Reduced-risk Insecticides for Control of Grape Berry Moth (Lepidoptera: Tortricidae) and Conservation of Natural Enemies

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ABSTRACT A 3-yr field study was conducted at commercial grape (*Vitis* spp.) farms to evaluate insect management programs for control of the grape berry moth, *Paralobesia viteana* Clemens (Lepidoptera: Tortricidae) and conservation of natural enemies. At each farm, one vineyard received only reduced-risk insecticides for control of second and third generation *P. viteana*, whereas the comparison vineyard received conventional insecticides. Both vineyards received a conventional insecticide application for control of first generation *P. viteana* and other insect pests. Monitoring with pheromone traps showed no differences between programs in the total number of adult male moths trapped in vineyards, and oviposition by *P. viteana* was similar between the two programs in all 3 yr. During weekly samples of crop infestation, both programs had a similar percentage of clusters infested by *P. viteana* larvae. Berries infested by *P. viteana* were collected from vineyard borders during the second and third *P. viteana* generations and held under controlled conditions. In eight of the nine berry samples, survival of larvae was significantly lower in berries collected from vineyards managed under the reduced-risk insecticide program compared with the conventional program. Parasitism of *P. viteana* larvae in these samples was not consistently different between the two insecticide programs over 3 yr, and similar captures of natural enemies were found on yellow sticky traps in the two programs throughout the study. Our results indicate that integrated pest management programs incorporating reduced-risk insecticides for control of *P. viteana* can obtain similar or greater control of *P. viteana* compared with programs based solely on conventional insecticides, but they may not lead to measurable long-term increases in parasitism of *P. viteana*.

KEY WORDS *Paralobesia viteana*, *Endopiza viteana*, methoxyfenozide, insect growth regulator, spinosad

The grape berry moth, *Paralobesia viteana* (Clemens) (Lepidoptera: Tortricidae) is a primary insect pest of eastern North American vineyards, and it was recently renamed from *Endopiza viteana* Clemens (Brown 2005, 2006). Grape berry moth is a monophagous insect, occurring naturally on wild and cultivated *Vitis* spp. vines, and it has become the main target of vineyard insect management programs in the eastern United States and Canada (Dennehy et al. 1990, Trimble 1993, Botero-Garcés and Isaacs 2003). This species overwinters as pupae, and first generation adults emerge each spring from late April to June. Grape berry moth is multivoltine, with three or more generations per year (Biever and Hostetter 1989, Hoffman and Dennehy 1989, Tobin et al. 2003), requiring management actions throughout the growing season. Once mated, females oviposit single eggs on developing buds, florets, or berries (Clark and Dennehy 1988, Tobin et al. 2003). Economic losses to *P. viteana* result from fruit contamination at harvest and reduced yield from the combination of insect feeding and associated diseases that opportunistically invade infested berries (Dennehy et al. 1990). Pest pressure varies among years and vineyards, and it is also generally greater at vineyard borders adjacent to deciduous woods (Hoffman and Dennehy 1989, Botero-Garcés and Isaacs 2003). Because of this, vineyard scouting is an important component of integrated pest management (IPM) programs, ensuring that management is targeted at the times and places where pest abundance warrants chemical control.

To control *P. viteana* and other vineyard insect pests in the eastern United States, growers currently rely on multiple applications of neurotoxic insecticides. These insecticides generally provide control of both primary and secondary pests. For example, secondary pests such as leafhoppers may be adequately controlled by insecticides targeting *P. viteana* applied immediately after bloom (Martinson et al. 1994, Martinson et al. 1997, Williams and Martinson 2000). Despite the availability of effective neurotoxic insecticides, alternative control options are needed for effectively managing vineyard insect pests, because the Food Quality Protection Act of 1996 has led to restrictions on the use

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of these insecticides in this industry. Additionally, resistance to carbaryl has recently been detected in populations of *P. viteana* (Nagarkatti et al. 2002). In preparation for increased regulation of organophosphate and carbamate insecticides for many food and fiber crops in the United States, the effectiveness of insect control programs that incorporate reduced-risk management approaches have been evaluated (Atanassov et al. 2002; Musser and Shelton 2003; Smirle et al. 2003a, 2003b; Doerr et al. 2004; Naranjo et al. 2004; Pineda et al. 2004; Brunner et al. 2005; Koss et al. 2005; Kovanci et al. 2005). The development and registration of two reduced-risk insecticides, methoxyfenozide (Intrepid 2 F) and spinosad (SpinTor 2 SC) (Dow AgroSciences, Indianapolis, IN), provide a new opportunity for control of *P. viteana.* Methoxyfenozide is an insect growth regulator (IGR) that binds to the ecdysone receptor complex in lepidopteran larvae and causes premature molting (Carlson et al. 2001). IGRs are most effective when ingested, but they also possess some topical and ovicidal properties (Pfeiffer 2000, Carlson et al. 2001, Myers and Hull 2003, Isaacs et al. 2005). Spinosad, an insecticidal macrocyclic lactone, is naturally derived from the soil actinomycete *Saccharopolyspora spinosa,* and it acts on the insect nervous system, causing hyperexcitation and paralysis (Salgado 1998, Salgado et al. 1998, Pfeiffer 2000). It is active against Lepidoptera, Coleoptera, Homoptera, Diptera, Phytoseiidae, and Hymenoptera, (Salgado 1998, Wilkinson 2002, Galvan et al. 2005, Pelz et al. 2005, Villanueva and Walgenbach 2005), and there are reports on its compatibility (Medina et al. 2001, Medina et al. 2003, Williams et al. 2003) and noncompatibility (Nowak et al. 2001, Cisneros et al. 2002, Mason et al. 2002, Penagos et al. 2005) with natural enemies. Both methoxyfenozide and spinosad are highly effective against *P. viteana* eggs and larvae in the laboratory (Isaacs et al. 2005; P.E.J., unpublished data), and they have provided similar control compared with conventional insecticides in multiple-year small-plot trials (Saunders et al. 2003, Williams et al. 2005, Wise et al. 2005). These products offer the potential for *P. viteana* control while minimizing the suppression of biological control agents commonly caused by the use of neurotoxic insecticides (Dhadialla and Jansson 1999, Legaspi et al. 1999, Trisyono et al. 2000, Medina et al. 2001, Carton et al. 2003, Hewa-Kapuge et al. 2003, Schneider et al. 2004), and their registration for use in vineyards provides an opportunity to determine whether adoption of reduced-risk insecticides in commercial vineyards provides effective control of *P. viteana* compared with a program based solely on conventional insecticides.

