Stage-specific control of grape berry moth, *Endopiza viteana* (Clemens) (Lepidoptera: Tortricidae), by selective and broad-spectrum insecticides

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ABSTRACT The insect growth regulators (IGRs) tebufenozide and methoxyfenozide and the broad-spectrum insecticides azinphosmethyl, carbaryl, and fenpropathrin were compared for their activity against adult, egg, and larval stages of the grape berry moth, *Endopiza viteana* (Clemens) (Lepidoptera: Tortricidae), under laboratory and vineyard conditions. Adult mortality was not affected by exposure to field-equivalent rates of tebufenozide or methoxyfenozide on grape clusters, whereas all the broad-spectrum compounds significantly reduced adult survival, compared with the untreated controls. Surviving adult moths laid significantly more eggs on berries treated with the IGRs than on berries treated with any of the broad-spectrum insecticides. Survival of these eggs through to late larval and pupal stages was significantly lower on methoxyfenozide-treated grapes than on untreated grapes, and no pupae were found when grapes were treated with azinphosmethyl or fenpropathrin. Neither of the growth regulator insecticides limited egg eclosion or larval development by *E. viteana* when insecticides were applied before egg laying, whereas broad-spectrum insecticides were effective against both eggs and neonates at this timing. When applied after egg eclosion, all insecticide treatments significantly reduced survival of grape berry moth larvae. Under vineyard conditions, berries with 1-d-old residues of tebufenozide or methoxyfenozide received more *E. viteana* eggs than berries treated with broad-spectrum compounds. After aging for 7 or 14 d, no significant effects on *E. viteana* survival were detected among treatments. Whereas broad-spectrum insecticides provide control of multiple life stages of *E. viteana*, integration of tebufenozide or methoxyfenozide into vineyard management programs for control of this pest will be most successful if applications are timed for egg hatch.

KEY WORDS tebufenozide, methoxyfenozide, insect growth regulator, larvae, bioassay

THE GRAPE BERRY MOTH, *Endopiza viteana* Clemens (Lepidoptera: Tortricidae), is the primary lepidopteran pest of grapes in eastern North America (Dennehy et al. 1990) and is the target of a majority of the insecticides applied to the 5,666 ha of vineyards in Michigan. Management programs for this pest currently include applications of the broad spectrum insecticides carbaryl, fenpropathrin, and azinphosmethyl (Wise et al. 2003), which also are active against homopteran and coleopteran pests of vineyards. In recent years, levels of *E. viteana* infestation in vineyards before harvest have increased across the northeastern United States, leading to rejection of entire loads of grapes by processors. Difficulties in controlling this pest may be due to the legislated loss of effective insecticides through implementation of the Food Quality Protection Act of 1996, although Nagarkatti et al. (2002) have reported resistance to carbaryl in *E. viteana* populations in Pennsylvania and New York vineyards. These changes in the availability and efficacy of broad-spectrum insecticides create a need to search for alternative insecticide chemistries that can effectively control this key vineyard insect pest.

The dibenzoylhydrazine ecdysteroid agonists are a class of insect growth regulator (IGR) insecticides with promise for use against *E. viteana.* Two of these compounds, methoxyfenozide and tebufenozide, have selective activity against Lepidoptera (Trisyono and Chippendale 1997, Sundaram et al. 1999, Waldstein et al. 1999, Waldstein and Reissig 2001), low mammalian toxicity (Dhadialla and Jansson 1999), and low activity against natural enemies (Smagghe and Degheele 1995, Brown 1996, Legaspi et al. 1999, Suh et al. 2000, McCravy et al. 2001). Both of these IGR insecticides cause a premature and fatal ecdysis when ingested by larval stages of Lepidoptera (Dhadialla et al. 1998; Smagghe et al. 1999), and ovicidal activity against some Lepidoptera has been reported (Biddinger et al. 1998, Dhadialla et al. 1998, Trisyono and Chippendale 1998, Pons et al. 1999, Knight 2000, Carlson et al. 2001). Exposure of adults to insecticides of this class can

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cause sublethal effects, reducing fecundity and egg viability (Biddinger and Hull 1999, Sun and Barrett 1999, Swevers and Iatrou 1999, Sun et al. 2000, Rodriguez et al. 2001). Because of the selective activity on target insects, the use pattern of these IGR insecticides may be different from broad-spectrum insecticides that primarily have contact or ingestion activity. Other potential benefits of methoxyfenozide and tebufenozide over some of the current insecticides registered for use in vineyards are longevity of activity and relative resistance to wash off under field conditions (Saunders et al. 2003, Wise et al. 2003). These properties may be important determinants of efficacy in eastern U.S. vineyards, where precipitation is common and oviposition by *E. viteana* often extends over a 4- to 6-wk period before harvest (R.I. and K.S.M., unpublished data).

