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Impact of Insecticide Efficacy on Developing Action Thresholds for Pest Management: A Case Study of Onion Thrips (Thysanoptera: Thripidae) on Onion

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ABSTRACT An action threshold (AT) is one of the most important decision-making elements in integrated pest management. Unlike economic thresholds, ATs are not typically derived from an economic injury level model, but they are more commonly used. ATs may be identified from research-based, pest–crop relationships, but they also may be based on experience. ATs may be adjusted depending on, e.g., weather and plant variety, but modifying ATs to accommodate differences in insecticide efficacy has received little attention. To examine this point, several combinations of ATs and insecticides were evaluated against onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), a major pest of onion (*Allium cepa* L.). Studies were conducted in New York onion fields from 2006 to 2008 by using registered insecticides for *T. tabaci* on onions. We hypothesized that the most efficacious insecticides would provide acceptable control of thrips populations regardless of AT (one, three, and five thrips per leaf), whereas less effective products would only control populations using the lowest AT (one thrips per leaf). Results indicated that *T. tabaci* infestations were managed effectively when spinetoram was applied after a three larvae per leaf threshold, but not when using lambda-cyhalothrin, methomyl or formetanate hydrochloride. However, *T. tabaci* infestations were managed well when methomyl and formetanate hydrochloride were applied after a one larva per leaf threshold. *T. tabaci* infestations were never controlled using lambda-cyhalothrin, regardless of the AT used. None of the products reduced *T. tabaci* populations to an acceptable level when applied at a five larvae per leaf threshold. Implications of adjusting ATs based on efficacy of different insecticides are discussed.

KEY WORDS *Thrips tabaci*, action threshold, insecticide, *Allium cepa*

More than 50 yr have passed since Stern et al. (1959) published their seminal article on the economic injury level (EIL) concept as a basis for integrated pest management (IPM). The EIL is defined as the lowest population density that will cause economic damage (Pedigo et al. 1986). Advancements in the theory and practice of EILs in IPM have been described in several prominent publications (Stone and Pedigo 1972; Norton 1976; Poston et al. 1983; Pedigo et al. 1986; Onstad 1987; Higley and Wintersteen 1992; Pedigo and Higley 1992; Higley and Pedigo 1993, 1996; Peterson and Hunt 2003). Over 225 articles on EILs were published by the early 1990s (Peterson 1996), and many more have been published since, reflecting the importance of the EIL concept on IPM.

The EIL model most commonly referred to is EIL = C/VIDK, where C is cost of the management tactic, V is the market value per production unit, I is injury units per pest, D is damage per injury unit, and K is the proportional reduction in the pest population (Pedigo et al. 1986). Calculating EILs is difficult for many reasons (Hammond 1996), but one of the most problematic reason is describing and interpreting the relationship between crop yield loss and insect density or feeding damage (components I and D) (Nault and Kennedy 1998). Many factors can affect this relationship, including weather, crop variety, partial plant resistance, crop phenology, and the insect stage targeted (Ostlie and Pedigo 1985, Bystrak et al. 1994, Fournier et al. 1995, Rueda et al. 2007). Models have been used to resolve uncertainty in levels of parameters in the EIL model (probabilistic EIL) (Peterson and Hunt 2003), and they have been modified to consider impacts of additional factors, such as the environment (environmental EIL; Higley and Wintersteen 1992, Pedigo and Higley 1992, Higley and Pedigo 1993), the potential control by natural enemies (Naranjo et al. 2002, Musser et al. 2006), esthetics (Sadof and Raupp 1986), and plant quality (Hutchins 1986).

The economic threshold (ET) is a pest density or injury level below the EIL. Curative control tactics are

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applied when pest densities or damage levels reach the ET to prevent pest damage from reaching the EIL and causing economic loss. For many of the reasons mentioned above, calculating research-based ETs are as difficult as determining EILs. The terms action threshold (AT) and ET are often used synonymously even though ATs are typically not derived from an EIL model. Like ETs, ATs may be identified from research-based field trials that evaluate pest-crop relationships, but they also may be best estimates based on experience. ATs generally do not include the full set of complexities of an ET. In many situations, ATs are more commonly available than ETs. This is especially true in situations where future pest damage to a high value crop is far greater than the cost of the treatment. In addition, ATs may be developed in cases where it is too difficult, for example, to quantify future prices of the commodity, yield loss, and damage by subsequent generations.

In our experience as entomologists working in vegetable IPM, it is common for crop consultants, extension educators and growers to ask us to provide a pest density at which they should treat their crop. Yet, research-based ATs are not available for many of the serious arthropod pests that attack major vegetable crops in the United States. Although we have not conducted a thorough literature review to illustrate the infrequency of ATs recommended for vegetable insect pests, the two references below offer a reasonable representation of such literature. In Vegetable Insect Management edited by Foster and Flood (2005), only 77 of 167 important arthropod pests are listed as having ATs. Of these 77 pests, thresholds have been adjusted to account for differences in plant phenology (n = 19), variety (n = 13) and stage of the insect targeted (n = 3). In Cornell University's Integrated Crop and Pest Management Guidelines for Commercial Vegetable Production, only 35 of 79 target arthropod pests of the primary vegetable crops or crop groups listed have recommended ATs (Reiners and Petzoldt 2009). For these 35 pests, ATs have been adjusted for differences in plant phenology (n = 8), variety (n = 6), and stage of the insect targeted (n = 2). No ATs were modified based on the efficacy of the insecticide used to control the pest, nor are we aware of any such examples.

Recommendations for arthropod pest management in vegetable crops are typically made with the expectation that a highly effective insecticide will be used. Because most vegetable crops are high in value, growers are generally risk adverse and they rarely consider using an insecticide or management activity unless it controls >90% of the pest population and protects the crop from economic damage. Such highly efficacious practices fit in well with the value K in most EIL models because it is fixed at 1.0 or 100% control. Yet, many factors can affect the efficacy of a potentially highly effective insecticide including rate, application method and amount of coverage, stage and age of the pest, plant type and growth stage, timing, insecticide resistance, behavior of the pest, mortality by natural enemies and weather. Many of these issues are critical to consider when developing management strategies for thrips (Parrella and Lewis 1997), including one of the most serious thrips pests worldwide, the onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) (Lewis 1997).

