Control of Grape Berry Moth (Lepidoptera: Tortricidae) in Relation to Oviposition Phenology

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ABSTRACT We monitored the phenology of oviposition by grape berry moth, *Paralobesia viteana* (Clemens) (Lepidoptera: Tortricidae), in grape (*Vitis* spp.) vineyards, to determine the optimal timing for control of this pest. Egg deposition was monitored throughout the growing season by visually inspecting grape clusters twice weekly and counting the number of eggs. Male moths were captured on pheromone-baited traps during the same period. Two main periods of egg deposition were detected in all farms and years: the first period in June–July and the second period during August. These episodes of concentrated oviposition were separated by a brief period of low intensity but continuous oviposition. The proportion of eggs laid during the first peak ranged from 9 to 35% of all eggs laid throughout the monitoring period at each site, whereas eggs laid during the second peak ranged from 43 to 78% of all eggs laid. From 49 to 99% of male moths were captured before or during the first peak in oviposition. In field trials with varying application timing of methoxyfenozide targeting the postbloom oviposition, a single application of this selective insecticide at ≈700 degree-days, or ≈12% of cumulative season-long oviposition, provided significant control of grape berry moth comparable with two applications of methoxyfenozide or a three-spray program with broad-spectrum insecticides. Use of predicted oviposition phenology and selective insecticides with long residual activity can improve protection of grapes against infestation by *P. viteana*.

KEY WORDS phenology, *Vitis*, integrated pest management

Grape berry moth, *Paralobesia viteana* (Clemens) (Lepidoptera: Tortricidae), is native to eastern North America and is the primary insect pest of grapes (*Vitis* spp.) grown in the Midwest and Northeast (Taschenberg et al. 1974, Dennehy et al. 1990). Wild hosts of grape berry moth include several native grapevines, such as *Vitis labrusca* L. and *Vitis riparia* Micheaux, often found growing in natural or disturbed areas in the vicinity of vineyards (Botero-Garcés and Isaacs 2004). In Michigan, moths emerge from overwintering pupae starting in early May. Females mate and begin laying eggs singly on developing flowers or young grape berries in June. Larvae eclosing from eggs during the first generation spin protective retreats while feeding on flowers or developing grapes. Later, larvae burrow into the berries and may web together several berries while feeding. Average male and female longevity at 23°C was 18.5 d and females laid an average of 33 eggs (Luciani 1987).

The number of generations varies with geographical location, with two or three generations reported in the Lake Erie region (Ingerson 1920, Gleissner and Worthley 1941) and central New York state (Hoffman et al. 1992) and up to four generations in southern Missouri (Biever and Hostetter 1989). The identification of the female sex pheromone of grape berry moth (Roelofs et al. 1971) and its subsequent use for trapping male moths provided insight into the phenology of this pest. However, male moth catches generally do not correlate with female oviposition (Hoffman et al. 1992) or crop infestation levels (Dennehy et al. 1990). In Michigan, pheromone-baited traps reveal a consistent pattern where captures of male moths peak during June and continue at much lower levels throughout the rest of the season, whereas damage to grape clusters starts at a low level and peaks late in the season (Botero-Garcés and Isaacs 2003, Jenkins and Isaacs 2007). The patterns of moth captures have precluded the use of pheromone-baited traps for determining the beginning of the second and third generations or for identifying optimal timing of insecticide sprays later in the season. Availability of site-specific phenological information and an improved understanding of the relationship between heat accumulation and oviposition phenology would improve grape berry moth control and decrease risks for nontarget species by reducing the need to repeat poorly timed sprays. Phenological information would be especially important when using novel insect growth regulator (IGR) insecticides that require accurate application timing at oviposition or eclosion by grape berry moth for optimal performance (Isaacs et al. 2005).