The typical insecticide program in eastern grape vineyards includes pyrethroids, organophosphates, and carbamates, and it is therefore expected to limit biological control due to the direct toxicity of these pesticides to most natural enemies (Van Driesche and Bellows 1996, Ruberson et al. 1998, Johnson and Tabashnik 1999). Many evaluations of insect control programs that incorporate reduced-risk management approaches support the expectation that natural enemy abundance will increase when pesticide toxicity to natural enemies is reduced (Atanassov et al. 2002; Musser and Shelton 2003; Smirle et al. 2003a, 2003b; Doerr et al. 2004; Pineda et al. 2004; Brunner et al. 2005; Koss et al. 2005; Kovanci et al. 2005). Some of the new insecticides registered for *P. viteana* control have little effect on survival of egg (Suh et al. 2004) or larval (Brown 1994, 1996) parasitoids of other Lepidoptera, but this is not known for the parasitoid species attacking *P. viteana.*

This study compared control of *P. viteana* with reduced-risk insecticides to that achieved with conventional insecticides over three growing seasons. Additionally, the effect of these two insecticide programs on natural enemies was evaluated. This project was conducted at commercial grape farms by using a combination of approaches to assess whether the two programs differed in their performance, in terms of overall *P. viteana* infestation and natural enemy conservation.

Materials and Methods

Study Sites. This study was conducted at two mature 1.4–4-ha *Vitis labrusca* L. 'Concord' grape vineyards at each of four farms in 2003, 2004, and 2005 in Van Buren and Berrien counties, MI. Vineyards were selected with histories of *P. viteana* infestation, and they were bordered on at least one side by deciduous woods, where pest pressure has been found to be greatest (Botero-Garcés and Isaacs 2004). The distance between the vineyard border and the wood border ranged from 6.4 to 20.3 m (Fig. 1). One farm selected in 2003 had very low pest pressure, and the data from this farm were omitted from the analysis. After the 2003 growing season, another farm with higher *P. viteana* pressure was added. Growers made all pesticide applications and other vineyard management actions. Vineyards within each farm received the same weed and disease control program, according to the grower's standard practices.

Insect Management. Both vineyards at each farm received a conventional insecticide immediately after bloom for control of first generation *P. viteana* and leaf-feeding pests (Table 1). Thereafter, at each farm one vineyard received only conventional insecticides (conventional program), made up of organophosphates, carbamates, and pyrethroids (Table 1). The other vineyard (reduced-risk program) received an insecticide program containing reduced-risk insecticides for control of the key insect pests (Table 1). The conventional vineyard received three or more insecticide applications insecticides whereas the reduced-risk vineyard received two or more insecticide applications for control of second and third generations of *P. viteana* (Table 1). In general, the two insecticide programs were distinct, even though participating growers were allowed to choose insecticides in the conventional program. Acetamiprid was applied in the reduced-risk vineyards at a rate to control Japanese beetle, *Popillia japonica* Newman, and eastern grape leafhopper, *Erythroneura comes* (Say), as needed

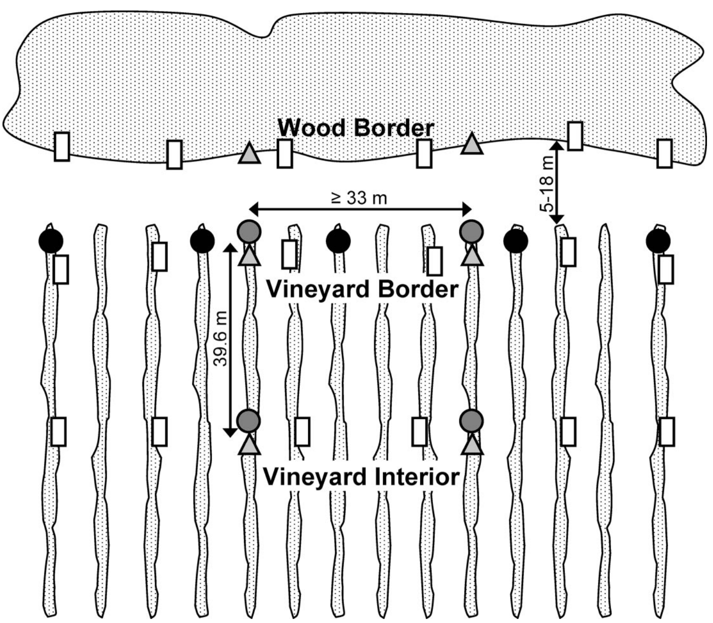

Fig. 1. Schematic diagram of a vineyard and adjacent wood habitat (not to scale). Triangles and rectangles represent pheromone trap placement and yellow sticky trap placement, respectively, at the vineyard interior, vineyard border, and wood border. Gray circles represent weekly sampling sites for infestation by *P. viteana* eggs and larvae at the vineyard border and vineyard interior. Black circles represent sampling sites for fruit infested by *P. viteana* larvae and parasitoids at the vineyard border.

(Table 1), but at a rate too low for control of *P. viteana* (R.I., unpublished data). Application timing for the reduced-risk program was based on weekly scouting of vineyards (see below), whereas the timing for the conventional vineyard followed the grower's standard program. Postbloom applications of conventional insecticides in both programs for control of first generation *P. viteana* were made using 234 liters of water per ha (25 gallons of water per acre). The applications of methoxyfenozide and spinosad in the reduced-risk program were made using 468 liters of water per ha (50 gallons of water per acre) and the volume of water used for late season conventional applications ranged from 187 to 468 liters of water per ha (20–50 gallons of water per acre).

