Performance of novel insecticide seed treatments for managing onion maggot (Diptera: Anthomyiidae) in onion fields

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Abstract

Management of onion maggot, Delia antiqua (Meigen), in onion requires the use of an insecticide applied at planting. Insecticide resistance and a dearth of available products have stimulated an effort to identify new insecticides for onion maggot control, especially chemistries that can be delivered as seed treatments. Onion seeds film-coated with fipronil, spinosad, clothianidin or thiamethoxam were evaluated for onion maggot control in muck soils located in two major onion-growing regions in New York, USA in 2001–2003. Fipronil, spinosad and clothianidin at rates of 25, 25 and 50 g (a.i.)/kg of seed, respectively, consistently provided excellent control of onion maggot (<5% seedling loss). Moreover, these seed treatments performed well during wet and dry seasons. In contrast, thiamethoxam at a rate of 50 g (a.i.)/kg of seed failed to control onion maggot in three of the five experiments. Cyromazine seed treatment, which is currently used by onion growers, provided an equivalent level of onion maggot control to fipronil, spinosad and clothianidin. The other commonly used treatment, chlorpyrifos in-furrow drench, performed poorly in three of the four experiments, resulting in an average seedling loss of 17%. Insecticide resistance was implicated as the reason for the failure in two of the trials where seedling loss averaged 24%. Seed treatments provide growers with a convenient, reliable and environmentally responsible method for managing economically damaging onion maggot infestations, including those that are resistant to chlorpyrifos. Fipronil, spinosad and clothianidin seed treatments should be considered for future registration on onion. Availability of these chemistries would allow rotation with the cyromazine seed treatment, which would likely prolong the longevity of all products.

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1. Introduction

Onion maggot, Delia antiqua (Meigen), is a chief pest of onion and other Allium spp. in many temperate regions of the world (Ellis and Eckenrode, 1979). If not controlled, onion maggot can reduce onion stands by as much as 55–80% (Straub and Davis, 1978; Taylor et al., 2001). Onion maggot has three generations per year in the northern US and Canada, but control of the first generation is sufficient, as long as the crop is healthy (Hoepfing et al., 2003). Healthy onions, once they begin to bulb, are more difficult for newly hatched onion maggot larvae to penetrate (Hausmann and Miller, 1989). Diseased or physically injured onions are susceptible to damage by second- and third-generation onion maggots because bulbs become more attractive to ovipositing flies and more penetrable to maggots (Finch et al., 1986; Eckenrode and Nyrop, 1986; Hausmann and Miller, 1989).
The standard method for managing onion maggot infestations in commercial onion fields has been to apply an insecticide in the furrow at planting. Granular or liquid formulations of organochlorine, organophosphate and carbamate insecticides were commonly used in the past, but have been discontinued due to insecticide resistance (Harris and Svec, 1976; Carroll et al., 1983) or regulatory reasons. However, an exception is the organophosphate chlorpyrifos, which is still commonly used despite the increasing frequency of chlorpyrifos-resistant onion maggot populations in some New York production areas (Nault, unpublished). Chlorpyrifos was registered for onion during the early 1980s, and represents the only in-furrow usage allowed and still recommended in New York. Because management of onion maggot is highly dependent upon soil insecticides, and because the development and registration of in-furrow insecticides for use on minor crops such as onion has become more difficult, the efficacy of seed treatments using organophosphate and carbamate insecticides was evaluated for onion maggot management (Suett et al., 1988). Subsequently, an application of the insect-growth regulator cyromazine proved toxic to onion maggot larvae when applied in-furrow (Robbins et al., 1989; Hayden and Grafius, 1990) and as a seed treatment (Taylor et al., 2001). Cyromazine seed treatment also was shown to control chlorpyrifos-resistant onion maggot infestations in both dry bulb and green onions (Taylor et al., 2001; Yildirim and Hoy, 2003).

Current seed treatment methods require much less active ingredient per unit area to provide a comparable level of control relative to in-furrow drench insecticide applications. For example, cyromazine seed treatment uses 85% less active ingredient per hectare compared with an in-furrow drench application of chlorpyrifos (Taylor et al., 2001). However, the total active ingredient applied per hectare is dependent upon seeding rate, so degrees of reduction will vary among farms.