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Management of grape berry moth in high-risk vineyards traditionally involves spraying of organophosphate, carbamate, or pyrethroid insecticides immediately after grape bloom. These treatments target moths of the overwintering generation, eggs and early instars of the first summer generation, plus early infestations of other pests. Later generations of grape berry moth are controlled by insecticide applications made in response to information from monitoring traps coupled with scouting that identifies infestation severity at key times (Hoffman et al. 1992). However, this system does not provide for the inherent between-season variation in the timing of grape berry moth phenology (Tobin et al. 2003). Recently, the IGR insecticides methoxyfenozide and tebufenozide have been registered for use against grape berry moth. These diacylhydrazine insecticides act as powerful ecdysone agonists and are most effective on lepidopteran larvae after ingestion but also have topical and ovicidal properties (Carlson et al. 2001, Isaacs et al. 2005). The efficacy of these IGR insecticides against grape berry moth has been studied in vineyards and was found equivalent to that of organophosphates, carbamates, and pyrethroids (Jenkins and Isaacs 2007). In studies with other tortricids, such as codling moth, *Cydia pomonella* (L.), and oriental fruit moth, *Grapholita molesta* (Busck), methoxyfenozide was shown to have extended field residual activity lasting at least 28 d (Borchert et al. 2004), and this duration of activity may prove useful against the long period of oviposition observed in grape berry moth. In addition, it has been reported that tebufenozide applied to control the first generation also controlled the second generation of the tortricid European grape moth, *Lobesia botrana* (Denis et Schiffermüller) (Pavan et al. 2005, and references therein). Residual half-life of tebufenozide concentration on apple (*Malus* spp.) leaves was 7.2 and 36.3 d in May and August, respectively, and the estimated time needed to decrease bioactivity by 50% was 36.6 and 18.7 d, respectively (Smirle et al. 2004). The long residual activity of diacylhydrazine insecticides indicates that the management strategy traditionally used with conventional insecticides, such as multiple insecticide applications throughout the season, could be modified. However, a new management strategy will require not only distinct treatment intervals but also accurate timing of insecticide application to ensure application just before oviposition increases and larvae hatch, further emphasizing the need for site-specific phenological information.

This study aimed to determine the phenology of oviposition by grape berry moth in commercial vineyards in Michigan. We also tested whether applications of IGRs aimed at the primary periods of oviposition by grape berry moth would improve control of this pest compared with conventional management programs.

Materials and Methods

Monitoring of Oviposition and Male Moth Flight. We determined oviposition by grape berry moth at two juice grape (*Vitis labrusca* L.) vineyards in 2006 and four vineyards in 2007, in Berrien and Van Buren counties, MI. These vineyards were managed using grower standard practices that included one spray with a broad-spectrum insecticide targeting grape berry moth ≈10 d after grape bloom, in mid-late June. Oviposition on grape berries was monitored twice weekly. Monitoring started on 18 and 22 May and ended on 3 October and 13 September in 2006 and 2007, respectively. In each vineyard, we visually inspected a sample of 100 clusters consisting of five randomly selected clusters from each of 20 vines spread along the outer edge of the vineyard. A hand lens was used to observe the appearance of the eggs and only unhatched eggs were counted. Newly laid grape berry moth eggs initially look opaque and later show signs of embryonic development, whereas hatched eggs look clear or have a visible opening. At the same vineyards used for monitoring oviposition, three pheromone-baited traps per site were deployed from 11 April to 13 October and from 23 April to 21 September in 2006 and 2007, respectively, hanging from vine trellises or vegetation. Male moths were captured using Large Plastic Delta Traps (Suterra LLC, Bend, OR) with rubber septa lures that contained 0.1 mg of a 9:1 blend of (Z)-9-dodecenyl acetate and (Z)-11-tetradecenyl acetate and were lined with sticky inserts. Traps were placed at the interior of the vineyard, at the edge of the vineyard, and at the border of a wooded area adjacent to the vineyard. Rubber septa were replaced monthly with new septa from the same batch. Traps were visited twice weekly and, at each date, moths were counted and removed from the sticky insert. Moth capture was calculated as the weekly total number of moths captured at the three locations where traps were deployed.