Captures of Male *P. viteana*. Flights of adult male *P. viteana* were monitored using large plastic delta traps (Suterra LLC, Bend, OR) baited with *P. viteana* sex pheromone [90:10 ratio of (Z)-9–dodecenyl acetate and (Z)-11–tetradecenyl acetate] (Suterra LLC). Two traps were placed at a height of 1.5 m at each vineyard border, vineyard interior, and wooded border adjacent to each vineyard. Traps were distributed across the length of the vineyard, at least 33 m apart, and vineyard interior traps were placed 39.6 m from the vineyard border (Fig. 1). The distance between the vineyard border traps and the wood border traps ranged from 6.4 to 20.3 m (Fig. 1). Traps were monitored weekly for the number of male *P. viteana* captured, and the males were removed, or traps were replaced with new inserts. Pheromone lures were replaced every 4 wk by using lures from the same lot in each season. Each year, the total captures from each trap were averaged within location across farms and compared between locations and programs using two-way analysis of variance (ANOVA) (PROC MIXED, SAS Institute 2001). Data were log-transformed [log $(n + 1)$] to meet normality assumptions before analysis and the significance level was $\alpha = 0.05$.

***P. viteana* Cluster and Berry Infestation.** Infestation by *P. viteana* was quantified weekly by visually examining 30 clusters (five clusters on three vines spaced ≈2.7 m apart, at two sampling sites) at the border and interior of the vineyard (Fig. 1). For each vine, the number of *P. viteana* eggs, *P. viteana* larvae, and clusters with *P. viteana* larvae was recorded and summed within each sampling site for each date. To determine the presence of larvae, berries showing signs of *P. viteana* infestation were scored positive, and adjacent berries webbed together were counted as one larva. The total number of eggs found at each farm throughout the season, and for each specific sampling date, was compared between programs and locations by using ANOVA (PROC MIXED, SAS Institute 2001). The weekly average of *P. viteana* larvae and clusters infested by *P. viteana* larvae for each farm were compared between programs and locations for each date and across each season by using two-way ANOVA (PROC MIXED, SAS Institute 2001). For these analyses, data were log-transformed [log $(n + 1)$] to meet normality assumptions before analysis.

Survival and Parasitism of *P. viteana* in Vineyards. To compare the effects of the two insecticide programs on *P. viteana* survival and parasitism, 100 berries

Table 1. Insecticides applied to Michigan juice grape vineyards managed using reduced-risk or conventional insecticide programs during 2003–2005

Farm	2003				2004				2005			
	Date	Conventional	Date	Reduced-risk	Date	Conventional	Date	Reduced-risk	Date	Conventional	Date	Reduced-risk
1	6/19	Azinphosmethyl (c)	6/30	Fenpropathrin (j)	6/17	Azinphosmethyl (b)	6/22	Fenpropathrin (j)	6/16	Fenpropathrin (j)	6/16	Fenpropathrin (j)
	6/30	Fenpropathrin (j)	7/24	Methoxyfenozide (m)	7/1	Fenpropathrin (j)	7/16	Methoxyfenozide (m) + Acetamiprid (a)	6/30	Phosmet (n)	7/8	Methoxyfenozide (m) + Acetamiprid (a)
	7/15	Fenpropathrin (j)	8/18	Methoxyfenozide (m)	7/15	Azinphosmethyl (b)			7/11	Bifenthrin (e)		
	7/24	Azinphosmethyl (c)	9/8	Methoxyfenozide (m)	8/4	Fenpropathrin (j)	8/6	Methoxyfenozide (m)	7/27	Fenpropathrin (j)	8/4	Methoxyfenozide (m)
	8/6	Azinphosmethyl (c)			8/28	Fenpropathrin (j)	9/1	Spinosad (p)	8/8	Bifenthrin (e)		
	8/26	Fenpropathrin (j)							8/27	Carbaryl (i)		
	9/9	Fenpropathrin (k)										
2	6/29	Fenpropathrin (j)	6/28	Fenpropathrin (j)	6/25	Carbaryl (f)	6/25	Carbaryl (f)	6/22	Carbaryl (f)	6/22	Fenpropathrin (j)
	7/15	Carbaryl (f)	7/16	Carbaryl (f)	7/12	Fenpropathrin (j)	7/14	Methoxyfenozide (m) +Acetamiprid (a)	7/14	Bifenthrin (e)	7/14	Methoxyfenozide (m) + Acetamiprid (a)
	7/29	Azinphosmethyl (b)	7/28	Methoxyfenozide (m)	8/3	Azinphosmethyl (b)			8/8	Bifenthrin (e)		
	8/18	Azinphosmethyl (b)	8/14	Methoxyfenozide (m) + Acetamiprid (a)	9/1	Carbaryl (g)	8/6	Methoxyfenozide (m) + Acetamiprid (a)			8/8	Methoxyfenozide (m) + Acetamiprid (a)
	9/3	Carbaryl (f)										
			9/3	Methoxyfenozide (m)			9/1	Spinosad (p)				
3	6/19	Fenpropathrin (j)	6/27	Fenpropathrin (j)	6/22	Fenpropathrin (j)	6/22	Fenpropathrin (j)	6/15	Fenpropathrin (j)	6/15	Fenpropathrin (j)
	7/8	Azinphosmethyl (b)	7/25	Methoxyfenozide (m)	7/15	Azinphosmethyl (b)	7/15	Methoxyfenozide (m) + Acetamiprid (a)	7/5	Carbaryl (f)	7/13	Methoxyfenozide (m) + Acetamiprid (a)
	7/25	Carbaryl (f)	8/15	Methoxyfenozide (m)	8/10	Azinphosmethyl (d)			8/2	Bifenthrin (e)		
	8/9	Azinphosmethyl (b)	9/5	Methoxyfenozide (m)	8/31	Carbaryl (h)	8/10	Methoxyfenozide (m)			8/2	Methoxyfenozide (m)
							8/31	Spinosad (p)				
4		Not in program			6/15	Fenpropathrin (j)	6/23	Fenpropathrin (j)	6/17	Fenpropathrin (j)	6/17	Fenpropathrin (j)
					7/9	Azinphosmethyl (c)	7/12	Methoxyfenozide (m) + Acetamiprid (a)	7/9	Carbaryl (f)	7/9	Methoxyfenozide (m) + Acetamiprid (a)
					8/2	Fenpropathrin (j)			8/3	Phosmet (n)		
					8/30	Phosmet (n)	8/6	Methoxyfenozide (m)	8/23	Phosmet (n)	8/3	Methoxyfenozide (m)
					9/10	Carbaryl (f)	9/1	Spinosad (p)	9/4	Carbaryl (f)	9/1	Spinosad (p)

Rates of application of active ingredient are provided in the footnote.