T. tabaci adults and larvae feed on onion leaves, thereby compromising photosynthesis and water retention, often resulting in the production of smaller and less valuable bulbs. This insect also is a vector of Iris yellow spot virus (family *Bunyaviridae*, genus *Tospovirus*), which also may reduce bulb yield and could add another layer of complexity to the development of an AT. Infestations of *T. tabaci* span 2 mo in most onion-growing regions in North America (Cranshaw et al. 2005), and as few as one and as many as 12 foliar applications of insecticides may be used to mitigate economic loss (Stivers 1997). Some onion growers use ATs to determine when to spray insecticides. In northeastern North America, ATs of 0.9 and 2.2 thrips per leaf were recommended for drought and normal seasons, respectively (Fournier et al. 1995). In other locations throughout North America, ATs reported vary from one thrips per plant in Texas (Edelson et al. 1989), three thrips per leaf in Michigan (Quartey 1982), 15–30 thrips per plant in Utah (Alston and Drost 2008), and 30 per plant in California (Anonymous 2002). Lower ATs are often recommended for thrips-susceptible varieties and for onions in the bulbing stage, whereas higher ATs are recommended for moderately tolerant varieties, young plants, and those near maturity (Cranshaw et al. 2005). In New York, an AT of three thrips per leaf was recommended (Shelton et al. 1987) when pyrethroids were first introduced and they provided excellent control.

Insecticides vary in their effectiveness against *T. tabaci* based on their inherent toxicity to this insect as well as evolving resistance due to overdependence on a single insecticide or class of insecticides. In small-plot onion studies in New York in 2005 (Nault and Hessney 2006) and 2007 (Nault and Hessney 2008b), potential and currently registered insecticides were evaluated against onion thrips, and the following insecticides were shown to reduce the *T. tabaci* infestation by a wide range of values relative to the untreated control: lambda-cyhalothrin by only 20% (2005), acetamiprid by 50% (2005) and 38% (2007), oxydemeton-methyl by 54% (2007), methomyl by 59% (2005) and 68% (2007), spinosad by 84% (2005), and formetanate hydrochloride by 98% (2005) and 97% (2007). Spinetoram, the only highly effective product registered in New York, reduced the population by 95% (2005) and 97% (2007) relative to the untreated control.

Not all insecticides, even when newly introduced, probably provide the ≥90% mortality desired by growers (Buntin 1986). Furthermore, their efficacy normally declines over time because of the evolution of insecticide resistance. An example of this phenomenon is that management of *T. tabaci* in onion by using insecticides has become difficult in northeastern North America since the late 1990s. Although initially effective, some populations of *T. tabaci* have developed some level of resistance to lambda-cyhalothrin, deltamethrin, and diazinon (Shelton et al. 2003, MacIntyre-Allen et al. 2005, Shelton et al. 2006). However, the threat of resistance to other classes of insecticides has forced growers to use less effective insecticides as part of an insecticide resistance management strategy to preserve more effective insecticides. This presents problems when applications are timed using the three thrips per leaf threshold, which works well for spinetoram, but may not be appropriate for other insecticides that are less effective. When this occurs, growers have resorted to either using lower ATs (e.g., one thrips per leaf) or ignoring thresholds altogether and spraying on a weekly basis (B.A.N., personal observation).

Onion growers are keenly interested in managing *T. tabaci* infestations in onion by using insecticides that are applied according to research-based ATs. A single AT is not likely to be appropriate for all insecticides registered for use on the onion crop, suggesting that ATs may have to be developed independently for each insecticide. For example, a lower AT (e.g., ≤1 thrips per leaf) might be appropriate for a mediocre-performing insecticide, whereas a higher AT (e.g., 3–5 thrips per leaf) could work well for a highly effective product. To investigate this concept and its ramifications, we compared levels of *T. tabaci* control by using highly effective and less effective insecticides applied after ATs ranging from one to five thrips per leaf. Our hypothesis was that the most efficacious insecticides would provide acceptable control of thrips infestations regardless of threshold (one, three, and five thrips per leaf), whereas less effective products would only provide control using the lowest threshold (one thrips per leaf).

Materials and Methods

Study Site and Experimental Design. Experiments were conducted in commercial onion fields in the Potter Muck region of Yates County, NY. Dry bulb onion seeds were planted on 3 April 2006, 1 May 2007, and 16 April 2008. Cultivars were 'Barrage', 'Sedona', and 'BGS 229′ for the years above, respectively. Each plot consisted of four 3.05-m-long onion rows, and rows were spaced every 38 cm. Plots were separated within rows by 0.9 m. Experimental sites were flanked on all sides by at least 1.5 m of insecticide-free onions within the grower's field. Onions in our studies were protected from onion maggot, *Delia antiqua* (Meigen), the only other insect pest of significance, by the nonsystemic insecticide seed treatment cyromazine (Trigard 75 WP). Diseases and weeds were controlled using several pesticides recommended for onion production in New York (Reiners and Petzoldt 2009). *T. tabaci* was not affected by these pesticide applications and onions were never irrigated.

Three insecticides (listed below) and three ATs were included in each year of this study. ATs included one, three, and five *T. tabaci* larvae per leaf. Treatments included all combinations of insecticides and thresholds plus an untreated control (10 treatments total). Treatments were arranged in a randomized complete block design with four replications.

Insecticides and Application Technique. Insecticides chosen for this study were either registered against *T. tabaci* on onions in New York or ones that we anticipated would soon be registered. In 2006 and 2007, lambda-cyhalothrin (Warrior, Syngenta Crop Protection, Greensboro, NC), methomyl (Lannate LV, DuPont Crop Protection, Wilmington, DE), and formetanate hydrochloride (Carzol SP, Gowan Company, Yuma, AZ) were chosen and expected to provide mediocre, good, and excellent control of *T. tabaci*, respectively. In 2008, methomyl, formetanate hydrochloride and spinetoram (Radiant SC, Dow AgroSciences, Indianapolis, IN) were used as the least effective, moderately effective, and most efficacious insecticide, respectively. High recommended labeled rates for all products were used. Lambda-cyhalothrin was applied at a rate of 33.5 g (AI) ha^{-1}, methomyl at 1,009 g (AI) ha^{-1}, formetanate hydrochloride at 64.4 g (AI) ha^{-1}, and spinetoram at 70 g (AI) ha^{-1}. Applications were made using a CO_2-pressurized backpack sprayer equipped with a single-row boom and a single nozzle. In 2006, the sprayer was calibrated to deliver 842 liters ha^{-1} at 276 kPa through a flat-fan nozzle (8004VS; TeeJet Harrisburg, Dillsburg, PA). In 2007 and 2008, the sprayer was calibrated to deliver 393 liters ha^{-1} at 276 kPa through a twin flat-fan nozzle (TJ60–8004VS; TeeJet Harrisburg). All treatments included the nonionic surfactant Induce (Helena Chemical Co., Collierville, TN) at 0.5% (vol:vol).