The efficacy of new insecticides should be tested against different developmental stages of the target insect (in the laboratory and under field conditions) before their use at commercial scales, to determine the appropriate timing for application relative to the pest life cycle. Comparison of new products with currently available insecticides also provides a measurement of relative efficacy. We report results of bioassays to test the relative effectiveness of methoxyfenozide, tebufenozide, fenpropathrin, carbaryl, and azinphosmethyl against *E. viteana.* The assays were designed to assess the importance of timing applications before oviposition, after oviposition, or after egg eclosion. Controlled vineyard studies also were conducted to compare the effectiveness of these insecticides under field conditions.

Materials and Methods

Insect Colony. Moths, eggs, and larvae used in this study were obtained from a colony of *E. viteana* maintained in the Small Fruit Entomology Laboratory at Michigan State University. This colony was started in summer 2000 by collecting larvae and pupae from infested grapes from a commercial juice grape vineyard in Van Buren County, Michigan. To help preserve colony vigor, larvae from the same site were added to the colony each year. The colony was maintained using methods similar to those reported by Nagarkatti et al. (2000), and voucher specimens are deposited in the A. J. Cook Arthropod Research Collection at Michigan State University.

Insecticide Treatments. To prepare for laboratory bioassays, grapes were immersed in a weak bleach solution for 5 min and then washed with deionized water for 5 min and then dried in a fume hood. Grapes were treated with 100 ml of aqueous insecticide solutions, equivalent to field rates of formulated product in 934 liters of water per hectare (100 gal/acre). Chemicals, suppliers, and the quantities for preparation of solutions are given in Table 1. One-liter solutions at the same concentration were prepared for treating clusters in the vineyard experiment. Latron B (0.625 ml/liter; 8 fl. oz/100 gal) was used as a surfactant in treatments with tebufenozide and methoxyfenozide as recommended by the manufacturer. No surfactant was used in the other treatments, because preliminary studies showed that Latron-B had no effect on survival of grape berry moth eggs (K.S.M., unpublished data).

Table 1. Insecticides and rates used in laboratory and vineyard tests against *E. viteana*

Active ingredient	Trade name	Field rate[a] (amt/ha)	AI rate (g/ha)	AI concn[b] (mg/liter = ppm)
Untreated				
Tebufenozide	Confirm 2F[c]	1,169 ml	280	300
Methoxyfenozide	Intrepid 2F[c]	585 ml	140	150
Fenpropathrin	Danitol 2.4 EC[d]	775 ml	91	100
Azinphosmethyl	Guthion 50 WP[e]	1,681 g	840	900
Carbaryl	Sevin 80S[e]	2,802 g	2,242	2,400

[a] Field rates are taken from labeled rates.
[b] Concentration of dipping solutions.
[c] Dow Agrosciences, Indianapolis, IN.
[d] Valent, Walnut Creek, CA.
[e] Bayer CropScience, Research Triangle Park, NC.

Laboratory Preoviposition Treatment. Cages to allow oviposition on insecticide-treated grapes were constructed by rolling a 30 by 20-cm-wide strip of #16 mesh aluminum cloth into an 8.5-cm-diameter cylinder and sealing the seam with hot glue. One end of the cylinder was reinforced with a 5-cm band (8.5 cm in diameter) of 0.8-mm (30-mil) acetate sheeting stapled to the mesh. An 8.5-cm petri dish bottom was fastened to one end of the cage using sticky tape, providing a resealable opening for the cage. A 1.5-ml centrifuge vial filled with a 3-cm piece of moistened dental wicking (Absorbal, Wheat Ridge, CO) was attached to the inside of the cage to provide water for adult moths.

Cluster segments (four grapes) cut from prewashed clusters of table grapes were dipped for 5 s in a 100 ml aqueous solution of one of the six treatments described in Table 1 and allowed to dry for 8 h in a fume hood. Ten replicate cluster segments were dipped in each treatment. A cluster segment was suspended in a cage by wrapping foam weather-stripping around the rachis of the cluster and folding the top of the mesh cage around the weather stripping. One centimeter binder clips were clasped to the folded mesh to secure the top of the cage. Twenty adult *E. viteana* (50:50 sex ratio) were placed in each cage, which was then covered with an 8.5-cm petri dish. Cages were stored in an environmental chamber (23.5°C, 75% RH, and a photoperiod of 16:8 [L:D] h). After 48 h, moths and grapes were removed from the cages, and adult mortality and egg laying were assessed. Individual grapes were removed from the rachis and each was placed in a 4.5-cm petri dish containing molten Paraffin wax (≈50°C) (Royal Oak Sales Inc., Roswell, GA). Grapes were positioned in the wax so that 10–20 eggs were visible. A mark was made with a permanent marker on the grape near each egg to facilitate monitoring. Each dish was placed in a mesh-covered 473-ml (16-oz) plastic container and returned to the environmental chamber for eight additional days, and egg survival was assessed 10 d after treatment (DAT).