[a] Acetamiprid (Assail 70WP) at 54 g/ha; Cerexagri Inc., King of Prussia, PA.

[b] Azinphosmethyl (Guthion 50WP) at 841 g/ha; Bayer CropScience LP, Research Triangle Park, NC.

[c] Azinphosmethyl (Guthion 50WP) at 560 g/ha; Bayer CropScience LP, Research Triangle Park, NC.

[d] Azinphosmethyl (Guthion 50WP) at 785 g/ha; Bayer CropScience LP, Research Triangle Park, NC.

[e] Bifenthrin (Capture 2EC) at 56 g/ha; FMC Corp., Philadelphia, PA.

[f] Carbaryl (Sevin XLR Plus) at 1681 g/ha; Bayer CropScience LP, Research Triangle Park, NC.

[g] Carbaryl (Sevin XLR Plus) at 2242 g/ha; Bayer CropScience LP, Research Triangle Park, NC.

[h] Carbaryl (Sevin XLR Plus) at 1793 g/ha; Bayer CropScience LP, Research Triangle Park, NC.

[i] Carbaryl (Sevin XLR 80S) at 1345 g/ha; Bayer CropScience LP, Research Triangle Park, NC.

[j] Fenpropathrin (Danitol 2.4 EC) at 224 g/ha; Valent USA Corp., Walnut Hills, CA.

[k] Fenpropathrin (Danitol 2.4 EC) at 168 g/ha; Valent USA Corp., Walnut Hills, CA.

[m] Methoxyfenozide (Intrepid 2F) at 210 g/ha; Dow AgroSciences LLC, Indianapolis, IN.

[n] Phosmet (Imidan 70W) at 1177 g/ha; Gowan Co., Yuma, AZ.

[p] Spinosad (SpinTor 2SC) at 105 g/ha; Dow AgroSciences LLC, Indianapolis, IN.

(five subsamples of 20 berries) showing signs of *P. viteana* infestation were collected from each vineyard border adjacent to woods (Fig. 1). Sampling dates were chosen each season to be ≈10 d after insecticide applications for control of *P. viteana* and when *P. viteana* larvae were susceptible to parasitism. Berry samples were taken on 14 August, 2 September, and 13 September 2003; on 29 July, 12 August, and 26 August 2004; and 14 July, 28 July, and 10 August 2005. In 2003, each subsample of 20 berries was placed in a 473-ml polypropylene deli container (Fabri-Kal, Kalamazoo, MI) and brought back to the laboratory where the container was held at 24°C and a photoperiod of 16:8 (L:D) h. These methods were changed to improve insect survival in 2004 and 2005; individual berries were placed into separate 37-ml plastic cups (Bioserv Corp., Frenchtown, NJ) with white paper insert lids (Bioserv, Frenchtown, NJ). In all years, small strips of plastic were provided in each container as pupation substrate for *P. viteana.* At the end of 5 to 6 weeks, samples were placed at −20°C for 24 h to ensure mortality of specimens. The containers were then opened and the numbers of *P. viteana* adults, pupae, larvae, and parasitoids of *P. viteana* were totaled and recorded. From these values, the proportion of *P. viteana* surviving and the proportion of parasitized *P. viteana* from each sampling date were calculated. *P. viteana* survival and parasitism data were compared between programs for each sample date using the Mann–Whitney *U* test (PROC NPAR1WAY, SAS Institute 2001). All parasitoids were identified by taxonomic specialists to genus or species. Voucher specimens of *P. viteana* and parasitoids are held in the A.J. Cook Arthropod Collection at Michigan State University.

Natural Enemies on Yellow Sticky Traps. Natural enemies were monitored each season using unbaited yellow sticky traps (Great Lakes IPM, Vestaburg, MI). Traps were deployed at three locations (vineyard interior, vineyard border, and wood border) (Fig. 1) from 16 May to 20 September 2003, from 17 April to 17 September 2004, and 16 April to 17 September 2005. In 2003, two traps per location were deployed, but power analyses (Analyst Application, SAS Institute 2001) on data collected in 2003 indicated that greater sample size was required, so six traps were deployed per location in 2004 and 2005 (Fig. 1). All traps in all years were collected and replaced with new traps ca. every 14 d. Upon return to the laboratory, all traps were placed at −20°C until assessed. Traps were assessed for the number of natural enemies in the following dominant groups: green lacewings (Neuroptera: Chrysopidae), brown lacewings (Neuroptera: Hemerobiidae), ladybird beetles (Coleoptera: Coccinellidae), parasitoid wasps (Hymenoptera: Ichneumonidae: Braconidae), and syrphid flies (Diptera: Syrphidae). Each year, the total number of natural enemies from each trap was compared between programs and locations by using two-way ANOVA (PROC MIXED, SAS Institute 2001). Additionally, the response of each individual natural enemy group to changes in insecticide program was analyzed separately using ANOVA (PROC MIXED, SAS Institute 2001). All data were log-transformed [log $(n + 1)$] to meet normality assumptions before analysis.

