Comparison of Neonicotinoid Insecticides for Use with Biodegradable and Wooden Spheres for Control of Key *Rhagoletis* Species (Diptera: Tephritidae)

LUKASZ L. STELINSKI, OSCAR E. LIBURD,[1] STARKER WRIGHT,[2] RONALD J. PROKOPY,[2] ROBERT BEHLE,[3] AND MICHAEL R. MCGUIRE[4]

Department of Entomology, Center for Integrated Plant Systems, Michigan State University, East Lansing, MI 48824

J. Econ. Entomol. 94(5): 1142–1150 (2001)

ABSTRACT Field-based studies and laboratory bioassays were conducted with apple maggot, *Rhagoletis pomonella* (Walsh), and blueberry maggot, *Rhagoletis mendax* Curran, flies to investigate the performance and duration of activity of insecticide-treated biodegradable and wooden spheres for control of *Rhagoletis* species. Four neonicotinoid insecticide treatments including imidacloprid, thiamethoxam, and thiocloprid at 2% (AI) were evaluated with biodegradable spheres. In 1999, significantly more apple maggot flies were found killed by imidacloprid-treated spheres compared with thiamethoxam-treated spheres during early and late season. In 2000, spheres treated with either of two formulations of imidacloprid killed significantly more apple maggot flies compared with thiamethoxam, thiocloprid, and untreated spheres. In blueberries, there were no significant differences between the numbers of blueberry maggot flies killed by both imidacloprid-treated or thiamethoxam-treated spheres in 1999. However, during the 2000 blueberry field season, both formulations of imidacloprid were significantly more effective in killing blueberry maggot flies compared with spheres treated with thiamethoxam, thiocloprid and untreated controls. Overall, spheres treated with thiocloprid were ineffective and did not kill significantly more apple maggot or blueberry maggot flies compared with the controls. Laboratory bioassays showed that the effectiveness of field-exposed spheres treated with imidacloprid at 4 and 8% (AI) and thiamethoxam at 4% (AI) in killing apple maggot flies was not significantly reduced over a 12-wk aging period. Additionally, wooden spheres aged outdoors for 12 wk with and without mold maintained residual activity in laboratory tests, whereas biodegradable spheres of equal aging, with and without mold lost their effectiveness in killing apple maggot flies. In other studies, we confirmed that the addition of an external feeding stimulant (sucrose) significantly increases the effectiveness of both biodegradable and wooden spheres treated with imidacloprid at 2% (AI).

KEY WORDS *Rhagoletis pomonella, Rhagoletis mendax,* insecticide-treated spheres

THE APPLE MAGGOT, *Rhagoletis pomonella* (Walsh), and the blueberry maggot, *Rhagoletis mendax* Curran, are the most important late-season insect pests of apples, *Malus domestica* Borkhausen, and blueberries, *Vaccinium* spp., respectively, in the northeastern and midwestern United States (Liburd et al. 1999). Sexually mature flies responding to visual and olfactory stimuli migrate into apple orchards and blueberry plantings and subsequently oviposit into ripening host fruit. The larvae develop inside the fruit rendering it unmarketable. To prevent fruit injury, commercial growers commonly apply an organophosphate insecticide every 10–14 d once the adult flies are active (Stanley et al. 1987, Agnello et al. 1990, Liburd et al. 1998a). Because of increasing restrictions on the use of broad-spectrum insecticides, resulting from Food Quality Protection Act (FQPA) regulations, the development of effective alternatives for management of key *Rhagoletis* species is of much importance to the fruit industry.

The literature documenting behavioral management techniques for apple maggot is voluminous (Prokopy 1975, Reissig et al. 1985, Prokopy and Mason 1996, Reynolds and Prokopy 1997). Kring (1970) evaluated several trap types and demonstrated that unbaited yellow panels with red hemispheres were effective in attracting apple maggot flies even at low population densities. Later, Reissig et al. (1985) showed that sticky red spheres (8.5 cm diameter) baited with synthetic apple volatiles were four times more effective than unbaited red spheres. Recently, Zhang et al. (1999) showed that a mixed blend consisting of butyl butanoate (10%), propyl hexanoate (4%), butyl hexanoate (37%), hexyl butanoate (44%), and pentyl hexanoate (5%) used as bait attractant was

[1] Department of Entomology and Nematology, University of Florida, Gainesville, FL 32611. E-mail: liburd@.msu.edu

[2] Department of Entomology, University of Massachusetts, Amherst, MA 01003.

[3] National Center for Agricultural Utilization Research, Bioactive Agents Research Unit, Agricultural Research Service, USDA, Peoria, IL 61604.

[4] Shafter Research and Extension Center, 17053 Shafter Avenue, Shafter, CA 93263.

significantly better in attracting apple maggot flies than the recently adopted butyl hexanoate alone. Their findings were supported by recent studies conducted in Michigan (L.L.S. and O.E.L., unpublished data), producing similar results using the same blend of mixed apple volatiles.

Considerable work has also been done on improving monitoring techniques for the *R. pomonella* species group (Prokopy 1977, Prokopy and Hauschild 1979, Liburd et al. 1998b). In blueberries, Pherocon AM yellow sticky panels (Great Lakes Integrated Pest Management [IPM], Vestaburg, MI) are the most common monitoring devices used by growers for timing the emergence of sexually immature blueberry maggot flies (Prokopy and Coli 1978, Liburd et el. 1998a). However, recent evidence has suggested that baited green or red sticky spheres can be used for monitoring sexually mature blueberry maggot flies (Liburd et al. 1998a, Liburd and Stelinski 1999). Although such monitoring devices allow more accurate timing of insecticide sprays, traps coated with sticky Tangle-Trap (Tanglefoot, Grand Rapids, MI) can be inefficient and costly (Prokopy et al. 1990, Liburd et al. 1999).