Currently, most onion growers in New York protect their onions from maggot infestations using a combination of cyromazine seed treatment and an in-furrow drench of chlorpyrifos. The rationale for this approach is that cyromazine will control chlorpyrifos-resistant onion maggots, while chlorpyrifos will control seedcorn maggot, Delia platura (Meigen), which is a sporadic pest of onion not adequately controlled by cyromazine. This practice is employed annually and is likely exacerbating insecticide resistance development in onion maggot populations. For this reason, the identification of alternative seed treatment chemistries is imperative.

There is evidence that several relatively new seed treatments may be useful for control of root maggots. Thiamethoxam and clothianidin delivered as seed treatments in snap bean, Phaseolus vulgaris L., reduced seedcorn maggot infestations in New York (Nault and Taylor, 2004). Recently, Ester et al. (2003) reported that film-coating cabbage seeds with spinosad gave good control of cabbage maggot, Delia radicum (Linnaeus) in the Netherlands. Hoeping et al. (2003) showed that fipronil seed treatment was effective against onion maggot in small plots of onion in Ontario, Canada.

Environmental conditions can affect efficacy of soil-applied insecticides. For example, excessive rainfall may cause leaching of the product, making it less effective. Below normal temperatures in the spring may delay pest emergence beyond the period that the product is efficacious. Therefore, temperature, rainfall and accumulated degree-day data are important factors to consider when evaluating seed treatments.

The focus of the research studies reported here was to evaluate the performance of seed treatments of novel insecticide chemistries in the field, especially those with favorable environmental profiles that would facilitate their registration. Included in the field trials were (a) thiamethoxam and (b) clothianidin, both systemic neonicotinoid insecticides that bind to the nicotinic acetylcholine receptor and disrupt nerve transmission; (c) spinosad, a spinosyn insecticide that alters acetylcholine receptor sites and disrupts binding; and (d) fipronil, a phenylpyrazole insecticide that interferes with the GABA receptors of insect neurons and is systemic in plants.

2. Materials and methods

Experiments were conducted in commercial dry bulb onion fields near Potter, New York from 2001 to 2003 and near Pine Island, New York in 2002 and 2003. Potter is located in Yates County in the Finger Lakes region of western New York, whereas Pine Island is in the lower Hudson Valley region of southeastern New York. The soil type in Potter and Pine Island is classified as Carlisle muck. Trials were conducted in the same non-rotated onion fields each year, which were selected because they had a history of high onion maggot infestations and considered difficult to control using chlorpyrifos. Dry bulb onion seeds, var. ‘Gazette’, were planted in the 2001 study and ‘Millennium’ seeds were planted in all other experiments. In Potter, seeds were planted on 20, 12 and 16 April 2001–2003, respectively; in Pine Island seeds were planted on 8 April in 2002 and 2003. Seeds were planted and treatments applied using a hand-pushed cone seeder, equipped with a gravity-fed system for pesticide in-furrow drenches, mounted onto a Planet Jr. frame. The seeding rate was 30 seeds/m. In all trials, each plot consisted of a single row that was either 7.6 m long in Potter or 12.2 m long in Pine Island and spaced 38 cm from other rows. Plots were separated within rows by at least 1.5 m. Treatments (described below) were arranged...
in a randomized complete block design including an untreated control, and blocks were replicated six and four times in the Potter and Pine Island trials, respectively.

2.1. Seed treatments and application procedures

A list of the insecticide treatments, rates evaluated, and chemical classes are presented in Table 1. The experimental seed treatments included fipronil, spinosad, clothianidin and thiamethoxam. Cyromazine seed treatment and a chlorpyrifos drench applied in the furrow at planting were included for comparison in most studies. In the 2002 trial in Potter and in both 2003 studies, a combination of cyromazine seed treatment and a chlorpyrifos in-furrow drench was included to represent the current industry standard. In the 2002 Pine Island experiment, only cyromazine was evaluated with the experimental treatments.

Seeds were treated with a solution containing a film-forming polymer (Disco®, A1.018. Incotec Inc., Salinas, CA, USA), that encapsulated the seed with a precise amount of active ingredient. Insecticides were applied to seeds using a film-coating procedure described in Taylor (2003). The film-forming polymer was first mixed thoroughly with water and then the insecticide was added. Chlorpyrifos was applied in-furrow during planting at a rate of 1.3 kg (a.i.)/ha in 560 l of water/ha.