Table 2. Mean total captures of male *P. viteana* moths per trap ± SE at wood borders and at the borders and interiors of Michigan juice grape vineyards managed using reduced-risk or conventional insecticides during 2003–2005

Location	Program	2003	2004	2005
Vineyard interior	Reduced-risk	86.7 ± 25.0	36.5 ± 10.1	43.4 ± 9.3
	Conventional	126.5 ± 23.0	66.4 ± 22.6	50.8 ± 14.5
Vineyard border	Reduced-risk	26.0 ± 1.7	10.7 ± 2.7	12.8 ± 1.6
	Conventional	45.1 ± 11.2	20.8 ± 7.3	21.1 ± 3.5
Wood border	Reduced-risk	94.6 ± 23.1	22.6 ± 5.1	36.2 ± 8.4
	Conventional	89.0 ± 8.7	23.9 ± 9.4	33.9 ± 13.4

Within location, there was no significant difference between programs ($P > 0.05$).

Results

Captures of Male *P. viteana*. Male *P. viteana* were monitored from early April until traps were collected before harvest in mid-September, with the greatest captures in May and June, before and during bloom. Similar numbers of adult males were captured in the reduced-risk program compared with the conventional program in all years ($F = 2.47$; df = 1, 2; $P = 0.26$ in 2003; $F = 0.03$; df = 1,3; $P = 0.87$ in 2004; and $F = 0.01$; df = 1,3; $P = 0.93$ in 2005) (Table 2). Male captures varied significantly by location within farms; in all years average male captures were significantly greater at the vineyard interior compared with the vineyard border ($F = 29.51$; df = 1, 8; $P = 0.0006$ in 2003; $F = 33.73$; df = 1, 12; $P < 0.0001$ in 2004; and $F = 16.53$; df = 1, 12; $P = 0.0016$ in 2005). In 2003, male captures were significantly greater at the wood border compared with the vineyard border ($F = 23.53$; df = 1, 8; $P = 0.0013$), and in 2004 more males were captured at the vineyard interior compared with the wood border ($F = 13.67$; df = 1, 12; $P = 0.003$). There was no significant interaction between program and location in the total number of males captured in any year ($F = 0.86$; df = 2, 8; $P = 0.46$ in 2003; $F = 2.16$; df = 2, 12; $P = 0.16$ in 2004; $F = 1.81$; df = 2, 12; $P = 0.21$ in 2005) (Table 2).

***P. viteana* Cluster and Berry Infestation.** Comparisons between the two programs indicated no significant difference in the number of eggs laid by *P. viteana* across each season ($F = 0.27$; df = 1, 2; $P = 0.66$ in 2003; $F = 0.24$; df = 1, 3; $P = 0.66$ in 2004; and $F = 2.75$; df = 1, 3; $P = 0.20$ in 2005) (Table 3). In all years, the number of *P. viteana* eggs detected was significantly greater at the vineyard border compared with the vineyard interior ($F = 74.19$; df = 1, 4; $P = 0.001$ in 2003; $F = 172.18$; df = 1, 6; $P < 0.0001$ in 2004; and $F = 33.89$; df = 1, 6; $P = 0.0011$ in 2005), but there was no significant interaction between program and location in any year ($F = 2.47$; df = 1, 4; $P = 0.19$ in 2003; $F = 0.2$; df = 1, 6; $P = 0.67$ in 2004; and $F = 1.28$; df = 1, 6; $P = 0.30$ in 2005) (Table 3).

Table 3. Mean total number of *P. viteana* eggs per season ± SE found on 30 clusters at borders and interiors of Michigan juice grape vineyards managed using reduced-risk or conventional insecticides during 2003–2005

Location	Program	2003	2004	2005
Vineyard interior	Reduced-risk	16.7 ± 4.2	14.8 ± 1.4	9.0 ± 3.3
	Conventional	9.7 ± 3.0	17.3 ± 2.8	9.3 ± 2.3
Vineyard border	Reduced-risk	107.7 ± 32.6	74.8 ± 11.4	34.0 ± 9.8
	Conventional	147.3 ± 65.9	78.0 ± 13.9	76.8 ± 16.5

Within location, there was no significant difference between programs ($P > 0.05$).

Infestation by *P. viteana* larvae was also greatest at vineyard borders throughout this study; the number of *P. viteana* larvae was significantly greater at the vineyard border compared with the vineyard interior ($F = 49.61$; df = 1, 4; $P = 0.0021$ in 2003; $F = 33.31$, df = 1, 6; $P = 0.0012$ in 2004; and $F = 98.66$; df = 1, 6; $P < 0.0001$ in 2005), with no significant interaction between program and location in any year ($F = 0.46$; df = 1, 4; $P = 0.54$ in 2003; $F = 0.17$; df = 1, 6; $P = 0.69$ in 2004; and $F = 0.19$; df = 1, 6; $P = 0.68$ in 2005). Overall comparisons between the two programs indicated that infestation by *P. viteana* larvae was not statistically significant ($F = 0.13$; df = 1, 2; $P = 0.76$ in 2003; $F = 0.15$; df = 1, 3; $P = 0.72$ in 2004; and $F = 1.19$; df = 1, 3; $P = 0.36$ in 2005) (Fig. 2). When analyzing by date, statistical separation between programs was seen on 31 July and 20 August 2003 when there were fewer larvae in the conventional program ($F = 35.11$; df = 1, 2; $P = 0.027$ and $F = 18.41$; df = 1, 2; $P = 0.05$, respectively), and on 30 August 2005 ($F = 10.81$; df = 1, 3; $P = 0.046$) when fewer larvae were found in the reduced-risk program (Fig. 2).

The number of clusters infested by *P. viteana* larvae was significantly greater at the vineyard border compared with the vineyard interior in each year ($F = 47.12$; df = 1, 4; $P = 0.0024$ in 2003; $F = 36.27$; df = 1, 6; $P = 0.0009$ in 2004; and $F = 124.84$; df = 1, 6; $P < 0.0001$ in 2005). There was no significant interaction between program and location ($F = 0.81$; df = 1, 4; $P = 0.42$ in 2003; $F = 0.11$; df = 1, 6; $P = 0.75$ in 2004; and $F = 0.05$; df = 1, 6; $P = 0.84$ in 2005). The number of clusters with larvae was not significantly different between programs ($F = 0.29$; df = 1, 2; $P = 0.64$ in 2003; $F = 0.23$; df = 1, 3; $P = 0.66$ in 2004; and $F = 0.47$; df = 1, 3; $P = 0.54$ in 2005), except for 31 July 2003, when more clusters with larvae were found in the reduced-risk vineyards ($F = 26.73$; df = 1, 2; $P = 0.035$).