Recently, a nonsticky, imidacloprid-treated, biodegradable sphere has been shown to be effective in killing apple maggot (Hu et al. 1998, Liburd et al. 1999) and blueberry maggot flies (Liburd et al. 1999). *Rhagoletis* flies foraging for suitable host plants are attracted to baited, insecticide-treated spheres for mating and oviposition (Liburd et al. 1999). Flies landing on these spheres die after consuming a lethal dose of insecticide. As discussed in Liburd et al. (1999), the use of biodegradable spheres offers several advantages over conventional trapping using sticky traps or insecticide spray applications, including the potential for season-long control of fruit flies by a single deployment of spheres at the onset of the season, a possible reduction of insecticide residues on the fruit, and a reduction in labor costs.

In field studies, Liburd et al. (1999) caught 25 times as many apple maggot and four times as many blueberry maggot flies on Plexiglas panes placed beneath biodegradable spheres treated with imidacloprid (Provado 1.6 F, Bayer, Kansas City, MO) compared with untreated (control) spheres. Further studies showed that the mean time that flies spent on imidacloprid-treated spheres was significantly longer than on untreated spheres. Most recently, Hu et al. (2000) achieved season long residual activity with 80% fly kill in laboratory assays after weathering spheres treated with imidacloprid (Merit 75 WP, Bayer) at 1.5% (AI) in an orchard for 3 mo. However, there are no studies on the effectiveness of the insecticides thiamethoxam (Actara, Novartis, Greensboro, NC) or thiocloprid (Calypso, Bayer) on apple maggot flies and only one recent paper (Ayyappath et al. 2000) has discussed the effects of thiamethoxam but not thiocloprid on blueberry maggot flies using insecticide-treated sphere technology.

As FQPA regulations lead to a reduction in the use of organophosphate insecticides, and public pressure against the use of broad-spectrum insecticides increases, it becomes necessary to identify effective nonorganophosphate insecticides for inclusion into novel pest management tactics. The objective of this study was to investigate the duration and performance of activity of biodegradable and wooden spheres treated with the neonicotinoid insecticides imidacloprid (Provado 1.6 F and Merit 75 WP), thiamethoxam (Actara), and thiocloprid (Calypso) on apple maggot and blueberry maggot flies.

Materials and Methods

Field experiments to determine the effectiveness of biodegradable, neonicotinoid-treated spheres in killing apple maggot and blueberry maggot flies were conducted in commercial apple orchards and blueberry plantings in southwestern Michigan during the 1999 and 2000 field seasons. Laboratory bioassays evaluating the effects of sphere aging, insecticide treatment, and feeding stimulant on *R. pomonella* using both biodegradable and wooden spheres were carried out at the University of Massachusetts, Amherst, MA, in 1999.

Biodegradable spheres (9 cm diameter) made from a combination of sugar, starch, and flour were obtained from the United States Department of Agriculture (USDA) laboratory in Peoria, IL. Specifications for sphere preparation were described in Liburd et al. (1999). Essentially, spheres consisted of a mixture of water (150 g), sucrose (360 g), high fructose corn syrup (330 g), pregelatinized corn flour (630 g), cayenne pepper (14.7 g), and sorbic acid (1.5 g). Before deployment in the field, spheres were brush-painted with a mixture containing DevFlex latex paint (ICI Paints, Cleveland, OH) (70%), sucrose feeding stimulant (20%), water (8%), and insecticide at 2% (AI). Wooden, 9-cm-diameter spheres used in Massachusetts bioassays were painted in the same manner as the biodegradable spheres. Spheres were painted red for apple maggot experiments and green for blueberry maggot experiments.

Michigan. Field Evaluation of Neonicotinoid-Treated Spheres. The experimental designs were completely randomized blocks (blocked by apple varieties and blueberry cultivars) with four replications. In apples, spheres were spaced 20 m apart within blocks (25 m between blocks) and were hung 1.5 m above ground within the canopy of 'Red Delicious' and 'Golden Delicious' trees. Spheres were positioned 0.25–0.5 m from fruit and foliage according to the guidelines suggested by Drummond et al. (1984). All biodegradable spheres used in apple maggot experiments were baited with polyethylene vials (Israel Andler and Sons, Evrett, MA) containing 4 ml of butyl hexanoate (Penta International Corporation, West Caldwell, NJ).

In blueberries, biodegradable spheres were hung within the canopy of Bluecrop and Jersey blueberries at a height 15 cm below the tops of blueberry bushes according to the recommendations of Liburd et al. (2000). Biodegradable spheres used in blueberry maggot experiments were baited with polycon dispensers (Great Lakes IPM) containing 5 g of ammonium acetate (Liburd et al. 1998a).

Apple Maggot (1999). Three treatments were evaluated that included the following: (1) spheres treated with imidacloprid (Provado 1.6 F), (2) spheres treated with thiamethoxam (Actara), and (3) untreated control spheres. The number of apple maggot flies killed was assessed using Plexiglas panes (60 by 45 cm) coated with sticky, aerosol-formula Tangle-Trap and placed horizontally ≈30 cm below each sphere (Liburd et al. 1999). Killed apple maggot flies were counted by sex and removed from panes twice per week. Data on the number of apple maggot flies killed were separated into four monitoring periods to reflect the seasonal abundance of apple maggot flies in Michigan (Howitt 1993) and to provide even comparisons with laboratory assays. During the first monitoring period (8–19 July), flies were beginning to emerge. The second (22 July–2 August) and third (5–16 August) monitoring periods constituted peak fly activity, depending on the predominant apple varieties within the area. During the final monitoring period (19 August–9 September), fly populations were in decline.