Sampling Thrips and Damage. *T. tabaci* is the dominant thrips species that colonizes onion fields in New York (Gangloff 1999). *T. tabaci* population densities were monitored weekly throughout the season until onions matured and >50–75% of the leaves had lodged. The total number of thrips larvae per plant was counted visually from 15 randomly selected plants within the center rows of each plot. Adults were not recorded because they move between plots and their presence does not always reflect the efficacy of the treatment. To determine the number of thrips per leaf each week, the number of green leaves per plant was recorded each week by randomly sampling 20 plants within the test site. *T. tabaci* voucher specimens are located in the Department of Entomology at the New York State Agricultural Experiment Station in Geneva, NY.

In 2006 and 2007, plots were visually rated for thrips damage using a scale ranging from 1 to 10: 1, no damage; 2, 1–10% of the leaves were white as a consequence of feeding damage; 3, 11–20% damage; 4, 21–35% damage; 5, 36–50% damage; 6, 51–65% damage; 7, 66–80% damage; 8, 81–90% damage; 9, 91–99% damage; and 10, complete damage (100% leaves white). An average rating of ≤2.0 was considered commercially acceptable. Visual ratings of damage were made on 7 August 2006 and 31 August 2007. No thrips damage ratings were made in 2008 because hail damaged plants near the end of the season and impaired the ability to assess damage made only by thrips.

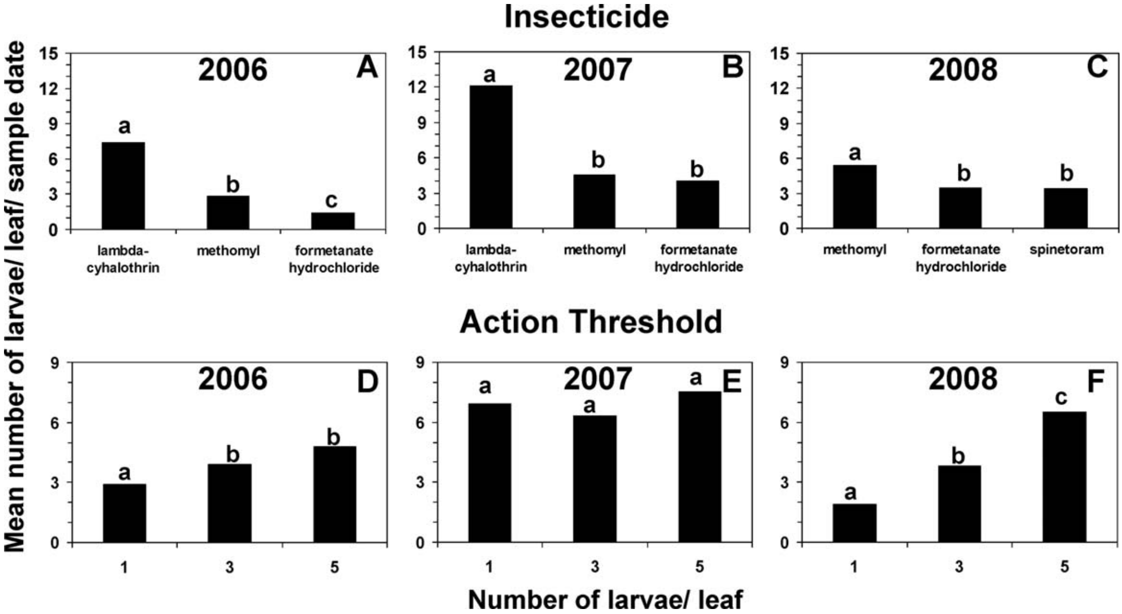

Fig. 1. Impact of insecticide and action threshold main effects on the mean number of *T. tabaci* larvae per leaf per sample date during the onion growing season in the Finger Lakes region of New York in 2006, 2007, and 2008.

Making Control Decisions Based on Action Thresholds. Thrips population densities were estimated by calculating the mean number of larvae per leaf across all four plots. If the mean reached or exceeded the target AT, all plots in the treatment were sprayed. Thrips sampling frequency occurred every 6–7 d. If the mean thrips density for a treatment was within 0.1 larva per leaf for a targeted threshold, a decision was often made to spray that treatment rather than waiting until the following week to make the decision. Sprays were made the same day plots were sampled.

Statistical Analyses. Mean densities of thrips larvae per leaf over the entire season were calculated by dividing the total number of thrips per leaf by the number of sampling dates. Mean number of thrips per leaf per sampling date was the response variable and was analyzed using regression analysis (PROC MIXED, SAS Institute 2008), which considered insecticide and AT as main effects and fixed in the model and replication as a random factor. All mean treatment comparisons were made using LSMEANS at $P < 0.05$ (SAS Institute 2008). No transformations were needed to stabilize variance in these data sets.

Results

Insecticide and Action Threshold Impact on Season Mean Thrips Densities. Seasonal mean thrips population densities were affected by the insecticides and ATs used (Fig. 1A–F). There were no significant interactions between insecticide and AT ($P > 0.05$), indicating that the trend in performance for each insecticide was similar across the three ATs evaluated.

Regardless of AT, the season mean thrips densities were significantly affected by insecticide in 2006 ($F = 55.0$; df = 2, 24; $P < 0.0001$) (Fig. 1A), 2007 ($F = 65.4$; df = 2, 24; $P < 0.0001$) (Fig. 1B), and 2008 ($F = 4.9$; df = 2, 24; $P = 0.0161$) (Fig. 1C). In 2006, the thrips population was reduced the most using formetanate hydrochloride, followed by methomyl and then lambda-cyhalothrin (Fig. 1A). In 2007, the thrips population was reduced to a similar level using formetanate hydrochloride and methomyl, which both reduced the thrips population significantly more than lambda-cyhalothrin (Fig. 1B). In 2008, the thrips population was reduced to a similar level by using spinetoram and formetanate hydrochloride, which both reduced the thrips population significantly more than methomyl (Fig. 1C).