Oviposition Phenology-Driven Application of IGRs. In 2006, we evaluated control of mid- and late-season grape berry moth infestation by using methoxyfenozide applied as Intrepid 2 F (Dow AgroSciences, Indianapolis, IN) sprayed at 0.877 liters/ha (0.21 kg/ha [AI]), and the organophosphate phosmet applied as Imidan 70W (Gowan Company, Yuma, AZ) applied at 1.5 kg/ha (1.0 kg/ha [AI]), by using a backpack sprayer at 795 liters of water per ha. To minimize phosmet breakdown, the water pH was adjusted to 6.0 by using 2 ml/liter of white vinegar. Treatments consisted of an untreated control, one spray of methoxyfenozide applied on 30 June, two sprays of methoxyfenozide applied on 30 June and 13 July or one spray of phosmet applied on 21 July (typical timing), arranged in a completely randomized block design with six replicate plots, in a commercial vineyard in Van Buren County, MI. Each 50-m^2 plot consisted of seven grape vines located at the edge of a larger vineyard adjacent to deciduous woods in Van Buren County, MI. The grower applied a spray of bifenthrin applied as Capture 2 EC (FMC Corp., Phil-

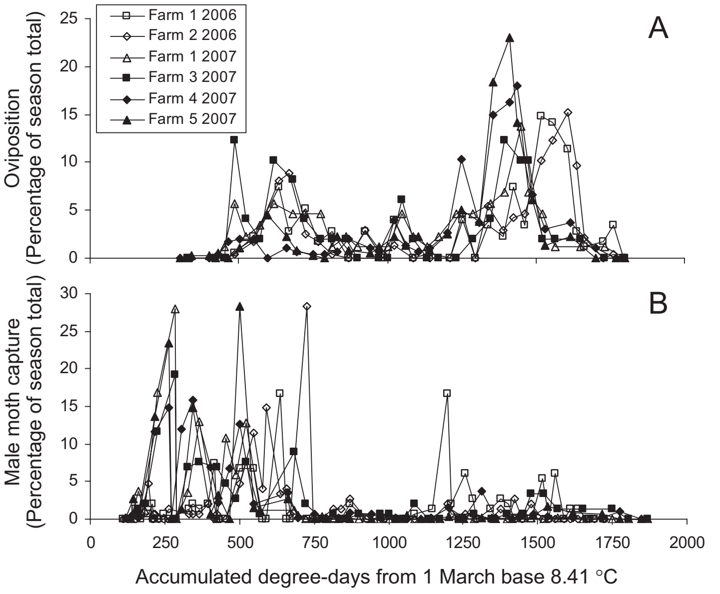

Fig. 1. Oviposition by grape berry moth and male moth capture on pheromone-baited traps at the same sites in southwest Michigan, in 2006 and 2007. Weekly egg count and moth capture were normalized by their respective season totals.

adelphia, PA) at 0.234 liters/ha (0.056 kg/ha [AI]) on 29 May, and a standard fungicide program. No other insecticides were applied to the vineyard except those used in the trial. A prespray estimation of damage on 30 June revealed no significant differences in grape moth infestation among treatment plots. Postspray grape berry moth infestation was evaluated on 3 August, 18 August, and 12 September by counting the number of grapes showing feeding damage in 25 randomly chosen grape clusters in the middle five vines of each plot.