Apple Maggot 2000. During our 2000 field season, three treatments from our 1999 apple maggot study were selected for further investigation. Two new neonicotinoid treatments, thiocloprid (Calypso) and another formulation of imidacloprid (Merit WP 75) were included in our 2000 evaluation of spheres. Spheres were prepared according to the previously described protocol and all insecticide concentrations were prepared at 2% (AI). The Merit WP 75 formulation was prepared as a slurry by mixing the wettable powder with distilled water before mixing this insecticide with paint. The number of apple maggot flies killed was assessed in the same manner as described for 1999. Field data collected in 2000 were not compared with laboratory assays. Therefore, data in 2000 were not divided into separate monitoring periods. The numbers of apple maggot flies killed over the course of the entire season were compared to determine the most effective insecticide treatment.

Blueberry Maggot (1999). Field experiments to compare the effectiveness of imidacloprid and thiamethoxam in blueberry plantings paralleled our apple maggot studies. The three treatments evaluated included the following: (1) spheres treated with imidacloprid (Provado 1.6 F), (2) spheres treated with thiamethoxam (Actara), and (3) untreated control spheres. The number of blueberry maggot flies killed was assessed twice per week using the Plexiglas pane monitoring system described in our apple maggot experiments. Blueberry maggot fly data were separated into two distinct monitoring periods to coincide with the seasonal abundance of blueberry maggot flies in Michigan (Liburd and Stelinski 1999).

Blueberry Maggot 2000. Our blueberry maggot fly experiment in 2000 likewise paralleled the 2000 apple maggot study. Five treatments were evaluated including the following: (1) imidacloprid (Provado), (2) imidacloprid (Merit WP 75) (3) thiamethoxam (Actara), (4) thiocloprid (Calypso), and (5) untreated spheres (control). All insecticide treatments were prepared at 2% (AI). The number of blueberry maggot flies killed was assessed using Plexiglas panes as described for the 1999 apple experiment. Treatments were compared by using total numbers of blueberry maggot flies found killed over the course of the entire season.

Massachusetts Laboratory Bioassays. In 1999, we conducted two laboratory bioassays in Amherst, MA, to determine the effectiveness and residual activity of biodegradable and wooden spheres in killing apple maggot flies. The first assay was conducted to compare three different concentrations (2, 4, and 8% [AI]) of imidacloprid (Provado 1.6 F) and thiamethoxam (Actara) on wooden spheres. The second assay was developed at standard active ingredients (2%) to compare wooden spheres with biodegradable spheres with respect to field exposure, mold development, presence of external feeding stimulant, and rodent feeding.

Bioassays were conducted with 10 female flies per treatment and each assay was replicated three times. Apple maggot flies were reared from larvae that were collected from apples of unsprayed trees in Amherst, MA. Flies were maintained in aluminum screen-Plexiglas cages (30 by 30 by 30 cm) and supplied with water and food strips consisting of filter paper 5 by 7 cm dipped in a solution of enzymatic yeast hydrolysate and sucrose (1:3) and dried 24 h before use. All females used in bioassays were sexually mature (14–20 d of age) and deprived of food, but not water, 10 h before testing (Hu et al. 2000). Spheres used in our aging experiment were hung in commercial apple orchards under natural environmental conditions and were retrieved from the field for laboratory bioassays at appropriate aging intervals (3, 6, 9, and 12 wk). Different sets of spheres were used for each interval. For baseline toxicity tests, "0 wk" (nonaged) spheres were also prepared.

Performance of Two Neonicotinoids at Various Percentages of Active Ingredients. Spheres used in bioassays were prepared according to the protocol described earlier and painted with DevFlex latex red paint. Seven treatments were used in our first bioassay. The first three treatments consisted of spheres treated with imidacloprid (Provado 1.6 F) at 2, 4, and 8% (AI). Treatments 4, 5, and 6 consisted of spheres treated with thiamethoxam (Actara) at the same concentrations (2, 4, and 8% [AI]). The seventh treatment was a sphere without insecticide. Randomly selected, sexually mature females were transferred using 35-ml plastic cups onto single treated spheres hung from the ceiling of Plexiglas cages (30 by 30 by 30 cm). Flies were allowed to feed for 10 min or until they fell off of spheres. After exposure to sphere treatments, flies were removed from cages and placed individually into plastic cups with food and water. Observations to determine mortality were made at intervals of 24, 48, and 72 h.

Effects of Aging, Feeding Stimulant, and Fungal Growth on Imidacloprid-Treated Spheres. Our second

Table 1. Effect of neonicotinoid-treated spheres on apple maggot fly, Michigan (1999)

Sphere treatments	1st monitoring period 8/7–19/7	2nd monitoring period 22/7–2/8	3rd monitoring period 5/8–16/8	4th monitoring period 19/8–9/9	Total season 8/7–9/9
Imidacloprid-treated (Provado 1.6 F)	98.8 ± 21.1a	63.3 ± 16.1a	48.0 ± 9.0a	36.8 ± 4.8a	280 ± 52.8a
Thiomethoxam-treated (Actara)	31.0 ± 6.1b	33.3 ± 3.0a	42.5 ± 9.6a	12.5 ± 0.9b	119.3 ± 10.6b
Untreated (control)	4.0 ± 3.0c	8.3 ± 7.0b	2.0 ± 1.4b	1.0 ± 0.0c	15.3 ± 11.3c