The number of eggs that eclosed, the number of dead eggs, and the number of visible dead larvae were then recorded. The proportion of eggs surviving in a replicate (referred to henceforth as egg survival) was calculated with the following formula: egg survival = $1 - ((E_D + L_{Din} + L_{Dout})/E_{Total})$, where E_D is the number of dead eggs, $L_{D\ in}$ is the number of dead larvae that did not emerge from eggs, $L_{D\ out}$ is the number of dead larvae outside of eggs on the grape surface, and E_{Total} is the total number of eggs laid on the surface of grapes in a cluster. Dead eggs were defined as those in which a white or yellowish mass formed within the egg, and no larval features were distinguishable. Eggs that were damaged in handling, and eggs suspected to be unfertilized (clear contents) were not included in the calculations.

Grapes with eggs and/or larvae that survived were returned to plastic containers, and two 2-cm^2 pieces of 0.04-mm (1.75-mil) plastic sheeting, a 3-cm length of moistened dental wicking, and 10–15 g of untreated grapes were added to the plastic containers. Containers were returned to the environmental chamber for 21–30 d, and the number of larvae that survived to the pupal stage was recorded. Larvae of *E. viteana* are highly cannibalistic, and grapes with multiple eggs typically support development of only one larva to pupation (K.S.M., unpublished data); therefore, treatment effects on larval survival to the pupal stage were analyzed as the proportion of replicates with at least one pupa, by using multiple comparison of proportions (Zar 1999). The proportion of adults surviving, average number of eggs per grape, the proportion of eggs that eclosed, and egg survival values were arcsine or log transformed as appropriate and analyzed by analysis of variance (ANOVA) with means separation by Fisher's protected least significant difference (PLSD) test (Statview 1996).

Laboratory Postoviposition Treatment. Grape clusters with *E. viteana* eggs laid on the surface (24–48 h old) were removed from the colony, and individual grapes were fixed in wax in separate petri dishes as described above. After the wax cooled to room temperature, dishes were dipped for 5 s in one of the treatments in Table 1, and this was replicated 10 times for each treatment. The dishes containing treated grapes were placed individually in plastic containers as described above and stored in a fume hood under constant overhead fluorescent lighting at 22°C and 50% RH. Egg survival was recorded as described for the preoviposition application. The proportion of eggs that eclosed and egg survival were arcsine transformed and analyzed by ANOVA with means separation by Fisher's PLSD (Statview 1996). Larval survival to the pupal stage was determined and analyzed as described above.

Laboratory Posteclosion Treatment. Grape clusters with *E. viteana* eggs laid on the surface (24–48 h old) were removed from the colony, and individual grapes were fixed in wax in separate petri dishes as described above. Dishes were stored in a fume hood under constant overhead fluorescent lighting at 22°C and 50% RH for 4 d or until most eggs had eclosed (at this point between 75 and 100% of the eggs had hatched). Individual grapes were then dipped for 5 s in one of the treatments listed in Table 1, placed in plastic containers as above and returned to the fume hood. We assumed the proportion of larvae that may have been washed off the grape surface during dipping was constant for all treatments. Grapes were dissected 7 DAT, and the number of surviving larvae was recorded. This was replicated 10 times for each treatment. For the reasons described in the previous section, data were analyzed as the proportion of replicates with at least one larva surviving, by using the multiple comparison of proportions (Zar 1999). There was no measure of survival to pupation for this experiment because treated grapes were destructively sampled to assess larval survival.

Vineyard Comparison of Field-Aged Insecticides. Insecticides were tested under vineyard conditions at Clarksville Horticulture Experiment Station in Clarksville, MI, on 3-yr-old *Vitis labrusca* (L.) variety Concord grapevines during summers 2001 and 2002. In both years, before the experiment multiple undamaged clusters from 20 vines were selected and marked with flagging tape. Vines did not receive fungicides or insecticides except for the treatments used in this experiment.