In 2007, we compared the efficacy of treatments consisting of an untreated control, one application of Intrepid 2F at 0.877 liters/ha (0.21 kg/ha methoxyfenozide) on 21 June, two applications of methoxyfenozide at 0.585 liters/ha (0.14 kg/ha methoxyfenozide) on 21 June and 24 July, two applications of methoxyfenozide at 0.877 ml/ha (0.21 kg/ha methoxyfenozide) on 21 June and 24 July, or a grower standard program at typical timing consisting of sprays of carbaryl applied as Sevin XLR Plus (Bayer CropScience, Research Triangle Park, NC) sprayed at 0.468 liters/ha (0.224 kg/ha [AI]) on 21 June, phosmet applied as Imidan 70W at 1.5 kg/ha (1.0 kg/ha [AI]) on 24 July, and β-cyfluthrin applied as Baythroid XL (Bayer CropScience, Research Triangle Park, NC) at 0.234 liters/ha (0.028 kg/ha [AI]) on 30 August. Each treatment was replicated six times and arranged in a randomized complete block design as described above, in the same commercial vineyard in Van Buren County, MI. All treatments were applied using a backpack sprayer at 795 liters of water per ha. The water pH for preparing phosmet was adjusted as described above. The grower applied a spray of bifenthrin applied as Capture 2 EC at 0.234 liters/ha (0.056 kg/ha [AI]) on 12 June, and a standard fungicide program. No other insecticides were applied to the vineyard except those used in the trial. A prespray estimation of damage on 21 June did not show differences in grape berry moth infestation among treatment plots. Postspray grape berry moth infestation was evaluated on 5 July, 19 July, 7 August, 21 August, 6 September, and 18 September by using the same methods as in 2006.

Degree-Day Accumulation. Daily degree-day (DD) accumulations were obtained from Michigan Automated Weather Network (MAWN) sites by using numerical integration of hourly air temperature. Weather stations were available within a 3-km distance of all sites used for monitoring oviposition and spray trials. Degree-day accumulation started on 1 March, using 8.41°C as the lower developmental threshold (Tobin et al. 2001) and no upper developmental threshold.

Data Analyses. Grape berry moth infestation was measured as the number of infested berries per 25 grape clusters. For each trial, infestation data were compared among treatments by analysis of variance (ANOVA) using PROC MIXED (SAS Institute 2001) after arcsine transformation for uniformity of variance, with block as random and treatment as fixed effects, followed by least significant difference (LSD) treatment means separation with $\alpha = 0.05$.

Cumulative oviposition distribution was calculated in relation to degree-day accumulation for each vineyard at 0, 1, 5, 10, ., 90, 95, 99, and 100% oviposition using PROC UNIVARIATE of SAS (SAS Institute 2001). A single site-independent oviposition distribution was calculated as the mean of the cumulative oviposition distributions for each year. Based on this curve, we calculated the oviposition percentile in relation to degree-day accumulation for each insecticide treatment date.

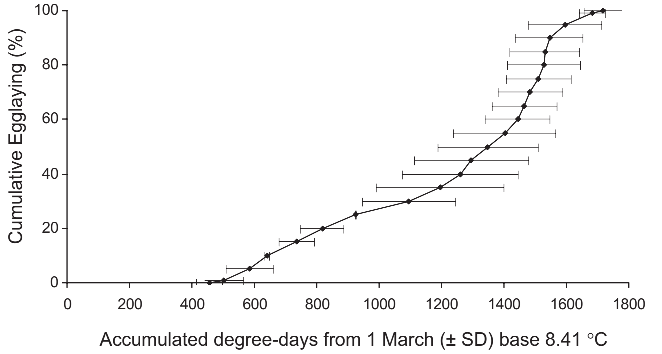

Fig. 2. Average cumulative percentile oviposition by grape berry moth at vineyards in southwest Michigan, in 2006 and 2007, as a function of heat accumulation.