Mean ± SEM number of flies found killed on Plexiglas. Means within the same column followed by the same letter are not significantly different ($P = 0.05$, LSD test).

laboratory assay was designed to investigate the impact of aging, feeding stimulant, and mold growth on the effectiveness of spheres treated with imidacloprid (Provado 1.6 F) and thiamethoxam (Actara), at 2% (AI). Fourteen treatments were evaluated. The initial seven treatments had a sucrose feeding-stimulant (20% sucrose/water solution) applied to their external surface after exposure to external environmental conditions and just before carrying out the assay. The treatments included the following: (1) wooden spheres exposed outdoors for 12 wk with no growth of mold, (2) wooden spheres exposed outdoors for 12 wk with 90% of their surface area covered with mold, (3) wooden spheres not exposed outdoors, (4) biodegradable spheres exposed outdoors for 12 wk with no mold cover, (5) biodegradable spheres exposed outdoors for 12 wk with 90% of their surface area covered with mold, (6) biodegradable spheres not exposed outdoors, and (7) biodegradable spheres exposed outdoors for 12 wk and having 50% of their mass eaten by rodents. Treatments 8–14 were identical to the previously described seven treatments; however, these lacked the application of the sucrose feeding-stimulant on their outer coating before the assay. The assay followed the same protocol as described for the first with respect to rearing and handling of apple maggot flies.

Statistical Analysis. Data from all experiments were square-root transformed ($x + 0.5$) and then subjected to an analysis of variance. Means were separated by least significant difference (LSD) ($P = 0.05$) (SAS Institute 1989). The untransformed means and standard errors are presented in tables and figures.

Results

Field-Based Evaluation of Neonicotinoid-Treated Spheres. During our 1999 apple maggot study, significantly ($F = 35.8$; df = 2, 6; $P < 0.01$) more apple maggot flies were found killed over the entire season on Plexiglas panes hung beneath biodegradable spheres treated with imidacloprid (Provado 1.6 F) compared with spheres treated with thiamethoxam (Actara) (Table 1). Both imidacloprid and thiamethoxam-treated spheres killed significantly more apple maggot flies compared with control (untreated) spheres (Table 1). The number of apple maggot flies killed by imidacloprid-treated and thiamethoxam-treated spheres averaged ≈18 and ≈8 times more, respectively, than the number killed by untreated spheres (Table 1).

As the growing season progressed, we noticed changes in the effectiveness of imidacloprid and thiamethoxam-treated spheres based on Plexiglas trap data. During the first monitoring period (8–19 July), we recorded significantly ($F = 26.4$; df = 2, 6; $P < 0.01$) more apple maggot flies on Plexiglas panes hung beneath imidacloprid-treated spheres compared with thiamethoxam-treated spheres (Table 1). During the second and third monitoring periods, there were no significant differences in the number of killed apple maggot flies beneath spheres treated with either insecticide (imidacloprid or thiamethoxam) (Table 1). During the fourth monitoring period, again significantly more apple maggot flies were killed by imidacloprid-treated spheres compared with thiamethoxam-treated spheres (Table 1).

The results of our second year's apple maggot study showed no significant differences in the number of killed apple maggot flies beneath spheres treated with either formulation of imidacloprid (Provado 1.6 F or Merit 75 WP) (Table 2). However, biodegradable spheres treated with either formulation of imidacloprid (Provado 1.6 F and Merit 75 WP) killed significantly ($F = 54.9$; df = 4, 12; $P < 0.001$) more apple maggot flies than other treatments tested (Table 2). There was no significant difference in the number of dead apple maggot flies beneath spheres treated with

Table 2. Comparison of neonicotinoid insecticides at 2% active ingredients using biodegradable spheres for control of apple maggot, Michigan (2000)

Sphere treatments	Mean ± SEM no. killed apple maggot flies 26/6–11/8
Imidacloprid-treated (Provado 1.6 F)	182.8 ± 13.6a
Imidacloprid-treated (Merit 75 WP)	190.0 ± 35.7a
Thiomethoxam-treated (Actara)	76.3 ± 8.6b
Thiocloprid-treated (Calypso)	10.8 ± 2.8c
Untreated (control)	9.8 ± 1.5c

Mean ± SEM number of flies found killed on Plexiglas. Means within the same column followed by the same letter are not significantly different ($P = 0.05$, LSD test).

Table 3. Effect of neonicotinoid-treated spheres on blueberry maggot fly, Michigan (1999)

Sphere treatments	1st monitoring period 16/7–22/7	2nd monitoring period 28/7–6/8	Total season 16/7–6/8
Imidacloprid-treated (Provado 1.6 F)	99.8 ± 17.2a	52.3 ± 9.9a	133.5 ± 30.4a
Thiomethoxam-treated (Actara)	71.3 ± 34.0a	27.5 ± 11.9a	127.3 ± 43.5a
Untreated (control)	12.3 ± 3.8b	3.5 ± 1.8b	15.8 ± 5.0b

Mean ± SEM number of flies found killed on Plexiglas. Means within the same column followed by the same letter are not significantly different, (P = 0.05, LSD test).

thiocloprid (Calypso) and our untreated (control) spheres (Table 2).