One-liter aqueous solutions of insecticides, at the concentrations described in Table 1, were prepared in 1-liter Nalgene bottles at the study site immediately before treatment. Solutions of each treatment were poured into separate open-topped 1-liter containers and raised from below the clusters to immerse them for 30 s in one of the six solutions. Limitations on the number of moths available for exposure to residues at each date necessitated dividing the eight replicates across four different treatment dates. Six clusters were prepared for each treatment on 8 August and 5 September 2001 and 19 July and 12 August 2002. This provided enough treated clusters for two replicates of each of three residue ages and untreated control clusters. After 1, 7, or 14 d of vineyard aging of the treatments, a metal screen cage was placed around the main stem (rachis) of treated clusters and sealed with weather stripping as described above, while leaving the cluster attached to the vine. Twenty adult moths (50:50 sex ratio) were added to each cage, and they were sealed with an 8.5-cm petri dish. The dish was taped firmly to the cage with duct tape and packing twine was used to secure the cage to the trellis in a horizontal orientation to minimize the moths being trapped in the tight corners of the cage and to prevent damage to the rachis. After adults were caged with clusters for 7 d, the clusters and cages were cut from the vine and transported intact to the laboratory where adult survival and oviposition were assessed.

On each berry, the location of each egg was marked with a permanent marker to simplify counting. Individual clusters were then placed in a 473-ml (16-oz) plastic container with a 3-cm piece of moistened dental wicking. The grapes were covered with five two by 10-cm strips of 0.04-mm (1.75-mil) plastic for pupation. One hundred grams of table grapes (20–25 ber-

Table 2. Mean ± SE survival of *E. viteana* adults and oviposition on grapes treated with different insecticides

Treatment	% adult survival	Eggs/grape
Untreated	87.0 ± 3.3a	16.5 ± 3.9a
Tebufenozide	82.7 ± 3.6a	9.7 ± 3.3ab
Methoxyfenozide	82.0 ± 3.2a	8.6 ± 3.3ab
Fenpropathrin	19.3 ± 4.5b	0.1 ± 0.1d[a]
Azinphosmethyl	24.5 ± 5.9b	2.4 ± 1.4cd
Carbaryl	37.2 ± 8.8b	2.5 ± 0.7bc

Means in a column followed by the same letter are not significantly different ($P > 0.05$).

[a] Eggs were laid on fenpropathrin-treated grapes in only two replicates (four eggs total) and none of these eggs survived to eclosion.

Table 3. Mean ± SE percentage of *E. viteana* egg eclosion on grapes treated with different insecticides either before or after oviposition

Treatment	% egg eclosion	
	Preoviposition	Postoviposition
Untreated	93.3 ± 2.1a	79.5 ± 9.8a
Tebufenozide	74.4 ± 10.2ab	73.7 ± 6.4a
Methoxyfenozide	57.2 ± 11.8b	77.2 ± 7.0a
Fenpropathrin	0.0 ± 0.0c[a]	7.1 ± 3.6b
Azinphosmethyl	9.1 ± 7.1c	26.7 ± 6.8b
Carbaryl	61.4 ± 11.5b	74.7 ± 5.9a

Means in a column followed by the same letter are not significantly different ($P > 0.05$).

[a] Eggs were laid on fenpropathrin-treated grapes in only two replicates (four eggs total).

ries) was added to each container to provide additional food for developing larvae. Containers were then covered with mesh and held in an environmental chamber (25°C, 75% RH, and a photoperiod of 16:8 (L:D) h) until larvae no longer pupated (21–30 d). Survival was measured by counting the number of pupae and adults that emerged in each container. For each residue age, the proportion of surviving adults, the number of eggs per cluster, and proportion of F_1 survival were arcsine or log transformed as appropriate and analyzed with ANOVA and means separation by Fisher's PLSD (Statview 1996).