Results

Monitoring of Oviposition and Male Moth Flight. We found two main periods of egg deposition in all farms and in both years, the first period from ≈500–900 DD in mid-June to mid-July 2006, and in early June to early July 2007 (Fig. 1). The second major period of egg deposition occurred from ≈1100 to 1600 DD in August to early September 2006, and from late July to late August 2007. The proportion of eggs laid during the first peak ranged from 9 to 35% of all eggs laid throughout the monitoring period, whereas eggs laid during the second peak ranged from 43 to 78% of all eggs laid. These episodes of concentrated oviposition were separated by a period of less intense but continuous oviposition. There was no clear demarcation between oviposition by different generations at the high-pressure sites that we monitored. In 2006, we counted 176 and 237 eggs throughout the season at farm 1 and 2, respectively. In 2007, we found 87, 49, 300, and 360 eggs at farms 1, 3, 4, and 5, respectively.

In 2006, male moths were trapped from early May to early July from ≈150 to 750 DD and August from ≈1200 to 1500 DD, whereas in 2007 the majority of moths were captured from early May to mid-June from ≈150 to 750 DD (Fig. 1). The proportion of moths captured during the first peak ranged from 49 to 99% of all moths captured throughout the monitoring period. In 2006, 148 and 150 moths were captured in pheromone-baited traps deployed throughout the season at farm 1 and 2, respectively. In 2007, the number of moths captured was 475, 146, 544, and 961 at farms 1, 3, 4, and 5, respectively.

The site-independent oviposition distribution (Fig. 2) shows continual oviposition starting (1%) at 488.7 ± 56.1 DD and ending (99%) at 1673.8 ± 60.0 DD. A marked and consistent increase in oviposition occurred at ≈1400 DD and accounted for >40% of eggs laid throughout the season. In 2006 and 2007, this DD accumulation was reached in mid-August.

Oviposition Phenology-Driven Application of IGRs. In 2006, there were significant differences in season-long grape berry moth damage among treatments in the spray trial ($F = 27.9$; df = 3, 15; $P < 0.001$). The prespray damage estimation conducted on 30 June showed that there were no significant differences in damage among treatment plots (Table 1). On 3 August and 21 September, the treatments consisting of one or two sprays of methoxyfenozide resulted in significantly fewer damaged berries than the treatment consisting of one spray of phosmet or the control. On 18 August, there were no significant differences among treatments of methoxyfenozide and phosmet, but the treatments of methoxyfenozide had significantly less damage than the control. There was no significant difference between the treatments in which methoxyfenozide was applied once or twice. Overall, grape damage levels were moderate in 2006.

In 2007, there were significant differences in grape berry moth damage among treatments ($F = 12.2$; df = 4,20; $P < 0.001$). The prespray damage estimation conducted on 21 June showed that there were no significant differences in damage among treatment plots (Table 2). Differences among treatments were significant starting on 7 August, and the pattern of differences among treatments remained the same throughout the trial. Treatments consisting of one spray of methoxyfenozide at 198.2 ml/ha, two sprays of methoxyfenozide at 132.1 or 198.2 ml/ha and the

Table 1. Control of grape berry moth by using one or two applications of methoxyfenozide, or one application of phosmet, in 2006

Treatment	Damage (damaged berries per 25 clusters)				
	30 June	3 Aug.	18 Aug.	21 Sept.	Avg
Untreated control	1.2 ± 0.6	16.3 ± 11.3a	17.7 ± 10.0a	16.7 ± 6.8a	16.9 ± 7.0a
Methoxyfenozide 30 June	2.3 ± 0.5	6.3 ± 4.3b	6.7 ± 2.6b	4.2 ± 3.3b	5.7 ± 2.0b
Methoxyfenozide 30 June + 13 July	0.7 ± 0.6	3.7 ± 3.4b	4.0 ± 2.1b	1.5 ± 1.2b	3.1 ± 1.9b
Phosmet 21 July	2.7 ± 0.9	12.8 ± 7.8a	10.7 ± 5.7ab	17.2 ± 6.7a	13.6 ± 4.3a

Means followed by different letters are significantly different ($P < 0.05$; LSD).