The results from our 1999 blueberry field experiments were different from those observed for apples. There were no significant differences between the number of killed blueberry maggot flies found on Plexiglas panes hung beneath spheres treated with either imidacloprid or thiamethoxam over the course of the season (Table 3). Also, there was no significant difference in the number of flies killed between imidacloprid and thiamethoxam-treated spheres in either first or second monitoring periods (Table 3). However, we recorded significantly ($F = 32.4$; df = 2, 6; $P < 0.01$) more killed blueberry maggot flies on Plexiglas panes placed beneath treated spheres compared with untreated spheres (Table 3).

Our second year's blueberry maggot results were similar to those observed in our apple maggot 2000 field studies. There were no significant differences in the number of blueberry maggot flies killed by either Provado 1.6 F or Merit 75 WP (Table 4). However, both imidacloprid treatments killed significantly ($F = 53.2$; df = 4, 12; $P < 0.001$) more blueberry maggot flies compared with spheres treated with thiamethoxam (Actara) (Table 4). On average, imidacloprid-treated spheres killed 2.3 times as many flies compared with spheres treated with thiamethoxam (Table 4). Finally, spheres treated with thiocloprid (Calypso) did not kill significantly more blueberry maggot flies compared with control spheres (Table 4).

Performance of Two Neonicotinoids at Various Percentages of Active Ingredients. In our 1999 sphere aging experiments, the cumulative rainfall exposures of spheres after each aging interval were 0.0, 3.6, 5.3, 15.5, and 43.2 cm at 0, 3, 6, 9, and 12 wk of exposure, respectively. We recorded no significant differences in the number of apple maggot flies killed by newly prepared spheres and spheres that were aged for 3 wk and treated with either imidacloprid or thiamethoxam at any of the percentages of active ingredients tested. However, all neonicotinoid-treated spheres killed significantly ($F = 19.3$; df = 6, 12; $P < 0.001$) more flies compared with the controls (Fig. 1). The effectiveness of aged imidacloprid-treated spheres at rates of four and 8% (AI) did not decrease significantly throughout the aging period (Fig. 1). However, there was a significant decrease in the performance of imidacloprid-treated spheres at 2% (AI) at 12 wk of aging outdoors compared with shorter aging periods (Fig. 1). Similar to imidacloprid-treated spheres, there was no significant decrease in the performance of thiamethoxam-treated spheres at 4% (AI) throughout the 12-wk aging

Table 4. Comparison of neonicotinoid insecticides at 2% active ingredients using biodegradable spheres for control of blueberry maggot flies, Michigan (2000)

Sphere treatments	Mean ± SEM no. killed blueberry maggot flies 26/6–11/8
Imidacloprid-treated (Provado 1.6 F)	512.0 ± 78.5a
Imidacloprid-treated (Merit 75 WP)	449.3 ± 72.0a
Thiomethoxam-treated (Actara)	216.3 ± 47.7b
Thiocloprid-treated (Calypso)	121.5 ± 8.6c
Untreated (control)	93.8 ± 19.9c

Mean ± SEM number of flies found killed on Plexiglas. Means within the same column followed by the same letter are not significantly different (P = 0.05, LSD test).

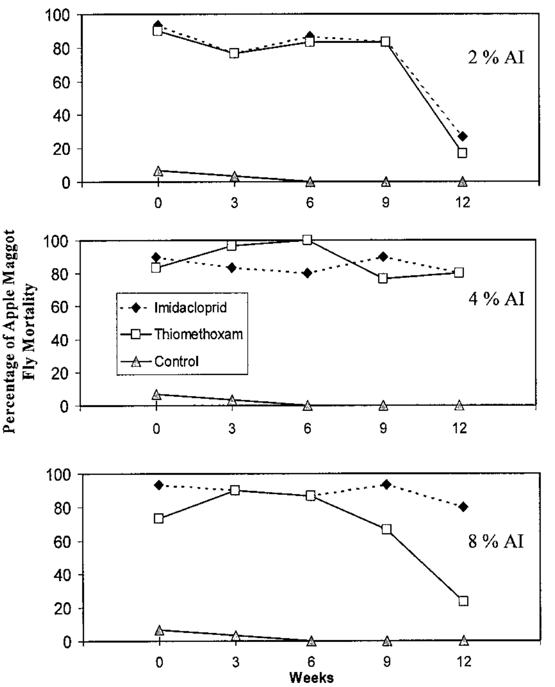

Fig. 1. Percentage mortality of apple maggot flies exposed to imidacloprid and thiamethoxam-treated spheres with varying percentage of active ingredients subjected to 3, 6, 9, and 12 wk of field aging.

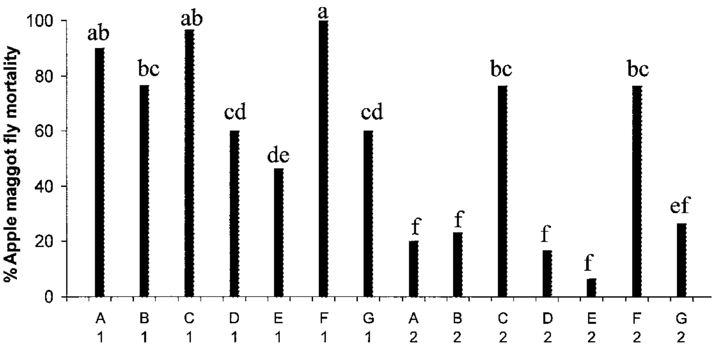

Fig. 2. Percentage mortality of apple maggot flies exposed to imidacloprid-treated spheres at 2% (AI) of varying composition, age, and mold coverage. Bars representing means that are labeled with the same letter are not significantly different, ($P = 0.05$, LSD test). (A) Wooden spheres exposed 12 wk with no mold. (B) Wooden spheres exposed 12 wk with 90% mold coverage on surface. (C) Wooden spheres not exposed outdoors. (D) Biodegradable spheres exposed 12 wk with no mold. (E) Biodegradable spheres exposed 12 wk with 90% mold coverage on surface. (F) Biodegradable spheres not exposed outdoors. (G) Biodegradable spheres exposed 12 wk with 50% of mass eaten by rodents. (1) Sphere with sucrose feeding stimulant added before testing. (2) Spheres without sucrose feeding stimulant added before testing