All onion seeds, even those that did not receive an insecticide treatment, also were treated using the same film-coating technique with carboxin (30%) and thiram (50%) (Pro-Gro®, Crompton Manufacturing Company Inc., Bethany, CT, USA) to control diseases early in the season. In all plots including the controls, mancozeb (Dithane®, F-45, Dow AgroSciences LLC, Indianapolis, IN, USA) was applied as a drench treatment at a rate of 2.7 kg (a.i.)/ha to provide additional disease control and foliar applications of insecticides were made to manage onion thrips, *Thrips tabaci* Lindeman. Crop maintenance procedures (e.g., fertilization, cultivation, etc.) were typical of those used for commercial onion farms in New York (Reiners and Petzoldt, 2004).

2.2. Environmental conditions and estimating adult emergence

Temperature, rainfall and accumulated degree-day data were recorded during this study, but only for the Potter trials. Weather data are accessible on the New York State IPM’s Northeast Weather Association website (http://newa.nysaes.cornell.edu/public/default.htm). For each year, the dates that onion maggot adults were predicted to begin emergence were based on an accumulation of 214 degree-days from 1 January using a developmental threshold of 4.8 °C (Eckenrode et al., 1975). Average daily temperatures from the estimated date of initial emergence through the end of June, when overwintering females typically cease ovipositing, were calculated by taking the sum of daily maximum and minimum temperatures and dividing by two. Average rainfall amounts for each month also were summarized from the day of planting through the end of June.

2.3. Damage assessment

A baseline plant stand count was taken approximately 4 weeks after planting in each trial. At this time, all seedlings had emerged, but there was little to no onion maggot damage. The number of seedlings affected by onion maggot feeding (e.g., dead or dying) was recorded on a weekly basis beginning approximately 4 weeks after planting, 10 May–2 June, until the end of the overwintering generation flight, usually in late June–early July. Yellow sticky cards were used to monitor onion maggot fly activity. Seedlings containing maggot larvae, as well as those without larvae but clearly damaged by maggots, were recorded as dead and removed from the plot. Twenty to 30 maggots were randomly collected from damaged seedlings at each site every week and reared to adult to ensure accurate identification as onion maggot.

2.4. Statistical analyses

Data were analyzed separately for each location each year. The degree of protection of onion seedlings from onion maggot infestations was determined by examining
the cumulative mean percentage of seedlings killed over time. Analyses using cumulative counts can lead to an accumulation of experimental and sampling errors, giving rise to a complicated correlation structure. Consequently, standard errors on individual weekly sampling times were not estimated. Instead, data were analyzed using a linear mixed model specifying random effects for the experimental errors combined with an unstructured variance-covariance matrix for the cumulative sampling errors (Schabenberger and Pierce, 2002). Models were implemented using PROC MIXED in SAS (SAS Institute, 2001). Cumulative mean percentages of maggot-killed seedlings were compared between each pair of treatments on every sampling date using the appropriate ESTIMATE statements at \( P < 0.05 \) (Littell et al., 1996).

For the Potter trials, average daily temperatures for May and June were analyzed using an analysis of variance (PROC GLM) and means for each month were compared among years using LSMEANS (\( P < 0.05 \); SAS Institute, 2001).

### 3. Results

At both locations, onion maggot infestations were moderate to high, causing significant reductions in plant stand where onions were not protected with an effective insecticide (i.e., range 20.4–57.4% plant stand loss). In general, protection of the onion crop by an insecticide that prevents stand loss from exceeding ~5% is considered commercially acceptable.

Weather conditions varied among years; May 2002 and 2003 were cooler than May 2001, and April and May 2002 and 2003 were much wetter than in 2001 (Table 2). Based on the accumulated degree-day model, the emergence of onion maggot adults was predicted to begin 5 and 10 days later in 2003 than in 2001 and 2002, respectively (Table 2). Additionally, May was significantly cooler in 2003 than in 2001 (\( F = 3.26; \text{df} = 2, 72; P = 0.0443 \)), although it did not differ from 2002 (Table 2). Taken together, the later adult emergence and cool spring conditions in 2003 were likely responsible factors for the delay in first occurrence of onion maggot-infested seedlings in 2003 compared with the previous years (2 June 2003 versus 10 May 2001 and 28 May 2002) (see Table 3).