Survival and Parasitism of *P. viteana* in Vineyards. In eight of nine samples of berries infested with *P. viteana* larvae collected from 2003 to 2005, survival of *P. viteana* was >23% lower in the reduced-risk insecticide program compared with the conventional insecticide program ($F > 7.5$; df = 1, 26; $P < 0.011$ in 2003; $F > 6.5$; df = 1, 38; $P < 0.015$ in 2004; and $F > 11.6$; df = 1, 38; $P < 0.0015$ in 2005) (Fig. 3). The samples taken on 29 July 2004 had similar levels of survival in the two programs ($F = 0.002$; df = 1, 38; $P = 0.96$).

In 2003 and 2004, there was no difference in parasitism of *P. viteana* between programs ($F < 2.0$; df = 1, 26, $P > 0.17$ in 2003; and $F < 2.7$; df = 1, 38; $P > 0.11$ in 2004), except on 14 August 2003 when parasitism was greater in the reduced-risk insecticide program compared with the conventional insecticide program ($F = 5.8$; df = 1, 26; $P = 0.023$) (Fig. 4). In 2005, parasitism of *P. viteana* was significantly greater in the conventional insecticide program compared with the reduced-risk insecticide program on 14 July and 28 July ($F > 5.85$; df = 1, 38; $P < 0.021$). The samples taken on 10 August 2005 had similar levels of parasitism ($F = 0.6$; df = 1, 38; $P = 0.4$) (Fig. 4).

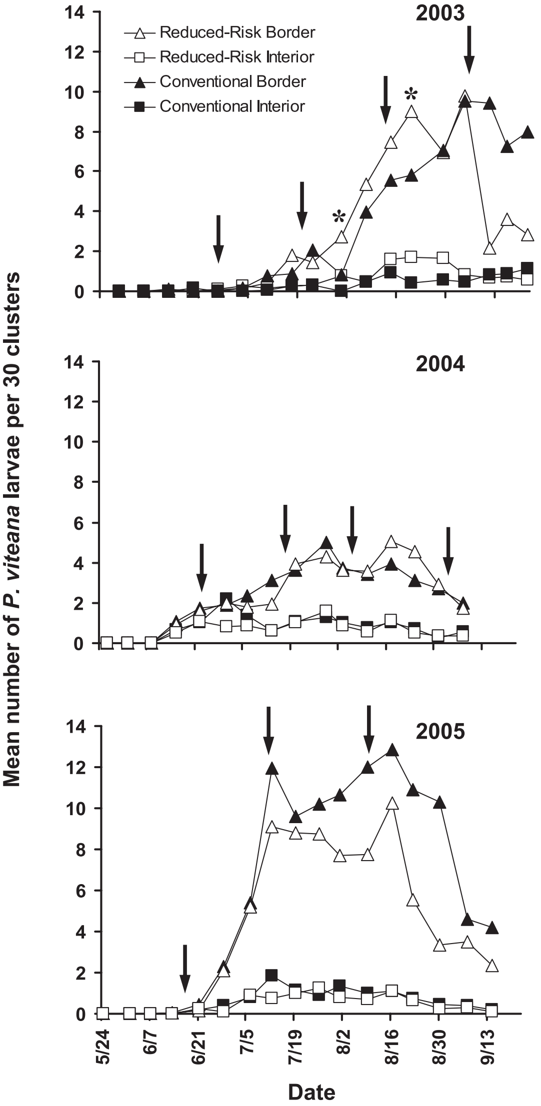

Fig. 2. Mean number of *P. viteana* larvae in grape clusters at vineyard borders and vineyard interiors in Michigan juice grape vineyards managed under conventional or reduced-risk insect control programs during 2003–2005. Arrows represent insecticide applications in the reduced-risk program. Vineyard border sample dates with an asterisk are significantly different between programs at $P < 0.05$.

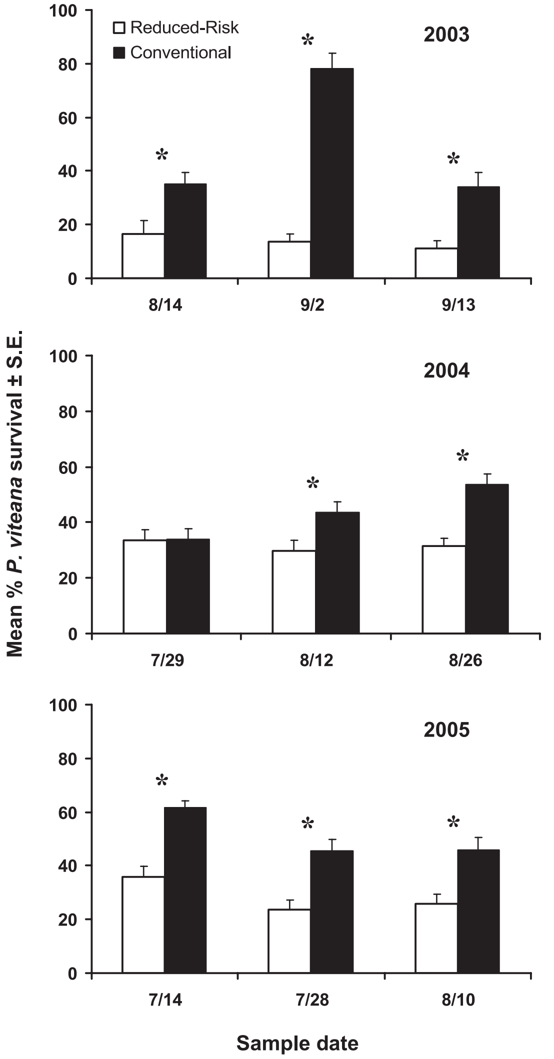

Fig. 3. Mean percentage of survival of *P. viteana* larvae ± SE from berries infested with *P. viteana* collected at the border of Michigan juice grape vineyards managed under conventional or reduced-risk insect control programs during 2003–2005. Pairs of bars with an asterisk are significantly different between programs at $P < 0.05$.