Regardless of insecticide, the seasonal mean thrips densities were significantly affected by ATs in 2006 ($F = 4.8$; df = 2, 24; $P = 0.0180$) (Fig. 1D) and 2008 ($F = 21.2$; df = 2, 24; $P < 0.0001$) (Fig. 1F) but not in 2007 ($P > 0.05$) (Fig. 1E). In 2006, the thrips population was reduced the most after the one larva per leaf threshold, whereas no significant differences existed between the three and five larvae per leaf thresholds. In 2008, control of the thrips population followed a similar trend observed in 2006. The greatest reduction in the thrips population was achieved after the one larva per leaf threshold, followed by the three larvae per leaf threshold and then the five larvae per leaf threshold. These results indicate that in two of 3 yr, season mean thrips populations decreased as the AT was reduced.

Insecticide and Action Threshold Influence on Thrips Population Dynamics and Damage. *Lambda-Cyhalothrin.* Compared with the untreated control, lambda-cyhalothrin failed to reduce the thrips population, regardless of the AT used (Fig. 2A–F). On

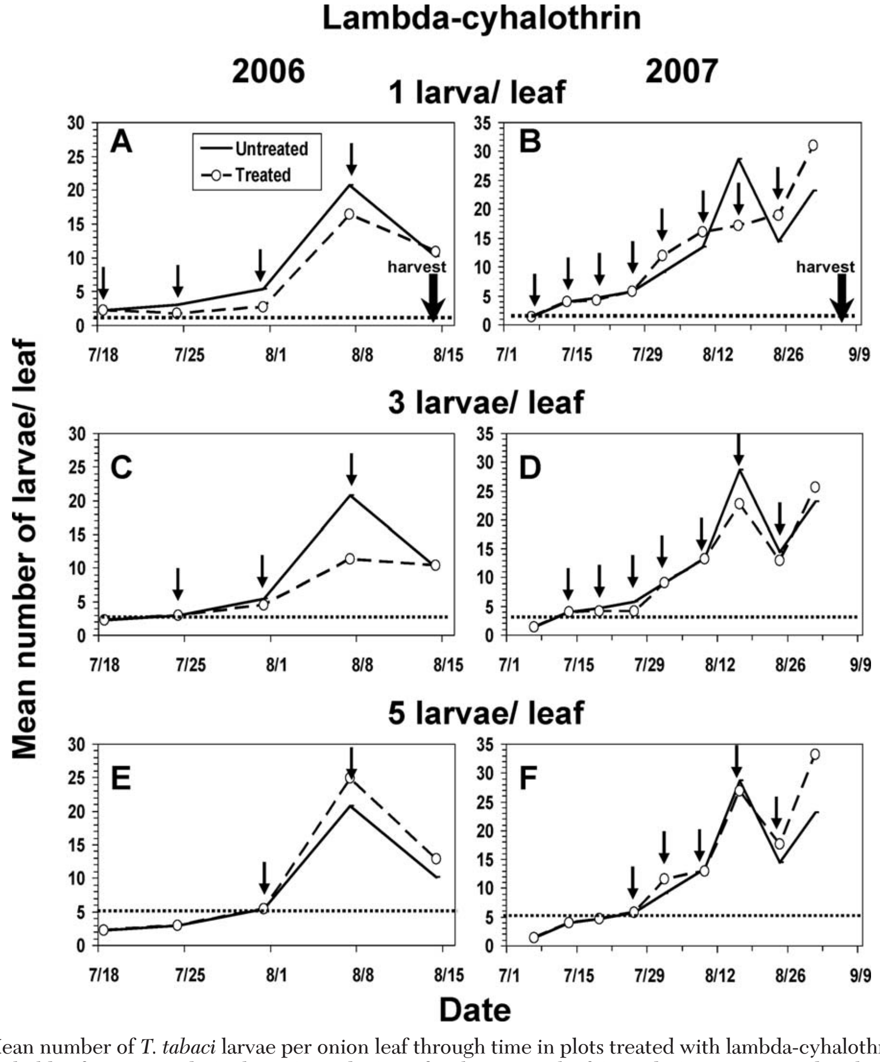

Fig. 2. Mean number of *T. tabaci* larvae per onion leaf through time in plots treated with lambda-cyhalothrin (Warrior) at action thresholds of one (A and B), three (C and D), or five larvae per leaf (E and F) or not treated with insecticides in the Finger Lakes region of New York in 2006 and 2007. The horizontal dashed line represents the action threshold. Small arrows signify application times and the large arrows indicate harvest dates.

nearly all sampling dates, populations of thrips in the lambda-cyhalothrin treatments mirrored those in the untreated control (Fig. 2A–F; Table 1). In 2006, the one, three, and five larvae per leaf thresholds were met on 18, 24, and 31 July, respectively (Fig. 2A, C, and E). In all cases, applications continued weekly after the threshold was reached because the population did not respond to the treatment. In 2007, the one, three, and five larvae per leaf thresholds were met on 7, 13, and 27 July, respectively (Fig. 2B, D, and F), and applications continued weekly because the population was not reduced by the treatment.

Thrips damage ratings in all lambda-cyhalothrin treatments were similar to those in the untreated control in both years (Table 1). Damage levels in all lambda-cyhalothrin treatments were high and generally greater than those in methomyl and formetanate hydrochloride treatments (Table 1). The damage rating results for lambda-cyhalothrin reflect a similar pattern observed for this product's impact on the season mean thrips density shown in Fig. 1.