#### 3.1. Potter, New York

Over 95% of all specimens were identified as onion maggot, whereas the remainder was seedcorn maggot. Onion maggot damage in untreated plots was severe each year, especially in 2001 and 2002 when final seedling loss was 53.7% and 57.4%, respectively (Table 3). The cumulative mean percent seedling loss in the insecticide-treated plots was significantly lower than the cumulative loss in untreated plots across all sampling dates (\( P < 0.05 \)), except the first two sampling dates in 2003. In 2003, thiamethoxam was the only treatment not significantly different than the control on the remaining sampling dates. The ensuing discussion will focus on comparing efficacies only among insecticide treatments.

In 2001, all treatments provided an equivalent level of onion maggot control up to 8 June (49 days after planting) (Table 3). From 15 June to 2 July (73 days after planting), fipronil and spinosad provided significantly better control of onion maggot than chlorpyrifos (\( P < 0.05 \)). During this same period, the levels of onion seedling protection in the thiamethoxam, clothianidin and cyromazine seed treatments were intermediate between levels in the fipronil, spinosad and chlorpyrifos treatments. By the end of the first generation (2 July), all treatments provided or approached a commercially acceptable level of onion maggot control except chlorpyrifos and thiamethoxam, which averaged 20% and 13%, respectively.

In 2002, all treatments except chlorpyrifos provided an equivalent level of onion maggot control up to 11 June (60 days after planting) (\( P < 0.02 \)) (Table 3). From 18 June to 3 July (82 days after planting), fipronil and spinosad provided significantly better control than thiamethoxam (\( P < 0.04 \)), whereas the other treatments

### Table 2

Predicted first emergence of onion maggot adults, *Delia antiqua*, average daily temperatures beyond initial emergence and average rainfall after planting near Potter, New York during the experiments in 2001–2003

<table>
<thead>
<tr>
<th>Year</th>
<th>Predicted first adult emergence</th>
<th>Average daily temperature (°C)</th>
<th>Average rainfall (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>First emergence through 31 May</td>
<td>June</td>
</tr>
<tr>
<td>2001</td>
<td>6 May</td>
<td>15 a</td>
<td>21 a</td>
</tr>
<tr>
<td>2002</td>
<td>1 May</td>
<td>13 b</td>
<td>21 a</td>
</tr>
<tr>
<td>2003</td>
<td>11 May</td>
<td>13 b</td>
<td>19 a</td>
</tr>
</tbody>
</table>

*aMeans followed by the same letter are not significantly different (\( P > 0.05 \); LSMEANS).

*bEstimated dates were based on an accumulation of 214 degree-days since 1 January using a developmental threshold of 4.8 °C.

*cPlanting dates were 20, 12 and 16 April in 2001, 2002 and 2003, respectively.
provided an intermediate level of control. At the end of the first generation, all treatments except chlorpyrifos and thiamethoxam provided an acceptable or nearly acceptable level of onion maggot control.

In 2003, all treatments except the thiamethoxam treatment provided an equivalent level of onion maggot control up to 17 June (62 days after planting) \((P < 0.05)\) (Table 3). The numbers of seedlings killed by onion maggot in the thiamethoxam treatments were equivalent to those in untreated plots. Fipronil provided significantly better control of onion maggot than chlorpyrifos, cyromazine or spinosad \((P < 0.05)\) through 23 June and 2 July (77 days after planting), whereas the clothianidin and the chlorpyrifos + cyromazine treatment provided an intermediate level of control between fipronil and the others. By the end of the first generation, all treatments except thiamethoxam provided acceptable or nearly acceptable control of onion maggots.

### 3.2. Pine Island, New York

Onion maggot infestation pressure was lower at the Pine Island site relative to the Potter site in both years. Cumulative percent seedling loss in untreated plots was 20.8% and 27.6% during 2002 and 2003, respectively (Table 4). As in the Potter trials, the cumulative mean percent seedling loss in the insecticide-treated plots was significantly lower than the cumulative loss in untreated plots on all sampling dates \((P < 0.05)\), except the first sampling date in 2003. The following discussion will concentrate on efficacy comparisons only among insecticide treatments.

During 2002, all seed treatments provided an equivalent level of onion maggot control up to 22 May (44 days after planting) (Table 4). From 28 May to 19 June (72 days after planting), fipronil, spinosad and clothianidin provided significantly better control of onion maggot than thiamethoxam \((P < 0.025)\), while cyromazine...
provided an intermediate level of control. In general, all seed treatments provided a commercially acceptable level of onion maggot control by the end of the first generation.