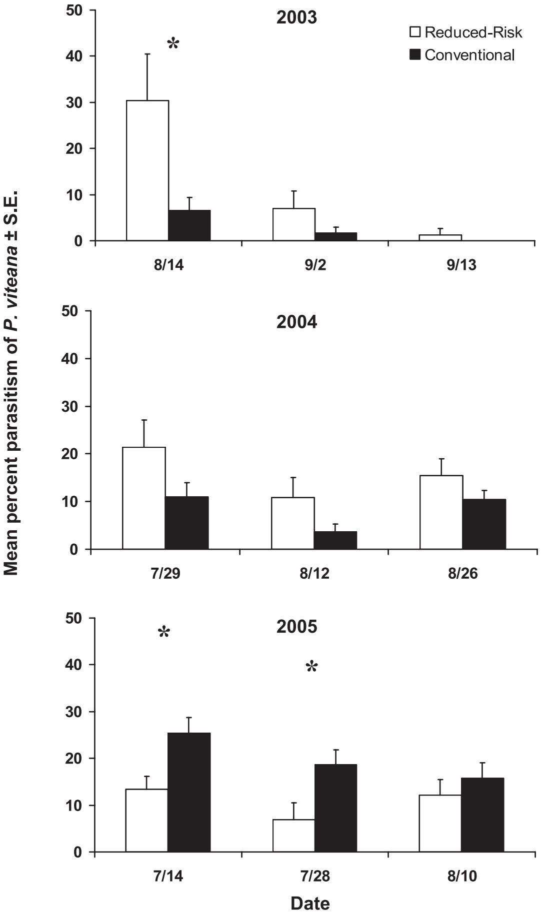

Fig. 4. Mean percentage of parasitism of *P. viteana* ± SE in juice grape vineyards in Michigan managed under conventional or reduced-risk insecticide control programs during 2003–2005. Pairs of bars with an asterisk are significantly different between programs at $P < 0.05$.

Natural Enemies on Yellow Sticky Traps. Each of the natural enemies sampled were found on each sampling date. The total number of all natural enemy groups combined was similar between insecticide programs for all 3 yr ($F = 1.73$; df = 1, 2; $P = 0.32$ in 2003; $F = 0.17$; df = 1, 3; $P = 0.71$ in 2004; and $F = 2.83$; df = 1, 3; $P = 0.19$ in 2005). In all years, the number of natural enemies was significantly greater at the wood borders compared with the vineyard border ($F = 118.24$; df = 1, 8; $P < 0.0001$ in 2003; $F = 45.68$; df = 1, 12; $P < 0.0001$ in 2004; and $F = 158.82$; df = 1, 12; $P < 0.0001$ in 2005), at the vineyard border compared with the vineyard interior ($F = 12.13$; df = 1, 8; $P = 0.0083$ in 2003; $F = 7.87$; df = 1, 12; $P = 0.016$ in 2004; and $F = 33.5$; df = 1, 12; $P < 0.0001$ in 2005), and at the wood border compared with the vineyard interior ($F = 54.64$; df = 1, 8; $P < 0.0001$ in 2003; $F = 15.63$; df = 1, 12; $P = 0.0019$ in 2004; and $F = 46.43$; df = 1, 12; $P < 0.0001$ in 2005). However, there was no significant interaction between program and location in any year ($F = 0.27$; df = 2, 8; $P = 0.77$ in 2003; $F = 0.38$; df = 2,12; $P = 0.69$ in 2004; and $F = 2.88$; df = 2, 12; $P = 0.095$ in 2005). In all years, there were no differences observed in the abundance of green lacewings, brown lacewings, ladybird beetles, parasitoid wasps, or syrphid flies between the two insecticide programs ($F < 2.39$; df = 1, 2; $P > 0.26$ in 2003; $F < 1.09$; df = 1, 3; $P > 0.66$ in 2004; and $F < 5.27$; df = 1, 3; $P > 0.11$ in 2005).

Discussion

This study indicates that grape pest management programs incorporating reduced-risk insecticides for control of *P. viteana* can result in similar or greater control of *P. viteana* compared with programs based solely on neurotoxic insecticides. Similar abundance of *P. viteana* was found in both programs when measured using monitoring traps and cluster sampling. The lower larval survival in vineyards managed using methoxyfenozide for control of late-season generations of *P. viteana* would be expected to have long-term effects on local populations of *P. viteana,* but this was not detected over the 3 yr of this study. The lower larval survival in preharvest samples from vineyards managed with reduced-risk insecticides would have reduced the likelihood of inspectors detecting larvae in harvested fruit, thus reducing the risk of rejection of grape loads by processors. When integrating alternatives methods for control of crop pests, the impact on natural enemies should be considered, and our study demonstrated that using reduced-risk insecticides for control of *P. viteana* does not cause a long-term consistent increase in parasitoids or predators.

In response to increased regulation of organophosphate and carbamate insecticides for many minor crops in the United States, similar studies have measured control of other key insect pests by using reduced-risk management approaches. For example, mating disruption and cover crop management in peaches and apples provided equal or improved control of the oriental fruit moth, *Grapholita molesta* (Busck), compared with broad-spectrum insecticides (Atanassov et al. 2002, 2003; Kovanci et al. 2005), and selective insecticides resulted in lower pest densities and greater predator densities compared with broad-spectrum insecticides in Washington potato fields (Koss et al. 2005). Plants expressing *Bacillus thuringiensis* and applications of spinosad provided equal control of lepidopteran pests and were less toxic to natural enemies in sweet corn compared with the pyrethroid lambda cyhalothrin (Musser and Shelton 2003), and methoxyfenozide and spinosad provided equivalent control of *Lacanobia subjunctata* (Grote & Robinson) in Washington apple (*Malus* spp.) orchards (Doerr et al. 2004). Additionally, fruittree leafroller, *Archips argyrospila* (Walker); European leafroller *Archips rosana* L.; obliquebanded leafroller, *Choristoneura rosaceana* Harris; threelined leafroller, *Pandemis limitata* Robinson; and *Spodoptera littoralis* (Boisduval) have all shown high susceptibility to methoxyfenozide and spinosad in the laboratory (Smirle et al. 2003a, 2003b; Pineda et al. 2004). However, limitations of reduced-risk approaches also have been found. For example, replacing organophosphate insecticides with neonicotinyl insecticides in apple orchards has provided acceptable control of only one of four species of lepidopteran pests in small plot trials (Brunner et al. 2005), and they also may increase mite outbreaks (Beers et al. 2005). Although field studies in cotton showed an increase in natural enemy conservation by using IGRs compared with conventional insecticides, pest densities were generally higher in the reduced-risk managed program (Naranjo et al. 2004). These and other research results confirm that there is a continued need to evaluate both short- and long-term effects of reduced-risk management approaches on insect communities.