Methomyl. Control of *T. tabaci* infestations was marginal using methomyl (Fig. 3A–I; Table 1). In 2007 and 2008, the thrips population was difficult to reduce below the target threshold in July and August (Fig. 3B, C, E, F, H, and I). At the end of the 2008 season, the thrips population increased sharply in the five larvae per leaf threshold treatment (Fig. 3I) but not as much in the one and three larvae per leaf threshold treatments (Fig. 3C and F). The reason for this difference was that no spray was made on 25 July in the five larvae per leaf threshold treatment but was made for the one and three larvae per leaf treatments. These late season sprays presumably reduced adult colonization and oviposition in August. In general in all 3 yr, the number of applications decreased as the AT increased, except

Table 1. Number of insecticide applications and mean onion thrips, *T. tabaci*, damage ratings for each insecticide, and action threshold treatment in Yates County, NY

Insecticide	Threshold	2006		2007		2008
		No. sprays	Damage rating[a,b]	No. sprays	Damage rating[a,b]	No. sprays
Untreated			7.2e		7.4c	
Lambda-cyhalothrin	1 larva/leaf	4	7.0e	8	8.0c	
Lambda-cyhalothrin	3 larva/leaf	3	6.2de	7	7.4c	
Lambda-cyhalothrin	5 larva/leaf	2	7.5e	5	7.5c	
Methomyl	1 larva/leaf	3	3.7c	6	2.5ab	7
Methomyl	3 larva/leaf	2	4.7cd	4	2.9b	5
Methomyl	5 larva/leaf	1	6.5de	4	2.7b	3
Formetanate hydrochloride	1 larva/leaf	2	1.0a	4	1.5a	6
Formetanate hydrochloride	3 larva/leaf	1	1.7b	3	1.4a	4
Formetanate hydrochloride	5 larva/leaf	1	3.7c	2	2.5ab	3
Spinetoram	1 larva/leaf					5
Spinetoram	3 larva/leaf					4
Spinetoram	5 larva/leaf					2

[a] Means within a column followed by the same letter are not significantly different ($P > 0.05$; LSMEANS).
[b] Damage ratings (scale of 1, no damage to 10, 100% damaged) were taken on 7 August 2006 and 31 August 2007; no ratings were taken in 2008.

in 2007 when the number of applications did not differ between the three and five larvae per leaf thresholds (Fig. 3E and H; Table 1).

Thrips damage levels in methomyl treatments were significantly lower than those in the untreated control in 2006 and 2007, with the exception of the five larvae per leaf threshold treatment in 2006 (Table 1). In both years, damage levels exceeded 2.0 in all threshold treatments (Table 1), indicating that methomyl alone was not effective enough to provide acceptable season-long control of *T. tabaci* infestations.

Formetanate Hydrochloride. Thrips were controlled relatively well using formetanate hydrochloride (Fig. 4A–I; Table 1). In 2007 and 2008, two sequential applications often were needed to reduce the population below the target threshold. At the end of the 2007 and 2008 seasons, the thrips populations increased dramatically in all treatments (Fig. 4B, E, F, H, and I), except for the one larva per leaf treatment in 2008 (Fig. 4C). The reason for the population increases in the three and five larvae per leaf treatments was that no sprays were made after 10 or 17 August 2007, or on 26 July and 1 August 2008. Although the larval density remained below threshold in these treatments during this period, adults were likely colonizing and ovipositing on the lush foliage in these plots rather than the heavily thrips-damaged plants in the untreated plots. The number of applications decreased as the AT increased, except in 2006 when the number of applications did not differ between the three and five larvae per leaf threshold treatments (Fig. 4D and G; Table 1).

Thrips damage in formetanate hydrochloride treatments was much lower than in the untreated control in 2006 and 2007 (Table 1). Damage levels never exceeded 2.0 in the one and three larvae per leaf threshold treatments but exceeded this level in the five larvae per leaf threshold treatment in both years (Table 1). These results indicate that formetanate hydrochloride could be used effectively to manage *T. tabaci* infestations in onion using either a one or three larvae per leaf threshold.

Spinetoram. Thrips were controlled most effectively using spinetoram (Fig. 5A–C). The only exception was that the population increased sharply at the end of the season in the five larvae per leaf treatment (Fig. 5C) because no sprays were made on 18 and 26 July and on 2 August. Although the larval density remained below the five larvae per leaf threshold during this period, it did not prevent colonization and oviposition by adults in August. Like the other insecticides, the number of applications decreased as the AT increased (Fig. 5A–C; Table 1).

Action Thresholds Recommended for Each Insecticide. The mean numbers of thrips larvae per leaf per sample date over the season for each insecticide and AT combination are illustrated in Fig. 6. An average of these means across years was calculated for all products, except spinetoram because there was only one season of data. For reference, a horizontal line at 2.2 larvae per leaf per sample date marks the AT recommended for *T. tabaci* control in onions in nearby Quebec (Fournier et al. 1995). The insecticide and AT combination in which the overall mean population density averaged nearest to 2.2 larvae per leaf per sampling date was selected as the most appropriate and is considered acceptable by most onion growers (B.A.N., personal observation).

None of the ATs evaluated in our study were appropriate for lambda-cyhalothrin (Fig. 6). Although none of the ATs examined for methomyl reduced the overall mean thrips density below 2.2 larvae per leaf per sampling date, the one larva per leaf threshold provided results closest to this density (Fig. 6). In 2006, the one larva per leaf threshold reduced the mean thrips density below 2.2 larvae per leaf per sampling date. Formetanate hydrochloride applied at the one larva per leaf threshold reduced the overall mean thrips density below 2.2 larvae per leaf per sampling date (Fig. 6). In 2006, the three and five larvae per leaf thresholds reduced the overall mean thrips density below 2.2 larvae per leaf per sampling date, but this did not occur in 2007 or 2008. Spinetoram