During 2003, all treatments equally controlled onion maggot up to 4 June (57 days after planting) (Table 4). On 10 June (63 days after planting), clothianidin, fipronil, cyromazine and the chlorpyrifos+cyromazine treatment gave the best control. At this time, clothianidin controlled onion maggot significantly better than thiamethoxam, spinosad and chlorpyrifos ($P_{0.026}$. With four treatments, means followed by the same letter on a particular sampling date are not significantly different ($P > 0.05$; ESTIMATE statement in SAS). Plant damage assessment begun on 22 May 2002 and 27 May 2003; no additional plant damage occurred beyond 19 June 2002.

During 2003, all treatments equally controlled onion maggot up to 4 June (57 days after planting) (Table 4). On 10 June (63 days after planting), clothianidin, fipronil, cyromazine and the chlorpyrifos+cyromazine treatment gave the best control. At this time, clothianidin controlled onion maggot significantly better than thiamethoxam, spinosad and chlorpyrifos ($P < 0.026$). On 16 June (69 days after planting), results were similar to those on 10 June with the exception that clothianidin provided significantly better control than cyromazine ($P < 0.033$). From 25 June to 7 July (90 days after planting), clothianidin protected the onion crop from onion maggot significantly better than the other treatments, except for fipronil and the chlorpyrifos+cyromazine treatment ($P < 0.013$). Fipronil and chlorpyrifos+cyromazine provided significantly better onion maggot control than thiamethoxam and chlorpyrifos alone ($P < 0.028$). At the end of the first generation, clothianidin, fipronil and the chlorpyrifos+cyromazine treatment provided commercially acceptable control.

### 4. Discussion

Insecticide seed treatment performance is best evaluated when pest pressure is high and when environmental conditions are variable, especially rainfall and temperature. These conditions were met during this 3-year study. Fipronil, clothianidin and spinosad were consistently the most effective new chemistries for protecting the onion crop from onion maggot. Fipronil and clothianidin ranked as the best or equivalent to the best seed treatment in all five data sets (Table 5). Hoepting et al. (2003) reported similar levels of onion maggot control (<4% seedling loss) using fipronil seed treatment (Regent® 80WS) in Ontario, Canada. In snap bean in New York, Nault and Taylor (2004) documented that clothianidin reduced seedcorn maggot damage by 50%. Spinosad ranked equivalent to the best in three of the five data sets, second best in the other two data sets and third among the new seed treatments (Table 5). Ester et al. (2003) showed that spinosad at a rate of 24 g (a.i) per 100,000 seeds completely protected white cabbage and cauliflower plants from the cabbage maggot, Delia radicum (Linnaeus). In our trials, all three chemicals applied as seed treatments protected the onion crop for a period extending 72–90 days after planting, a period spanning the window that first-generation maggots attack. An additional and necessary attribute of the fipronil, spinosad and clothianidin seed treatments is that they demonstrated high degrees of residual toxicity during both wet and dry growing seasons.

Thiamethoxam was the least effective seed treatment evaluated (Table 5). In three of the five experiments, it did not provide an acceptable level of control.

### Table 4

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Cumulative mean percent onion seedling loss by first-generation onion maggot, Delia antiqua, in Pine Island, New York in 2002 and 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>22 May</td>
</tr>
<tr>
<td>2002</td>
<td>Untreated</td>
<td>11.0 a</td>
</tr>
<tr>
<td></td>
<td>Cyromazine</td>
<td>1.4 b</td>
</tr>
<tr>
<td></td>
<td>Fipronil</td>
<td>0.7 b</td>
</tr>
<tr>
<td></td>
<td>Spinosad</td>
<td>0.4 b</td>
</tr>
<tr>
<td></td>
<td>Clothianidin</td>
<td>0.5 b</td>
</tr>
<tr>
<td></td>
<td>Thiamethoxam</td>
<td>3.1 b</td>
</tr>
</tbody>
</table>