period. However, when the active ingredient was lowered to 2%, thiamethoxam-treated spheres killed significantly fewer flies at 12 wk compared with shorter aging periods. In addition, thiamethoxam-treated spheres at the higher rate of 8% (AI) killed fewer apple maggot flies at the 9- and 12-wk aging intervals compared with the shorter aging periods. Spheres treated with either insecticide at all of the rates tested killed significantly ($P < 0.001$) more flies compared with control spheres at every aging interval (Fig. 1).

Effect of Aging, Feeding Stimulant, and Fungal Growth on Imidacloprid-Treated Spheres. All biodegradable and wooden sphere treatments exposed outdoors with 20% sucrose (feeding stimulant) killed significantly ($F = 19.8$; df = 13, 26; $P < 0.001$) more apple maggot flies compared with spheres that lacked such an application of sucrose (Fig. 2). There was no significant difference in mortality of apple maggot flies between biodegradable and wooden spheres before aging (Fig. 2). There was a significant ($P < 0.001$) decrease in the number of apple maggot flies killed by biodegradable spheres containing feeding stimulant that were aged outdoors for 12 wk compared with unexposed biodegradable spheres, although such decrease was not observed for wooden spheres after exposure for 12 wk (Fig. 2). The effectiveness of both biodegradable and wooden spheres that were exposed outdoors for 12 wk and with 90% mold cover was not statistically different from spheres of equal aging with no fungal mold. Biodegradable spheres that had 50% of their mass removed by rodent feeding killed significantly ($P < 0.001$) fewer apple maggot flies compared with unexposed biodegradable spheres. However, the rodent-damaged biodegradable spheres killed statistically equal numbers of apple maggot flies to undamaged biodegradable spheres that were exposed outdoors for 12 wk with and without 90% mold coverage. (Fig. 2).

Discussion

The study demonstrated that baited, biodegradable spheres treated with the insecticide imidacloprid, irrespective of formulation (Provado 1.6 F or Merit 75 WP), were more effective in killing apple maggot flies than identical spheres treated with thiamethoxam or thiocloprid. Upon initial field deployment, imidacloprid-treated spheres killed high numbers of apple maggot flies, but there was a gradual decrease in the number of flies killed as the season progressed. Alternatively, thiamethoxam-treated spheres killed fewer apple maggot flies initially and the numbers of flies killed also gradually decreased as the season progressed. The decreased numbers of dead flies over time may be due to a number of factors, including loss of insecticide from sphere coating, aging effects on spheres, decreasing fly populations in late season, or a combination of these factors.

During our second (2000) field season, spheres treated with either formulation of imidacloprid showed equal effectiveness in killing apple maggot flies. Thiamethoxam-treated spheres again killed fewer apple maggot flies than imidacloprid-treated spheres. Our laboratory bioassays supported field data by indicating that imidacloprid-treated spheres were more effective in killing apple maggot flies compared with thiamethoxam-treated spheres. Spheres treated with thiocloprid (Calypso), however, were no more effective than control spheres in the field. We believe that treating spheres with imidacloprid rather than thiamethoxam or thiocloprid may result in more effective control of apple maggot flies in commercial orchards.

The results from our blueberry studies were slightly different from those in apples. In 1999, imidacloprid- and thiamethoxam-treated spheres showed statistically equal effectiveness in killing blueberry maggot flies throughout the blueberry-growing season. By contrast, in 2000 imidacloprid-treated spheres performed better than thiamethoxam-treated spheres over the course of the season. In 2000, we captured our first blueberry maggot fly on monitoring traps two weeks earlier than in 1999. Therefore, all biodegradable sphere treatments were deployed in the field 2 wk earlier in 2000 (26 June) than in 1999 (July 16). However, during both years blueberry maggot fly mortality was monitored until the end of berry harvest (6 August in 1999 and 11 August in 2000). The longer field exposure of thiamethoxam-treated spheres in 2000 may have resulted in the greater observed decline in efficacy near the end of that field season, while such a decline was not observed for imidacloprid-treated spheres. These results imply that thiamethoxam may have been lost from biodegradable spheres at a greater rate than imidacloprid. As observed for the apple maggot fly, spheres treated with thiocloprid were no more effective in killing blueberry maggot flies than control spheres in the field.

Our laboratory bioassays using biodegradable and wooden spheres provided us with data similar to those obtained in the field and helped explain some of the differences and changes in effectiveness that were observed over the course of the growing season in Michigan. The assays also showed that the effectiveness and period of activity of imidacloprid-treated spheres could be lengthened by increasing the percentage of (AI) of insecticide in the spheres above 2%. Such a change in formulation needs further research before it can be implemented in commercial apple orchards. However, increasing the concentration of (AI) of imidacloprid-treated spheres above 2% may not be necessary for blueberry maggot fly management. The results of our bioassays also showed that 4% (AI) might be optimal for thiamethoxam-treated spheres against the apple maggot fly. Spheres treated in this manner killed significantly more apple maggot flies compared with similar spheres treated at both two and 8% (AI) (Fig 1). It is possible that the 8% (AI) treatment of thiamethoxam acted as a phago- or tarsal-deterrent for the apple maggot flies, resulting in lesser mortality compared with similar spheres treated at 4% (AI). The efficacy of insecticide-treated spheres depends on the flies' acceptance of the phago-stimulant (sucrose) in order for it to imbibe the insecticide. Therefore, it is crucial that insecticide formulations and application rates used with insecticide-treated spheres do not present feeding or tarsal deterrents.