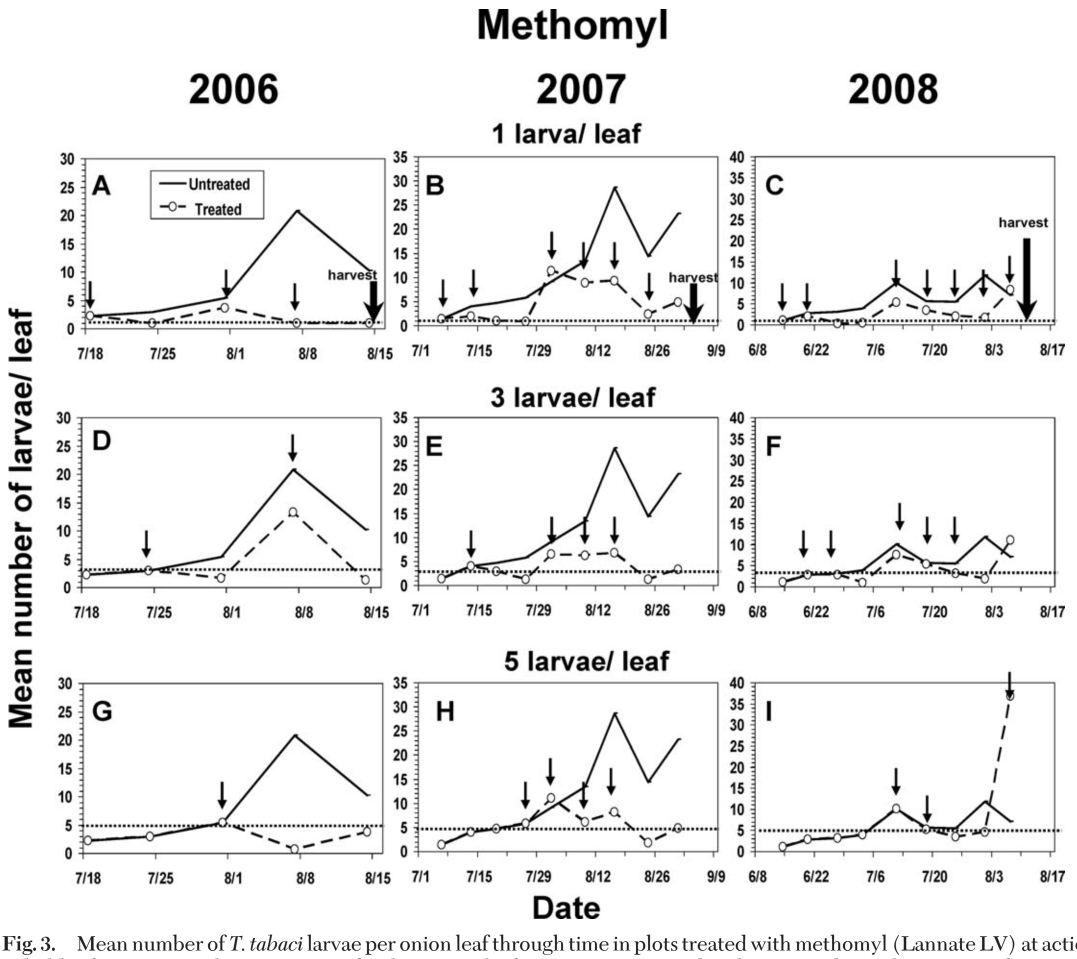

Fig. 3. Mean number of *T. tabaci* larvae per onion leaf through time in plots treated with methomyl (Lannate LV) at action thresholds of one (A–C), three (D–F), or five larvae per leaf (G–I) or not treated with insecticides in the Finger Lakes region of New York in 2006, 2007, and 2008. The horizontal dashed line represents the action threshold. Small arrows signify application times and the large arrows indicate harvest dates.

applied at one and three larvae per leaf reduced the overall mean thrips density at or below 2.2 larvae per leaf per sampling date, but not when applied at five larvae per leaf (Fig. 6).

Discussion

These studies demonstrated the complexity of developing reliable ATs because our results indicated that *T. tabaci* population densities on onion were differentially impacted by the insecticides and ATs evaluated. Insecticide efficacy had a profound influence on an AT and this has important implications for using the treatment threshold concept, a cornerstone of IPM.

Our results were contrary to the hypothesis that the most highly effective insecticide would provide equally high levels of control regardless of the action threshold used. Rather, we found that the average mean number of thrips per leaf per sampling date tended to increase similarly for each AT and insecticide combination, except for lambda-cyhalothrin (Fig. 6). The major difference among the various threshold and insecticide combinations was the magnitude of control, and this was surprising to us. Across all ATs, spinetoram had the lowest mean thrips densities followed by formetanate hydrochloride, methomyl, and finally lambda-cyhalothrin (Fig. 6). *T. tabaci* infestations were reduced to an acceptable level when spinetoram was applied after a three larvae per leaf threshold, but lambda-cyhalothrin, methomyl, and formetanate hydrochloride either did not control the population or were inconsistent in controlling the population when applied at this threshold. *T. tabaci* infestations were typically reduced to an acceptable level when methomyl and formetanate hydrochloride were applied after a one larva per leaf threshold. None of the products in our study reduced *T. tabaci* populations or feeding damage to an acceptable level when applied at an AT of five larvae per leaf. *T. tabaci* infestations were never controlled using lambda-cyhalothrin, regardless of the AT examined. Although these thrips populations were not tested for resistance to lambda-cyhalothrin, resistance has been confirmed