Results

Laboratory Preoviposition Application. All of the broad-spectrum insecticides significantly decreased adult survival compared with the untreated control ($F = 29.39$; df = 5, 54; $P < 0.0001$; Table 2), and they also caused a significant reduction in oviposition ($F = 8.13$; df = 5, 54; $P < 0.0001$; Table 2). In contrast, both IGRs did not cause significant mortality to adults and did not reduce oviposition compared with the untreated control. Ten days after oviposition, there were significant differences among treatments in the proportion of eggs that eclosed (Table 3) ($F = 10.25$; df = 5, 37; $P < 0.0001$). All broad-spectrum insecticides significantly reduced egg eclosion compared with the untreated control. Fenpropathrin completely prevented egg eclosion in all replicates, and azinphosmethyl significantly reduced egg eclosion compared with carbaryl, methoxyfenozide, and tebufenozide (Table 3). Methoxyfenozide significantly reduced the proportion of eggs that eclosed compared with the control and the magnitude of this effect was similar to that on carbaryl-treated grapes (Table 3). Egg survival was significantly different among treatments ($F = 9.63$; df = 5, 34; $P < 0.0001$) and was significantly reduced in the methoxyfenozide, carbaryl, azinphosmethyl, and fenpropathrin treatments compared with survival in the untreated control (Fig. 1). Additionally, azinphosmethyl and fenpropathrin significantly reduced egg survival compared with tebufenozide, methoxyfenozide, or carbaryl treatments (Fig. 1). The proportion of replicates in which larvae feeding on treated grapes completed pupation was significantly lower for methoxyfenozide and azinphosmethyl treatments compared with the untreated control (Table 4). Pupal survival in carbaryl and tebufenozide treatments was not significantly different from the untreated control, methoxyfenozide, or azinphosmethyl treatments (Table 4). Eggs were laid on grapes treated

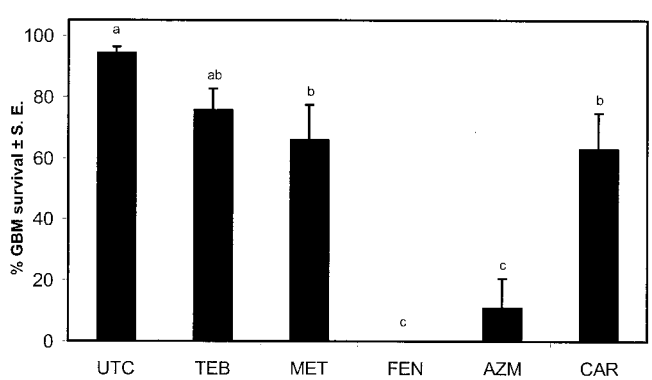

Fig. 1. Mean survival (±SE) of *E. viteana* eggs through to larvae, 10 d after the eggs were laid onto grapes treated with different insecticides or a water control. Columns with the same letter above are not significantly different ($P > 0.05$). Eggs were laid on fenpropathrin-treated grapes in only two replicates, and no eggs survived to eclosion. Treatments include UTC, untreated control; TEB, tebufenozide; MET, methoxyfenozide; FEN, fenpropathrin; AZM, azinphosmethyl; and CAR, carbaryl.

Table 4. Average proportion (p) of replicates with at least one *E. viteana* larva surviving when insecticide applications were made before oviposition, after oviposition but before eclosion, or after eclosion

Treatment	Preoviposition		Postoviposition		Posteclosion	
	n	*p*	*n*	*p*	*n*	*p*
Untreated	10	0.90a	10	0.8a	10	0.7a
Tebufenozide	9	0.33ab	10	0.0b	10	0.1b
Methoxyfenozide	8	0.13b	10	0.0b	10	0.0b
Fenpropathrin	0[a]	-	5	0.0b	10	0.0b
Azinphosmethyl	5	0.0b	10	0.0b	10	0.33ab
Carbaryl	8	0.63ab	10	0.0b	10	0.33ab

Survival was measured at pupation in the pre- and postoviposition experiments and at 7 d after application in the posteclosion experiments. Means in a column followed by the same letter are not significantly different ($P > 0.05$).

[a] No eggs survived on fenpropathrin-treated grapes.

with fenpropathrin in only two replicates and none of these eggs eclosed, so there was no measure of pupal survival for this treatment (Table 4).

Laboratory Postoviposition Application. When insecticides were applied to eggs laid on the surface of grapes, there were significant differences among treatments in the proportion of eclosed eggs ($F = 13.79$; df = 5, 54; $P < 0.0001$), and fenpropathrin and azinphosmethyl significantly reduced the proportion of eggs that eclosed compared with all the other treatments (Table 4). A significant treatment effect was detected for egg survival (Fig. 2) ($F = 20.29$; df = 5, 54; $P < 0.0001$). Fenpropathrin, azinphosmethyl, and carbaryl caused a significant reduction in survival of *E. viteana* eggs to larvae compared with the untreated control, and fenpropathrin and azinphosmethyl reduced egg survival to a greater extent than either of the IGRs (Fig. 2). There was no significant reduction in egg survival after application of either tebufenozide or methoxyfenozide compared with the untreated control (Fig. 2). Although there was considerable variation among treatments in the degree of toxicity to eggs and early instar *E. viteana* larvae (Fig. 2), no larvae survived to pupation in any of the insecticide treatments (Table 4).