| 2003 | Untreated | — | 0.8 a | 3.4 a | 6.7 a | 19.0 a | 24.2 a | 27.6 a |
|      | Chlorpyrifos | — | 0.1 a | 0.1 b | 1.7 bc | 8.3 bc | 13.1 b | 15.0 b |
|      | Cyromazine | — | 0.1 a | 0.4 b | 1.2 cd | 4.6 bc | 7.8 bc | 9.7 bc |
|      | Chlor. + cyro.c | — | 0.0 a | 0.0 b | 0.9 cd | 3.4 cd | 4.8 cd | 5.9 cd |
|      | Fipronil | — | 0.0 a | 0.5 b | 1.2 cd | 3.4 cd | 4.5 cd | 5.4 cd |
|      | Spinosad | — | 0.2 a | 0.7 b | 2.3 bc | 6.4 bc | 8.6 bc | 11.6 bc |
|      | Clothianidin | — | 0.2 a | 0.2 b | 0.2 d | 0.6 d | 1.0 d | 1.8 d |
|      | Thiamethoxam | — | 0.5 a | 1.5 b | 2.7 b | 10.8 b | 15.1 b | 16.3 b |

aAll treatments are seed treatments except chlorpyrifos, which was applied as an in-furrow drench treatment.

bWithin each year, means followed by the same letter on a particular sampling date are not significantly different ($P > 0.05$; ESTIMATE statement in SAS). Plant damage assessment begun on 22 May 2002 and 27 May 2003; no additional plant damage occurred beyond 19 June 2002.

cChlorpyrifos in-furrow drench + cyromazine seed treatment.
(e.g., 13.1%, 16.3% and 37% seedling loss). Thiamethoxam is highly soluble in water (Maienfisch et al., 2001), an attribute that could reduce efficacy when soil conditions are saturated. In contrast, clothianidin is 13 times less soluble in water than thiamethoxam (L.L.C. Gustafson, pers. comm.). At Potter during 2002 and 2003, the period after planting through the end of June was extremely wet (Table 2). Despite these conditions, thiamethoxam provided much better onion maggot control in 2002 (9.5% seedling loss) than in 2003 (37% seedling loss). We attribute the failure in 2003 to extremely wet and unusually cold soil conditions during early spring. Such conditions resulted in the delayed emergence of over wintered onion maggot adults, and hence delayed oviposition. When onion maggot larvae ultimately attacked the crop, thiamethoxam was no longer efficacious. Nault et al. (2004) reported that levels of thiamethoxam in snap bean leaf tissue dissipated rapidly and were near zero 3–4 weeks after planting.

Cyromazine was ranked as the fourth best seed treatment (Table 5). The level of control was equal to that afforded by fipronil, clothianidin and spinosad in three of the five cases. Similarly, the combination of cyromazine and the chlorpyrifos drench treatment effectively controlled onion maggot (Table 5); however, this level was not significantly better than the level provided by cyromazine alone. Degrees of control using cyromazine alone were similar to those reported by Taylor et al. (2001).

Chlorpyrifos performed poorly in three of the four data sets and ranked last among the insecticides evaluated (Table 5). Resistance to chlorpyrifos within the Potter onion maggot population was confirmed during 2001 and 2002 using an assay in which flies are treated topically with a diagnostic dose (Nault et al., 2003). After subjecting flies from the Potter site to a 500-ppm dose of chlorpyrifos, only 62% and 41% died in 2001 and 2002, respectively, whereas 100% of the flies from an insecticide-susceptible colony died after exposure to this dose each year. The populations in Pine Island and the 2003 population in Potter were not examined for chlorpyrifos resistance. Chlorpyrifos dissipates slowly in muck soils (Davis and Kuhr, 1976), but growers are concerned that chlorpyrifos may lose efficacy quickly if leaching occurs.

In Potter during 2001 and 2002, onion maggots caused a similar level of damage (20–28% seedling loss), but average spring rainfall in 2002 was over twice that of 2001 (Table 2). These observations suggest that rainfall was not a critical factor in reducing chlorpyrifos efficacy in Potter in 2002. However, excessive rainfall (e.g., >5 cm) within a short duration has caused chlorpyrifos to become ineffective against onion maggot in the Hudson Valley region of New York (RWS, pers. obs.).

There is an increasing trend among onion growers in New York to manage onion maggot using a combination of cyromazine seed treatment and chlorpyrifos in-furrow treatments. The consequence of this strategy may be the loss of both products to insecticide resistance. The registration of at least one new, effective chemistry as a seed treatment on onion would provide growers with an alternative for managing onion maggot, especially those already resistant to chlorpyrifos. Rotation with a new seed treatment or treatments also would likely prolong the longevity of all seed treatments. Because onion growers have readily accepted the use of cyromazine seed treatment, widespread adoption of a new seed treatment would be anticipated.

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References