Table 2. Control of grape berry moth by using one or two applications of methoxyfenozide at two rates, or a standard program consisting of applications of carbaryl, phosmet and β-cyfluthrin, in 2007

Treatment	Damage (damaged berries per 25 clusters)							
	21 June	5 July	19 July	7 Aug.	21 Aug.	6 Sept.	18 Sept.	Avg
Untreated control	0.5 ± 0.2	2.5 ± 1.3	3.2 ± 1.6	5.3 ± 1.4a	9.5 ± 2.5a	10.0 ± 3.3a	9.5 ± 2.1a	6.7 ± 4.6a
Methoxyfenozide 0.21 kg/ha 21 June	1.3 ± 0.8	1.5 ± 0.6	2.7 ± 1.1	1.2 ± 0.5b	5.8 ± 2.4ab	4.2 ± 1.2b	2.7 ± 1.3bc	3.0 ± 2.1b
Methoxyfenozide 0.14 kg/ha 21 June + 24 July	0.3 ± 0.2	1.3 ± 0.6	1.2 ± 0.5	1.2 ± 0.6b	1.8 ± 0.7b	1.7 ± 0.6b	1.3 ± 0.4bc	1.4 ± 1.0b
Methoxyfenozide 0.21 kg/ha 21 June + 24 July	0.7 ± 0.3	0.8 ± 0.4	1.2 ± 0.5	1.3 ± 0.8b	2.0 ± 1.0b	2.0 ± 0.9b	0.8 ± 0.4c	1.4 ± 1.0b
Carbaryl 21 June, phosmet 24 July, β-cyfluthrin 30 Aug.	0.3 ± 0.2	0.2 ± 0.2	1.0 ± 0.4	1.8 ± 0.7b	2.0 ± 0.5b	3.3 ± 0.9b	3.5 ± 1.1b	2.0 ± 1.1b

Means followed by different letters are significantly different ($P < 0.05$; LSD).

grower standard program consisting of three broad-spectrum insecticide sprays, resulted in significantly lower damage than the untreated control plots. There were no significant differences among the different spray programs. In general, grape infestation levels were low at this site in 2007.

Timing of applications In Relation to Degree-Day Accumulation and Oviposition Phenology. In 2006, the first treatment of methoxyfenozide on 30 June was applied at 680.3 DD, which was when 12% cumulative oviposition had occurred (Table 3). The second spray on 13 July was applied at 857.5 DD when 23% of oviposition had occurred. The treatment of phosmet on 21 July was applied at 985.9 DD and 27% cumulative oviposition by grape berry moth. In 2007, the first treatment of methoxyfenozide and the spray of carbaryl were applied on 21 June at 710.0 DD, which was when 13% cumulative oviposition had occurred. The second treatment of methoxyfenozide and the spray of phosmet were applied on 24 July at 1134.7 DD and 32% cumulative oviposition. The treatment of β-cyfluthrin was applied on 30 August at 1640.8 DD and 97% cumulative oviposition by grape berry moth.

Discussion

This study provides the first systematic assessment of grape berry moth egg deposition phenology in Michigan's grape juice vineyards. The pattern of oviposition observed was characterized by fluctuating but continuous oviposition from June until September and was consistent over all vineyards and years. In particular, we did not find a clear demarcation between moth generations in the vineyards that we monitored, whether the sampling was conducted using pheromone-baited traps or oviposition sampling. Using egg and larval counts or moth captures, other studies have shown two to three generations of grape berry moth in the Great Lakes area (Ingerson 1920, Gleissner and Worthley 1941, Hoffman et al. 1992). Laboratory studies with grape berry moth have shown that this species requires 423.9 $DD_{8.41\ °C}$ for development from egg to adult (Tobin et al. 2001). Adding a 73 DD oviposition lag (Luciani 1987) to this result, our data show that in addition to the overwintering generation, there is sufficient heat accumulation for two summer generations of grape berry moth at the locations we monitored.