Laboratory Posteclosion Application. When insecticides were applied after larvae emerged and began to penetrate the berry surface, there was a significant reduction in larval survival 7 DAT in the grapes treated with either of the IGRs or fenpropathrin compared with the untreated control, but larval survival in azinphosmethyl or carbaryl treatments was not significantly reduced (Table 4). No significant differences were found in the survival of larvae among any of the insecticide treatments; however, methoxyfenozide and fenpropathrin completely prevented the maturation of larvae (Table 4).

Vineyard Comparison of Field-Aged Insecticides. Adult survival was low (7.3 ± 2.6% overall) after 1-wk of caging on grape clusters, in comparison with the bioassays described above. This may be because caged moths were unable to take refuge from high temperatures and rain that may have occurred in the cages. Adult survival was not significantly affected by the presence of any insecticide residues, even when residues were 1 d old (Table 5). Adult survival within treatments did not consistently increase as residues aged, and in many treatments survival on older, less active residues was lower than that on younger residues.

Despite low adult survival, an average of 66.1 ± 16.0 eggs were laid by *E. viteana* adults (10 mating pairs per replicate) on untreated clusters during 7 d of exposure. Insecticide treatments affected the number of eggs laid only when residues were 1 d old ($F = 11.01$; df = 5 42; $P < 0.0001$). One-day-old residues of all the broad-spectrum insecticides and methoxyfenozide significantly reduced oviposition compared with the untreated control (Table 5). The largest reduction in egg laying (compared with the untreated control) occurred on fenpropathrin-treated clusters (98.9%), followed by carbaryl (94.3%), azinphosmethyl (77.3%), and methoxyfenozide (62.9%). One-day-old residues of tebufenozide did not result in a significant reduction in egg laying (Table 5). After insecticide residues were aged for 7 d in the vineyard, egg laying was not significantly reduced in any treatment, despite a 91% average reduction in egg laying by fenpropath-

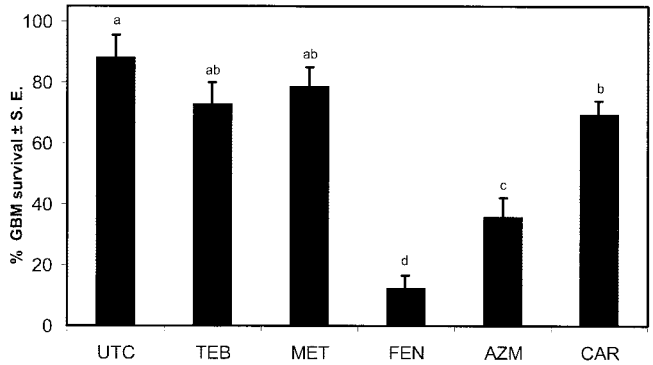

Fig. 2. Mean survival (±SE) of *E. viteana* eggs through to larvae, 10 d after the eggs were treated with different insecticides or a water control. Columns with the same letter above are not significantly different ($P > 0.05$). Treatment abbreviations are the same as Fig. 1.

Table 5. Average ± SE adult survival, oviposition, and larval survival of *E. viteana* on grape clusters treated with different insecticides, after residues were aged in a vineyard for 1, 7, or 14 d

Treatment	1 DAT	7 DAT	14 DAT
% adult survival			
Untreated	11.25 ± 5.07a	7.50 ± 5.67a	3.13 ± 2.10a
Tebufenozide	14.37 ± 7.35a	9.38 ± 4.01a	0.63 ± 0.63a
Methoxyfenozide	6.25 ± 3.24a	10.00 ± 5.77a	3.57 ± 1.43a
Fenpropathrin	0.63 ± 0.63a	7.50 ± 3.13a	1.25 ± 0.81a
Azinphosmetyl	2.50 ± 1.90a	5.71 ± 5.71a	3.13 ± 1.62a
Carbaryl	1.89 ± 1.32a	2.50 ± 2.50a	2.14 ± 1.49a
Eggs/cluster			
Untreated	44.13 ± 12.32a	88.75 ± 35.76a	65.38 ± 34.75a
Tebufenozide	35.25 ± 11.19ab	54.63 ± 24.28a	69.13 ± 24.93a
Methoxyfenozide	16.38 ± 5.07b	54.00 ± 20.56a	57.00 ± 15.38a
Fenpropathrin	0.50 ± 0.38c	8.00 ± 4.72a	83.00 ± 34.13a
Azinphosmethyl	10.00 ± 7.66c	54.86 ± 33.79a	68.00 ± 33.57a
Carbaryl	2.50 ± 1.14c	65.88 ± 31.28a	84.14 ± 23.58a
% F_1 survival			
Untreated	7.63 ± 2.73a	16.78 ± 4.12a	25.53 ± 11.12a
Tebufenozide	1.37 ± 0.67a	0.00 ± 0.00a	4.28 ± 4.05a
Methoxyfenozide	3.90 ± 3.90a	2.50 ± 2.50a	2.76 ± 2.50a
Fenpropathrin	0.00 ± 0.00a	2.08 ± 2.08a	5.67 ± 3.49a
Azinphosmethyl	0.95 ± 0.95a	5.23 ± 2.61a	8.83 ± 3.91a
Carbaryl	3.57 ± 3.57a	9.77 ± 7.09a	11.55 ± 6.57a