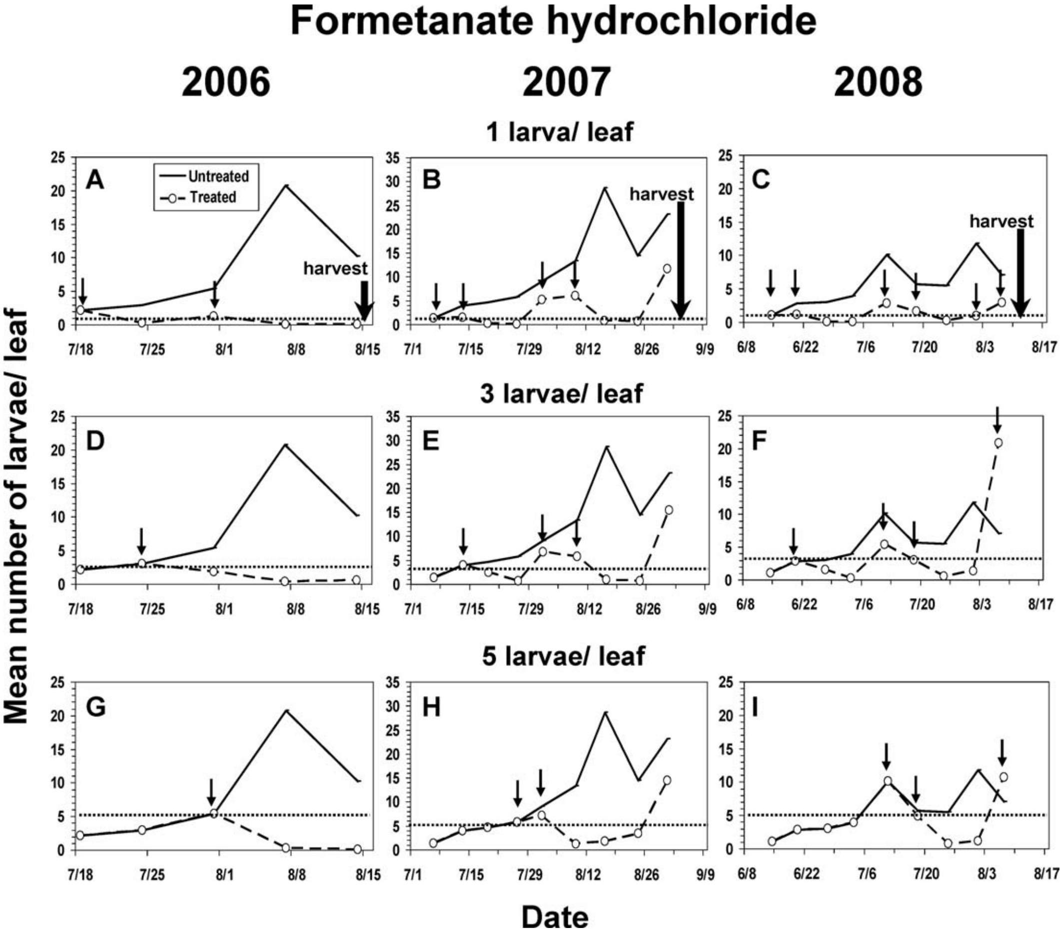

Fig. 4. Mean number of *T. tabaci* larvae per onion leaf through time in plots treated with formetanate hydrochloride (Carzol SP) at action thresholds of one (A–C), three (D–F), or five larvae per leaf (G–I) or not treated with insecticides in the Finger Lakes region of New York in 2006, 2007, and 2008. The horizontal dashed line represents the action threshold. Small arrows signify application times and the large arrows indicate harvest dates.

for populations near this test site in previous seasons (Shelton et al. 2003, Shelton et al. 2006).

Populations of *T. tabaci* were managed more effectively when methomyl, formetanate hydrochloride, and spinetoram were applied early in the season (June) compared with later in the season (July and August), when thrips develop more quickly and populations build more rapidly. Applications of these products in June and/or early July after either the one or three larvae per leaf threshold reduced the thrips density level below that target threshold for up to 2–3 wk (Figs. 3B, C, E; 4B, C, E, F; and 5A and B). In contrast, applications of these products after these ATs in late July and August rarely reduced the thrips density to a level below the target AT by the following week. Our results are similar to those reported by Fournier et al. (1995) and Hoffmann et al. (1996) who recommended ATs for *T. tabaci* ranging from one to three thrips per leaf for onions grown in northeastern North America.

In the standard EIL model, the K value accounts for a proportional reduction of the target pest population when a management tactic, usually an insecticide, is applied. If insecticide efficacy varies among products used to manage the target pest, K should be adjusted accordingly to reflect the difference. EIL models typically assume a K value near or equal to 1.0 (100% control). In some cases, this is reasonable if the insecticide is extremely effective and is applied in a manner in which nearly all the insects become exposed. If K is <1.0, due to less inherent toxicity of the insecticide, and all of the other variables in the model stay the same, the EIL will increase. However, if the insecticide applied is marginally effective, the EIL could inflate to a point that no control would be justified because there would be no economic return for using that insecticide. Such a scenario is likely for a product such as lambda-cyhalothrin, which had little to no control on *T. tabaci* in our study.

Developing an EIL model for a pest like *T. tabaci* that has multiple overlapping generations, an exponential phase in population growth and requires multiple insecticide applications to manage it is much more difficult than developing an EIL model for pests

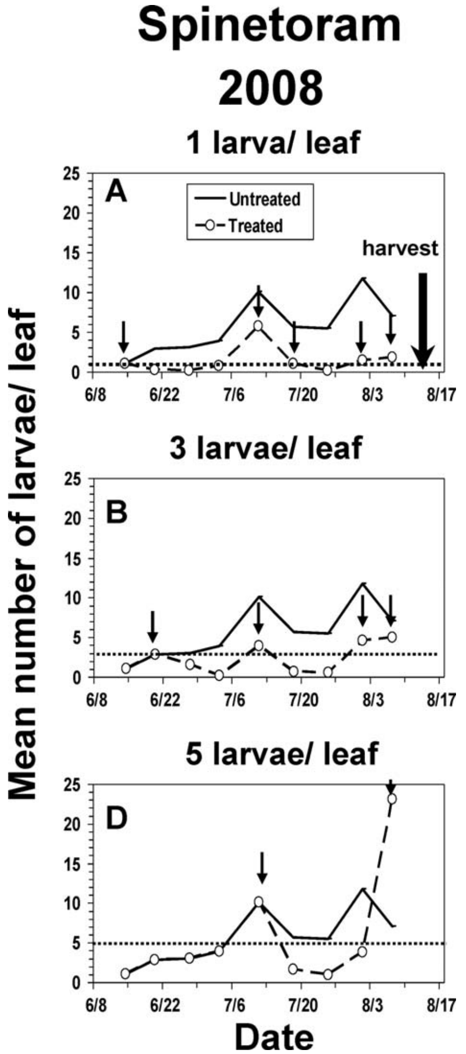

Fig. 5. Mean number of *T. tabaci* larvae per onion leaf through time in plots treated with spinetoram (Radiant SC) at action thresholds of one (A), three (B), or five larvae per leaf (D) in 2008 or three larvae per leaf (C) in 2009 or not treated with insecticides in the Finger Lakes region of New York. The horizontal dashed line represents the action threshold. Small arrows signify application times and the large arrows indicate harvest dates.

that have discrete generations on a crop and may require only a single curative measure for control. Onstad (1987) developed a more complex EIL model that would account for some of these parameters, but developing an EIL model for *T. tabaci* on onion would still be difficult for several reasons. Identifying the value of fresh-market onions is challenging because prices fluctuate greatly during the year. Generally, growers receive the highest prices for the portion of their crop that is sold soon after harvest, but prices can drop considerably for the remainder of the crop that is stored and sold the following winter and spring. Yield loss caused by *T. tabaci* and damage per future living larva are hard to predict because the yield-damage relationship varies based on growing conditions for the crop (e.g., edaphic factors, rainfall, temperature) (Rueda et al. 2007), temperature-driven development of the thrips populations (Mo et al. 2009) and date of onion harvest (Hsu et al. 2010). Consequently, the relatively straightforward development of ATs for *T. tabaci* management in onion outweighs the complications of calculating the parameters mentioned above to develop an EIL model and an ET. Still, for the reasons noted herein, even the complexities of developing "simplistic" ATs are not fully appreciated and have impeded the development of robust ATs for this pest in onion production systems.

