will be needed to ensure long-term success of this program.

Research on action thresholds and insecticide sequences to manage onion thrips populations in New York has been ongoing for the past three decades.[36,50,51] However, results from grower surveys in New York in 2014 indicated a relatively low adoption of either practice, with approximately 40% of growers using an action threshold and 52% rotating between chemical classes ($n = 45$) (Nault BA, unpublished). After 1 year of working with growers in our study, adoption of both IRM tactics was higher than levels in the 2014 survey. The adoption of a given tactic or innovation depends on many characteristics, including the ability to observe or experiment with an innovation or tactic.[52] In this study, we sought to increase the opportunities for growers to experiment with either IRM tactic on a portion of their farm and to observe the success of other growers implementing these IRM tactics through annual meetings. Most growers (94%) stated that they positively benefitted from participating in the program. Growers stated that participation in our program enabled them to better understand when to spray for onion thrips, and what types of products would be most effective. Furthermore, many growers stated that they trusted their scout, and valued their scout's time and communication. Studies have suggested the importance of face-to-face contact in strengthening the relationship between growers and extension educators to increase IPM adoption,[12,53] and this study further verifies the importance of intensive interactions between growers, researchers and extension educators in increasing the adoption of management practices.

Specifically, onion growers who participated in the 'IRM adoption program' gained experience with new, recently registered insecticides. Prior to 2008 in New York, most insecticides used to manage onion thrips in onion were contact insecticides (e.g. organophosphates, carbamates and pyrethroids), and provided 1 week of onion thrips control. Since 2008, multiple insecticides have been registered that have either translaminar or systemic activity (e.g. spirotetramat, spinetoram, cyantraniliprole) and greater efficacy against onion thrips compared with older insecticides.[54–56] These new insecticides have residual activity ranging from 5 to 14 days[41] and can offer weeks of onion thrips control in onion. For example, the systemic insecticide spirotetramat can provide 2–3 weeks of onion thrips control after one application.[57] Consequently, growers do not necessarily need to make an insecticide application every week as they needed to in the past. However, the prices of these newer insecticides are approximately two to four times more expensive than the older insecticides. Presumably, the higher costs of the newer insecticides inhibited growers from experimenting and regularly applying these newer products. The 'IRM adoption program' enabled growers to observe and experiment with these newer, more effective insecticides.

Our study documents further evidence that extension-based programs can significantly impact the actions of growers. Functionally, extension educators are a conduit between growers and researchers and extension's communication of research findings can be a major factor determining IPM adoption.[24,58] Consistently in our study, growers from specific counties tended to manage thrips on their farms similarly, although this was not statistically significant. For example, growers in Orleans County consistently followed the action threshold and adherence to the recommended insecticide sequence and rotation restrictions in all years of the program. Research and extension conducted by Cornell Cooperative Extension educators and Cornell entomologists have had a strong presence in Orleans County over the past decade, and growers and Cornell personnel frequently and openly communicate (i.e. weekly meetings between growers and Cornell extension). Conversely, we observed that Oswego County onion growers, who had much lower levels of extension and research involvement on their farms, had the lowest initial level of adoption of either IRM tactic. Our case study showed that the installment of greater extension resources and communication with growers led to fewer insecticides being applied to manage onion thrips. In year 1 in Oswego County, only 38% of applications made by growers followed the action threshold, but approximately 57% of the applications followed the action threshold in years 2 and 3.

Interestingly, our study identified a potential synergy between the two IRM practices implemented. Significant reductions in insecticide applications were recorded with increased use of the action threshold and insecticide class rotation. Specifically, those growers with fewer insecticide applications were more likely to successfully rotate between insecticide classes. On average, use of an action threshold reduced the number of insecticide applications in most agricultural production systems when compared with a standard (or weekly) insecticide program.[36,39,50] Fewer insecticide applications present fewer opportunities for growers to incorrectly rotate insecticide products. Therefore, use of an action threshold may facilitate insecticide class rotation. This finding highlights the potential importance of fully evaluating IRM programs such that returns can be maximized to the grower and the onset of insecticide resistance is slowed.

The use of inexpensive insecticides may be a significant barrier in IRM adoption. Consistently, increased numbers of inexpensive insecticide applications were negatively associated with percentage adoption of either the action threshold or insecticide rotation. Interestingly, the use of inexpensive lambda-cyhalothrin was also negatively associated with proper insecticide rotation. Many onion thrips populations in New York are resistant to lambda-cyhalothrin[34,35]; however, some growers still apply this insecticide with hopes to reduce thrips infestations. Inexpensive insecticides, regardless if they are effective or not (as is the case with lambda-cyhalothrin), are unlikely to incentivize the adoption of IRM tactics, especially in high-value commodities. The perception of risk imposed by the insect pest will often supersede recommendations from an action threshold.[58] The cost of pesticides has been implicated as a potential barrier to the adoption of resistance management practices in other systems as well.[59,60] Thus, IRM programs should dissuade growers from repeatedly applying inexpensive insecticides because overuse may result in insecticide resistance.

Adoption of IRM and associated IPM practices can be challenging in high-value commodities, where losses in yield can be economically devastating.[13] In our study, the primary reason growers declined using the action threshold was, 'the insecticide price was lower than risk of the thrips population building [and not being controllable in the future]'. In many cases, growers also mentioned that they had experienced 'bad years' in which they had great difficulty managing thrips, and thus were more averse to the risk of skipping a weekly insecticide application routine. Additionally, growers responded that the cost savings generated by using an action threshold was not perceived as a large benefit, as only 33% of growers indicated that reducing their insecticide bill was a reason for adopting the action threshold. Because onion is a high-value crop, the cost savings of eliminating an insecticide application is marginal. For example, assuming an average value of \$16/cwt with an average yield of 864 cwt/ha would amount to a gross revenue of \$13,824.[61] Therefore, even a 1% loss in yield would amount to a loss of \$138, which is similar to the average cost of insecticide savings we have demonstrated in this study (\$148/ha). The economic incentives of using an action threshold to determine pest control decisions in a high-value crop are less compelling than benefits like slowing the onset of insecticide resistance by making fewer applications. The primary reason onion growers in our study cited for following the action threshold was to slow the onset of insecticide resistance and thereby preserve the efficacy of currently labeled insecticides. Therefore, New York onion growers appeared to be responsive to adopting IRM tactics that are predicated largely on IRM principles, which is consistent with other studies.[20] Therefore, this study further verifies the need for IRM and related programs to appeal to resistance management rather than economics for high-value commodity farmers.

5 CONCLUSION

The 'IRM adoption program' successfully increased grower education of insecticide resistance management tactics. As a result, participating growers substantially increased usage of both the action threshold and rotation of insecticide classes, which reduced numbers of insecticide applications and saved them money. However, since the 'IRM adoption program' was free to the grower, long-term impacts and sustainability of this effective program will depend on the complexity of the IRM tactics and returned benefits to the grower. Action thresholds are notoriously difficult to implement, as they can be complicated and time consuming to the grower or practitioner.[12] Scouting incurs a cost to growers, either through their time spent scouting or paying for a scouting service, which can further limit the economic incentive of implementing an action threshold. Therefore, further innovation and technology is needed to address this issue to ensure that growers can implement these tactics in a timely and affordable manner.

ACKNOWLEDGEMENTS

Many thanks to the growers who participated in the project, and to J. Gibbons, K. Besler, and J. Kocho-Schellenberg for their assistance in scouting. We also thank Dr. Erika Mudrak for her assistance with the statistical analysis. This project was funded by the New York Farm Viability Institute.

SUPPORTING INFORMATION

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

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