The bioassays indicated that fungal infestation acquired by both biodegradable and wooden spheres over the course of the growing season does not significantly decrease the spheres' effectiveness in killing apple maggot flies. Such fungal growth was observed in the field during the fourth monitoring period in apple orchards in Michigan. The problem of fungal growth was less apparent in our blueberry field experiments. The shorter sphere deployment period necessary for control of blueberry maggot flies may account for the observed differences in fungal growth on the spheres.

Laboratory assays also showed that biodegradable spheres treated with imidacloprid at 2% (AI) that were deployed in the field for 12 wk had a decreased effectiveness compared with unexposed biodegradable spheres treated in a similar manner (Fig. 2). In addition, biodegradable spheres exposed for 12 wk and without fungal growth performed similarly to spheres exposed for 12 wk with 90% fungal growth and biodegradable spheres exposed for 12 wk having 50% of their mass removed by rodents (Fig 2). Such a decrease in effectiveness was not observed with wooden imidacloprid-treated spheres that were exposed in the field for 12 wk. These results indicate that the decrease in effectiveness of biodegradable spheres after 12 wk of field exposure might not be due to fungal infestation or rodent damage. However, the results imply that wooden spheres treated with imidacloprid at 2% (AI) may retain residual insecticidal activity in the field longer than biodegradable spheres treated in the same manner.

Although our assays confirmed that 50% damaged biodegradable spheres are not less effective than undamaged spheres, the complete loss of spheres in the field due to animal feeding is a significant problem. In Michigan, loss of biodegradable spheres due to animal feeding appeared to be insignificant in 1999 when ≈95% of spheres deployed in field studies were retrieved at the end of the season. However, in 2000, ≈20% of biodegradable spheres deployed in an abandoned apple orchard required replacement one month after initial deployment because of rodent feeding. Effective rodent/animal deterrents must be developed before biodegradable spheres can be recommended for commercial use.

Our findings with respect to feeding stimulants were consistent with the earlier studies of Hu et al. (1998). The use of a feeding stimulant (sucrose) encourages prolonged feeding and increases the potential for *Rhagoletis* flies to ingest a greater dosage of insecticide. Although aged wooden spheres performed equally well or better than aged biodegradable spheres in our Massachusetts laboratory studies, previous field studies have shown that the use of wooden spheres requires the periodical reapplication of feeding stimulant, because the externally applied sucrose is washed off by rain. Therefore, we still support further development and future use of biodegradable spheres or the development of a constant release sucrose dispenser to be used with wooden spheres as a control tactic for key *Rhagoletis* species.

Overall, both field and laboratory experiments confirmed several crucial requirements that must be met in order for insecticide-treated spheres to be effective throughout the growing season. First, they must deliver a lethal dose of insecticide over the course of the entire growing season to provide adequate fruit protection. Second, they must be able to withstand adverse weather conditions and present a feeding deterrent for rodents. Future prototypes of biodegradable spheres should include appropriate anti-fungal agents and rodent-feeding deterrents.

Recent studies have shown that insecticide-treated spheres can achieve comparable control of the apple maggot fly (Propkopy et al. 2001) and the blueberry maggot fly (Stelinski and Liburd 2001) to the use of organophosphate insecticides. This study demonstrated that field-deployed imidacloprid-treated spheres are more effective in killing apple maggot and blueberry maggot flies than similar spheres treated with thiamethoxam or thiocloprid. The study also provided initial evidence that the use of the neonicotinoid insecticide thiocloprid at 2% (AI) with biodegradable spheres may be an ineffective tactic. Our results showed that insecticide formulation, percentage of active ingredients, sphere material (sugar/flour versus wood), and presence of phago-stimulant impacted the effectiveness of insecticide-treated spheres. Currently, imidacloprid is the most effective neonicotinoid insecticide tested for use with both biodegradable and wooden spheres against both apple maggot and blueberry maggot flies. In addition, the increase of imidaclopid from 2 to 4% (AI) improved the effectiveness of insecticide-treated spheres. Finally, our results provided initial evidence that wooden spheres treated with imidacloprid maintain longer lasting insecticidal activity than identically treated biodegradable spheres.

Acknowledgments

We thank Tapper's Apple Orchard, Dan's blueberry plantation, and the owner of blueberry plantation # 4, who wished to remain anonymous, for allowing us to conduct our experiments. We thank Dan Young for his assistance with sampling and fieldwork. We are grateful to Bradley Chandler for conducting laboratory-based assays. We thank John Wise and the staff at the Trevor Nichols Research Complex for their valuable assistance on this project. We also acknowledge David Bloomberg (Fruitspheres, Inc., Macomb, IL) for providing us with biodegradable spheres to conduct our research in 2000. The research reported here was supported by USDA Special Fruit Grant No. 61-4058.

References Cited

Ayyappath, R., S. Polavarapu, and M. McGuire. 2000. Effectiveness of thiamethoxam-coated spheres against blueberry maggot flies (Diptera: Tephritidae). J. Econ. Entomol. 93: 1473–1479.

Agnello, A. M., S. M. Spangler, and W. H. Ressig. 1990. Development and evaluation of a more efficient monitoring system for apple maggot (Diptera: Tephritidae). J. Econ. Entomol. 83: 539–546.