In 1986 and 1993, New York onion growers averaged 8.9 and 7.6 insecticide applications per season, respectively, to manage *T. tabaci* (Hoffmann et al. 1995). Currently, onion growers average eight applications per season. Past attempts to convert onion growers to an AT-based, decision-making system for *T. tabaci* control in onion were promising. A group of New York onion growers followed ATs of three thrips per leaf in 1986 and 1.5 thrips per leaf in 1993 to determine when to make insecticide applications. Ethyl parathion and permethrin were the most commonly used products in 1986 and 1993, respectively. The result was a 52 and 38% reduction in the number of applications made in 1986 and 1993, respectively, to manage the infestations (1986: 4.3 applications and 1993: 4.8 applications) (Hoffmann et al. 1995). Thrips presumably were managed effectively using these ATs, but no data were presented. Results from our study showed that only four applications of spinetoram by using a three thrips per leaf threshold were needed to provide acceptable control of the thrips infestation, whereas an average of five applications of formetanate hydrochloride and an average of 6.5 applications of methomyl after a one thrips per leaf threshold were needed. Onion growers can clearly gain equivalent levels of *T. tabaci* control in onion fields using fewer insecticide applications after our ATs compared with a calendar-based decision system, if they use a highly efficacious insecticide such as spinetoram.

Currently, there are few highly effective products registered to manage *T. tabaci* in onion in the United States (Nault and Hessney 2006, 2008a,b). In addition to spinetoram, there are several other effective products such as spirotetramat, abamectin, and cyantraniliprole (Nault et al. 2010), but they are in various stages of the registration process. If these new products become registered for use on onion, the number of applications permitted may be limited to mitigate the possibility of resistance development in thrips populations. In 2009 and 2010, Emergency Use Permits for spirotetramat and abamectin were granted by the Environmental Protection Agency in several major onion-producing states in the United States. Both active ingredients were limited to two consecutive applications. Because the period of protection against *T. tabaci* in onion spans 6 to 8 wk, multiple products will be needed and used in a sequence to provide season-long protection of the crop. ATs for these products

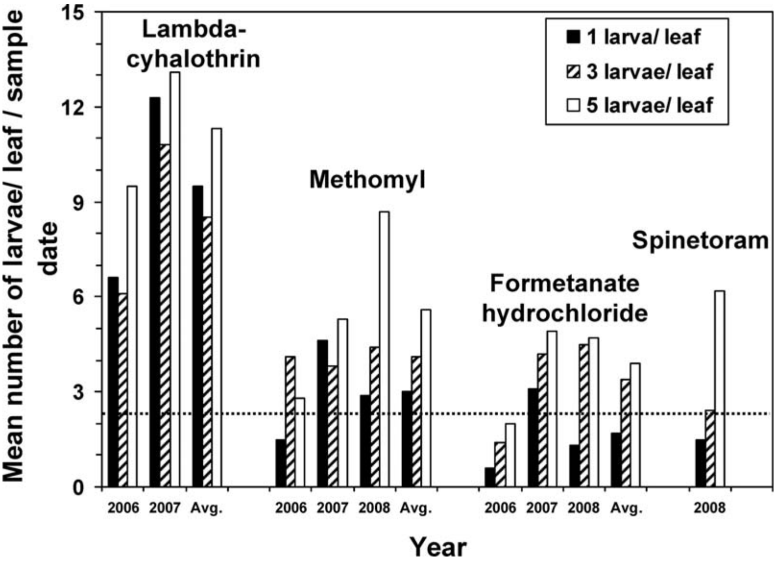

Fig. 6. Summary of *T. tabaci* season average densities in onion treated with certain insecticides and action thresholds in New York from 2006 to 2009. The horizontal dotted line signifies an action threshold of 2.2 thrips per leaf as suggested by Fournier et al. (1995).

should be identified as soon as possible so that onion growers can integrate them into an onion thrips management program.

T. tabaci management in onion should advance with the use of ATs, but onion growers could ignore them if the incidence of plant pathogens associated with thrips and their feeding increases. For instance, Hsu et al. (2010) reported a positive relationship between *T. tabaci* densities and levels of Iris yellow spot virus in New York onion fields at the end of the season. A higher AT could permit more viruliferous adults to colonize onion fields and spread the virus compared with a lower AT that might increase the number of insecticide applications, but would reduce thrips densities and the incidence of Iris yellow spot virus. Thrips damage also creates entry points for other pathogens to infect the crop. A relatively new and serious bacterial pathogen that occurs throughout New York is *Pantoea ananatis* (Serrano) Mergaret, which causes center rot (Carr et al. 2009). This pathogen enters through wounds on leaves and it also can be transmitted by tobacco thrips, *Frankliniella fusca* (Hinds) (Gitaitis et al. 2003). It is not known whether *T. tabaci* can transmit *P. ananatis* to onion. Thus, it is possible that the use of ATs, rather than a calendar-based, weekly spray schedule, for managing *T. tabaci* could result in more thrips feeding injury and lead to a greater incidence of center rot and Iris yellow spot virus.

Treatment guidelines, based on either ETs or ATs, are core to IPM programs and essential for transitioning away from traditional, calendar-based spray programs, which may result in unnecessary insecticide use. Our results with *T. tabaci* in onion suggest that thresholds should be developed with strong consideration for the insecticide's effectiveness. Furthermore, we suggest that the thrips-onion system is similar to other insect-crop complexes that confront applied entomologists, and this issue should be considered in those systems. Some insecticides may only be effective over a few years, and it would be difficult, and probably unrealistic, to create a threshold for each one, especially if there is a range of recommended rates and if the effectiveness of the insecticide declines over time because of evolving resistance. Regardless, we suggest that those developing thresholds and those who promote them in extension efforts recognize the limitations of thresholds if they are disassociated with the effectiveness of registered insecticides.

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