Means in a column followed by the same letter are not significantly different ($P > 0.05$).

rin compared with the untreated control (Table 5). There was no significant protection from egg laying by any of the treatments once residues were aged for 14 d (Table 5).

When *E. viteana* eggs from clusters treated in the vineyard were reared through to pupae or adults in the laboratory, untreated clusters always supported numerically greater survival of *E. viteana* than the insecticide-treated clusters, but no significant differences in F_1 survival were detected among treatments for residues at any age.

Discussion

Under laboratory and vineyard conditions the IGR insecticides methoxyfenozide and tebufenozide were effective at killing immature stages, but not adults, of *E. viteana.* Methoxyfenozide was more active than tebufenozide, even though the field equivalent rate of active ingredient was one-half that of tebufenozide. Higher toxicity of methoxyfenozide than tebufenozide has been shown previously for European corn borer, *Ostrinia nubilalis* (Hübner) (Trisyono and Chippendale 1997) and southwestern corn borer, *Diatraea grandiosella* Dyar, (Trisyono and Chippendale 1998). Methoxyfenozide was ovicidal (as measured by percentage of egg eclosion) when eggs were laid on treated grapes but not when treatments were applied after oviposition. In contrast, ovicidal activity of comparable rates of methoxyfenozide applied after oviposition has been reported for *O. nubilalis* (Trisyono and Chippendale 1997). The reason for the relative lack of ovicidal activity of methoxyfenozide when applied after egg laying is not known, but our results suggest that immature *E. viteana* eggs are more permeable or sensitive to methoxyfenozide than eggs that are 1–2 d old. A similar difference in response to treatment timing was demonstrated by Pons et al. (1999) who showed the toxicity of tebufenozide was 30 times greater when eggs of codling moth, *Cydia pomonella* (L.), were laid on sprayed leaves compared with eggs treated after oviposition.

The reduction of egg laying by *E. viteana* on grapes treated with either growth regulator insecticide under laboratory and vineyard conditions suggests there may be sublethal effects on adults that limit oviposition, similar to that described for *C. pomonella* (Sun and Barrett 1999, Knight 2000), and for redbanded leafroller, *Argyrotaenia velutinana* (Walker), and obliquebanded leafroller, *Choristoneura rosaceana* (Harris) (Sun et al. 2000). It is possible the surfactant Latron B (used with both growth regulators in our experiments) may have reduced oviposition of *E. viteana,* but Knight (2000) has previously shown no effect on oviposition when male and female *C. pomonella* were exposed to Latron B-treated surfaces. Whether Latron-B reduced oviposition in the current study is not known. Reduced responsiveness to females has been documented in male *A. velutinana* (Hoelscher and Barrett 2003a) and *C. pomonella* (Hoelscher and Barrett 2003b) when exposed to methoxyfenozide-treated surfaces, and this mechanism also may explain reduced oviposition in this study.

The rate of tebufenozide used in this study was not toxic against *E. viteana* eggs. This differs from previously reported results such as work on the tufted apple bud moth, *Platynota idaeusalis* (Walker), in which Biddinger et al. (1998) showed that treating egg masses in tebufenozide solutions as low as 9–90 ppm significantly reduced egg survival. Similarly, dipping eggs in tebufenozide solutions between 100 and 200 ppm has been shown to kill eggs of *O. nubilalis* (Trisyono and Chippendale 1997), *D. grandiosella* (Trisyono and Chippendale 1998), and the sugarcane borer, *Diatraea saccharalis* (F.) (Rodriguez et al. 2001). However for *C. pomonella,* significant reductions in egg survival were seen only after dipping eggs in tebufenozide solutions of at least 300 ppm (Pons et al. 1999, Knight 2000). The reason for the differences in ovicidal activity of this compound among species is not known, but Pons et al. (1999) suggested the chorion of eggs laid on leaves may be more permeable than those laid on fruit due to the higher humidity in the microclimate of the boundary layer of leaves. Mortality of mature *E. viteana* eggs may require a rate of tebufenozide that is prohibitively expensive, and the recent registration of methoxyfenozide (Intrepid) for use in vineyards against *E. viteana* renders tebufenozide (Confirm) almost obsolete for this crop in the United States.