In this study, implementation of a reduced-risk insect management program focused on control of the key insect pest *P. viteana*, and it revealed similar abundance of moths, eggs, and larvae of this pest compared with the grower's conventionally managed vineyards. In addition to this evidence that reduced-risk insecticides can achieve effective crop protection from *P. viteana,* the lower survival of larvae in the reduced-risk program compared with the conventional program on eight of the nine sampling dates indicates improved control of *P. viteana* in the reduced-risk program. The improved control may be due to reduced toxicity caused by the insecticides applied and/or increased activity of natural enemies in response to the use of reduced-risk insecticides. IPM programs incorporating reduced-risk insecticides in place of neurotoxic insecticides should provide greater opportunity for conservation of natural enemies and greater biological control of pests, because the compounds have lower toxicity to biological control agents than neurotoxic insecticides (Trisyono et al. 2000, Medina et al. 2001, Hewa-Kapuge et al. 2003, Schneider et al. 2003). Despite this potential benefit, our data from these vineyard trials suggest that the toxicity of the insecticides leading to reduced survival of *P. viteana* is more important for achieving pest control than reducing the negative impacts of pesticide programs on natural enemies.

Observations in Michigan vineyards indicate that the abundance of parasitoids attacking *P. viteana* larvae are typically low until later in the season (P.E.J., unpublished data), and so this study compared parasitism rates in larvae of the second and third generation of *P. viteana.* In 2003 and 2004, parasitism levels were consistently higher in vineyards managed with reduced-risk insecticides, but there was no significant difference in percentage of parasitism between programs. In 2005, this trend reversed, and parasitism of *P. viteana* was significantly greater in the conventional insecticide program for two of the three sampling dates. There are three potential reasons for this change in the relative parasitism rates. First, in 2003 and 2004, azinphosmethyl was used in ≈40% of the conventional program sprays (Table 1) and, after 2004, it was no longer produced with a label for applications in vineyards. Because azinphosmethyl was no longer being applied in the conventional program during 2005, greater parasitoid survival and hence greater parasitism of *P. viteana* may have been possible in the conventional program. Second, in 2004 vineyards in the reduced-risk program needed protection from late-season *P. viteana* infestation and spinosad was applied in the reduced-risk vineyards due to its short preharvest interval. Although spinosad is considered a reduced-risk insecticide, recent literature has shown that it can have sublethal effects on natural enemies (Galvan et al. 2005, Wang et al. 2005). Local parasitoid populations within the reduced-risk vineyards may have been affected by this late-season spinosad spray in 2004, leading to a reduction in parasitism in 2005. Lastly, parasitism in this system may be host-density dependent. The lower larval survival of *P.*

viteana in vineyards managed using reduced-risk insecticides would be expected to have long-term effects on local populations of *P. viteana,* potentially providing fewer larvae for parasitism.

Similar captures of green lacewings, brown lacewings, ladybird beetles, parasitic hymenoptera, and syrphid flies on yellow sticky traps throughout three growing seasons indicate that the distribution of natural enemies was similar across the two management programs and suggests that the natural enemies in this system are highly mobile and are likely operating on a larger spatial scale than that used to compare the two management programs. Natural enemy populations measured in this study may be responding to the abundance of prey other than *P. viteana.* However, weekly scouting of vines did not detect significant populations of other grape pests that could be affecting natural enemy abundance. Although green lacewings, *Chrysoperla carnea* Stephens, will feed on *P. viteana* under no-choice laboratory conditions (P.E.J., unpublished data), the effect of predation on *P. viteana* by these natural enemies in vineyards has not been documented. Further research to quantify predation of *P. viteana* by generalist insect predators in vineyards is needed. Although yellow sticky cards are useful for measuring the abundance of natural enemies within a system, alternative methods for assessing predation, such as deployment of sentinel prey, should be considered in future research.

P. viteana infestation is often greatest at vineyard borders (Biever and Hostetter 1989, Hoffman and Dennehy 1989, Trimble et al. 1991, Botero-Garcés and Isaacs 2004), and this pattern also was found in our study. Regular pest scouting is an important component of vineyard IPM, and the lower levels of survival by *P. viteana* larvae in the vineyards managed using reduced-risk insecticides may in part be because insecticide applications were timed more appropriately due to weekly scouting information, whereas the conventional vineyards were sprayed in response to regional recommendations or the grower's standard spray timing. Because IGRs are most effective when ingested (Carlson et al. 2001), applications of reduced-risk insecticides were targeted at *P. viteana* during peak second and third generation oviposition as determined by direct observations of clusters. In addition to regular scouting, growers were advised to apply these insecticides at a higher volume of water per acre and to spray every row to achieve good cluster coverage. This is essential for control of this pest, particularly late in the season when the leaf canopy in juice grape vineyards makes it difficult for spray material to reach the fruit.

This multiyear evaluation of reduced-risk IPM programs in Michigan vineyards provides evidence that control of *P. viteana* is achievable using a program that depends on methoxyfenozide and spinosad for control of late-season generations of this pest. As additional reduced-risk insecticides with high activity against this pest become registered for use in vineyards, a more integrated approach that further promotes biologically based management of *P. viteana* will be possible.

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