An extended moth emergence period, coupled with asynchronous flight period in vineyards and adjacent wooded areas, and moth dispersal from the woods to the vineyard, may be among the causes of the continuous egg deposition by grape berry moth observed in this study. Emergence of the overwintering generation takes place during a 6-wk period (Tobin et al. 2002). Pheromone-baited trap captures indicate that flight of grape berry moth starts earlier in the woods than the vineyards (R.I., unpublished data). In addition, there is evidence for moth movement from the woods to the vineyards, as shown by increased infestation of vineyard rows closer to habitats containing wild hosts (Botero-Garcés and Isaacs 2003, 2004).

It is unlikely that grape growers will adopt the practice of timing insecticide sprays based on monitoring for egg deposition because this method requires specialized knowledge and is very time-consuming. But, as long as pheromone-baited traps remain ineffective for monitoring the phenology of this species late in the season, an oviposition degree-day model may be the best available tool for predicting grape berry moth phenology. Timing sprays of insecticides, especially IGRs, by using this model may be an effective alternative to calendar sprays for control of grape berry moth (see below). This study showed that methoxyfenozide applied at 680–710 DD, when 12–13% of the

Table 3. Correspondence between the date of insecticide application for control of grape berry moth, degree-day accumulation, and percentile season-long oviposition, in 2006 and 2007

Date	Treatment	DD[a]	Oviposition (%)
2006			
30 June	Methoxyfenozide (1 of 1) Methoxyfenozide (1 of 2)	680.3	12
13 July	Methoxyfenozide (2 of 2)	857.5	23
21 July	Phosmet	985.9	27
2007			
21 June	Methoxyfenozide high (1 of 1) Methoxyfenozide high (1 of 2) Methoxyfenozide low (1 of 2) Carbaryl	710.0	13
24 July	Methoxyfenozide high (2 of 2) Methoxyfenozide low (2 of 2) Phosmet	1,134.7	32
30 Aug.	β-Cyfluthrin	1,640.8	97

[a] DD accumulated from 1 March, base 8.41°C.

season-long oviposition of grape berry moth had occurred, significantly decreased grape berry moth infestation throughout the season. Moreover, this treatment was equivalent to a program including one additional spray of methoxyfenozide, or a standard program consisting of three sprays of broad-spectrum insecticides. Previous studies indicated that applications of methoxyfenozide should be timed to the beginning of oviposition to reduce survival of eggs and first instars (Isaacs et al. 2005). Our field trials, together with the degree-day oviposition data, indicate that an IGR insecticide spray relatively early in the season will remain effective in controlling infestation late in the season, when most eggs are laid. These data suggest that when using IGR insecticides with long residual action, effective season-long control of grape berry moth is possible by slightly delaying the standard 10 d postbloom spray to ≈700 DD. Methoxyfenozide is significantly less toxic for humans than the conventional insecticides it can replace (Dhadialla et al. 1998) and has low activity against beneficial insects (Dhadialla and Jansson 1999, Carton et al. 2003, Hewa-Kapuge et al. 2003, Schneider et al. 2003), although 3 yr of grape pest management by using only reduced-risk insecticides, including methoxyfenozide, did not result in increased captures of beneficial insects or greater parasitism of this pest (Jenkins and Isaacs 2007).

The long activity period of methoxyfenozide observed in this study was similar to that found with other diacylhydrazines and IGRs. It seems that this residual activity is based on persistence of insecticide residue on treated plants and not on sublethal effects of insecticide applied against a previous generation (Smirle et al. 2004, Borchert et al. 2005, Pavan et al. 2005). Therefore, residue dilution on plant surface by factors such as temperature, UV light, rainfall, and plant growth will interact with pest phenology to determine the duration of efficacy of methoxyfenozide. Our results indicate that sufficient insecticide remains on grape clusters to significantly decrease infestation by grape berry moth for >2 mo. However, the risk of development of resistance increases with the exposure of several generations in the same season to residues of the same compound. To reduce the development of resistance to diacylhydrazine insecticides, the use of methoxyfenozide against the first generation should be avoided.

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