Drummond, F., E. Groden, and R. J. Prokopy. 1984. Comparative efficacy and optimal positioning of traps for monitoring apple maggot flies (Diptera: Tephritidae). Environ. Entomol. 13: 232–235.

Duan, J. J., and R. J. Prokopy. 1995b. Development of pesticide-treated spheres for controlling apple maggot flies (Diptera: Tephritidae): pesticides and residue-extending agents. J. Econ. Entomol. 88: 117–126.

Howitt, A. H. 1993. Common tree fruit pests, pp. 170–173. North Central Regional Extension Publication #63. Michigan State University, East Lansing, MI.

Hu, X. P., B. S. Shasha, M. R. McGuire, and R. J. Prokopy. 1998. Controlled release of sugar and toxicant from a novel device for controlling pest insects. J. Control Release 50: 257–265.

Hu, X. P., R. J. Prokopy, and J. M. Clark. 2000. Toxicity and residual effectiveness of insecticides on insecticide-treated spheres for controlling females of *Rhagoletis pomonella* (Diptera: Tephritidae). J. Econ Entomol. 93: 403–411.

Kring, J. B. 1970. Red spheres and yellow panels combined to attract apple maggot flies. J. Econ. Entomol. 63: 466–469.

Liburd, O. E., and L. L. Stelinski. 1999. Apple maggot fly and its sibling species: physiological and environmental status. MSU CAT Alert Ext. Bull. 14: 3–4.

Liburd, O. E., S. R. Alm, R. A. Casagrande, and S. Polavarapu. 1998a. Effect of trap color, bait, shape and orientation in attraction of blueberry maggot (Diptera: Tephritidae) flies. J. Econ. Entomol. 91: 243–249.

Liburd, O. E., S. R. Alm, and R. A. Casagrande. 1998b. Susceptibility of highbush blueberry cultivars to larval infestation by *Rhagoletis mendax* (Diptera: Tephritidae) flies. Environ. Entomol. 27: 817–821.

Liburd, O. E., L. J. Gut, L. L. Stelinski, M. E. Whalon, M. R. McGuire, J. C. Wise, X. P. Hu, and R. J. Prokopy. 1999. Mortality of *Rhagoletis* species encountering pesticide-treated spheres (Diptera: Tephritidae). J. Econ. Entomol. 92: 1151–1156

Liburd, O. E., S. Polavarapu, S. R. Alm, and R. A. Casagrande. 2000. Effects of trap size, placement and age on captures of blueberry maggot flies (Diptera: Tephritidae). J. Econ. Entomol. 93: 1452–1458.

Prokopy, R. J. 1975. Apple maggot control by sticky red spheres. J. Econ. Entomol. 68: 197–198.

Prokopy, R. J., and J. Mason. 1996. Behavioral control of apple maggot flies, pp. 555–559. *In* B. A. McPherson and G. J. Steck [eds.], Fruit fly pests: a world assessment of their biology and management. St. Lucie Press, Delray Beach, FL.

Prokopy, R. J. 1977. Attraction of *Rhagoletis pomonella* (Diptera: Tephritidae) to red spheres of different sizes. Can. Entomol. 109: 593–59.

Prokopy, R. J., and K. I. Hauschild. 1979. Comparative effectiveness of sticky red spheres and Pherocon AM standard traps for monitoring apple maggot flies in commercial orchards. Environ. Entomol. 8: 696–700.

Prokopy, R. J., and W. M. Coli. 1978. Selective traps for monitoring *Rhagoletis mendax* flies. Prot. Ecol. 1: 45–53.

Prokopy, R. J., S. A. Johnson, and M. T. O'Brien. 1990. Second-stage integrated management of apple arthropod pests. Entomol. Exp. Appl. 54: 9–19.

Prokopy, R. J., S. E. Wright, J. L. Black, X. P. Hu, and M. R. McGuire. 2001. Attracticidal spheres for controlling apple maggot flies: commercial-orchard trials. Entomol. Exp. Appl. (in press).

Reissig, W. H., B. H. Stanley, W. L. Roelofs, and M. R. Schwarz. 1985. Tests of synthetic apple volatiles in traps as attractants for apple maggot flies (Diptera: Tephritidae) in commercial apple orchards. Environ. Entomol. 14: 55–59.

Reynolds, H. A., and R. J. Prokopy. 1997. Evaluation of odor lures for use with red sticky spheres to trap apple maggot (Diptera: Tephritidae). J. Econ. Entomol. 1655–1660.

SAS Institute. 1989. SAS/STAT user's guide, version 6, 4th ed., vol. 1. SAS Institute, Cary, NC.

Stanley, B. H., W. H. Reissig, W. L. Roelofs, M. R. Schwarz, and C. A. Shoemaker. 1987. Timing treatments for apple maggot (Diptera: Tephritidae) control using sticky spheretraps baited with synthetic apple volatiles. J. Econ. Entomol. 80: 1057–1063.

Stelinski, L. L., and O. E. Liburd. 2001. Evaluation of various deployment strategies of imidacloprid-treated spheres in highbush blueberries for control of *Rhagoletis mendax* Curran (Diptera: Tephritidae). J. Econ. Entomol. (in press).

Zhang, A., C. Linn, Jr., S. Wright, R. Prokopy, W. Reissig, and W. Roelofs. 1999. Identification of a new blend of apple volatiles attractive to the apple maggot, *Rhagoletis pomonella.* J. Chem. Ecol. 25: 1221–1232.

Received for publication 24 October 2000; accepted 30 March 2001.