Egg survival was reduced by methoxyfenozide when applied before oviposition, but survival was not reduced when application was made after oviposition before egg eclosion. In both conditions, active insecticide residues were present on the grape surface before egg eclosion, so the reduced survival in the preoviposition assessments suggests the chorion of a newly deposited egg is more penetrable by methoxy-

fenozide. Once inside the egg, the toxin may be taken up by the developing embryo, and this exposure combined with that during berry penetration may be sufficient to kill the larva by stimulating a premature first molt. Larvae exposed to either tebufenozide or methoxyfenozide were able to penetrate the berry surface and feed inside the berry, suggesting that if these products are used for *E. viteana* control, berries may become susceptible to opportunistic diseases. However, additional experiments are needed to determine at what instar larvae are dying in methoxyfenozide treatments, and whether fruit penetration by larvae incurred before the larvae die affects disease, yield, and marketability of grapes.

Methoxyfenozide was effective at preventing survival to pupation in the preoviposition and postoviposition laboratory experiments. This result is similar to bioassays of several species of larvae raised on diet containing methoxyfenozide (Carlson et al. 2001). S*podoptera exigua* (Hübner) and *Chilo suppressalis* (Walker) were similarly sensitive to these compounds during larval development (Smagghe et al. 1999). In the current study, sublethal effects were not addressed, and it is not known whether pupae from methoxyfenozide-treated grapes would emerge as adults or whether those adults would produce similar numbers of viable offspring as untreated insects. Methoxyfenozide and tebufenozide reduced larval survival when these compounds were applied during the period when larvae were entering the berry. The greater performance of these compounds when applied after egg eclosion compared to the postoviposition application may have been because the insecticides reached the internally feeding larvae through the feeding holes. A larva already inside the berry may then have ingested a larger dose of insecticide than if the insecticide was only on the grape surface.

In general, broad-spectrum insecticides were highly active against multiple life stages, performing better than the IGRs, particularly in laboratory bioassays. Fenpropathrin and azinphosmethyl consistently caused mortality of adults, eggs, and developing larvae, but carbaryl was generally less effective. Carbaryl resistance has been demonstrated in *E viteana* populations in Pennsylvania (Nagarkatti et al. 2002), but whether the relatively poor performance of carbaryl in our experiments is evidence of resistance to this compound in Michigan is not known. Significant reduction in egg laying associated with high adult mortality was found for all three broad-spectrum insecticides. Because of this and the contact activity of these compounds against eggs and first instars, *E. viteana* are much less likely to penetrate the berry surface if it has a residue of one of these broad-spectrum insecticides.

Fenpropathrin was the most active compound used in the experiments described above, with fresh residues of this insecticide almost completely preventing egg laying in the laboratory and vineyard assays, killing adults and larvae of *E. viteana.* The extremely high activity of fenpropathrin on this and other pest species makes this an attractive pest management option, but its activity on nontarget organisms results in its suitability for only specific situations.

Although high efficacy of the organophosphate insecticide azinphosmethyl and to a lesser extent the carbamate insecticide carbaryl was demonstrated against *E. viteana* in these experiments, restrictions on the use of these classes of insecticides in response to FQPA are expected to further limit how these compounds can be incorporated into *E. viteana* management programs. For example, azinphosmethyl is no longer manufactured for use in grapes, and other broad-spectrum insecticides are under review by the U.S. Environmental Protection Agency. The loss of these effective insecticides makes the evaluation of reduced risk insecticides a high priority so insect pests can be kept below economic thresholds. Based on the present work, methoxyfenozide has the greatest utility if applied before the peak of the 4–6 wk egg-laying period by *E. viteana* seen in recent years before harvest (R.I. and K.S.M., unpublished data). Applications made at this timing would ensure active residues are on the grape surface before the majority of egg laying to reduce survival of eggs and first instars. Future vineyard integrated pest management programs that use IGRs for control of *E. viteana* would be expected to contribute to the conservation of natural enemies, reduce worker exposure to toxic residues, decrease environmental impacts, and decrease the risk of broad-spectrum insecticide residues in harvested fruit.

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