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Spatially Targeted Applications of Reduced-Risk Insecticides for Economical Control of Grape Berry Moth, *Paralobesia viteana* (Lepidoptera: Tortricidae)

Keith S. Mason,[1,2] Craig R. Roubos,[1,3] Luis A.F. Teixeira,[1,4] and Rufus Isaacs[1]

[1]Department of Entomology, Michigan State University, East Lansing, MI 48824 (masonk@msu.edu; craigroubos@gmail.com; luis.a.teixeira@usa.dupont.com; isaacsr@msu.edu), [2]Corresponding author, e-mail: masonk@msu.edu, [3]Current Address: Emergent BioSolutions, 3500 N Martin Luther King Jr Blvd., Lansing, MI 48906, and [4]Current Address: DuPont Crop Protection, Stine-Haskell Research Center, 1090 Elkton Rd., Newark, DE 19711

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Abstract

The grape berry moth, *Paralobesia viteana* Clemens (Lepidoptera: Tortricidae), is a key economic pest of vineyards in eastern North America, and prevention of fruit infestation is particularly challenging along vineyard borders that are adjacent to wooded areas containing wild grape (*Vitis* spp.). For three years, infestation and damage in vineyards where reduced-risk insecticides were applied to borders at timings based on a degree day model (Integrated Pest Management program) were compared to that in vineyards where broad-spectrum insecticides were applied across the whole vineyard (Standard program). Infestation at vineyard borders immediately prior to harvest was consistently lower in IPM vineyards than in Standard program vineyards, and in two of the years this was also true at veraison (fruit coloring). Grape berry moth infestation was similar between treatments at vineyard interiors throughout the study, despite no insecticide applications to the interiors of the IPM program vineyards. Populations of two other key vineyard pests, the eastern grape leafhopper, *Erythroneura comes* (Say) (Hemiptera: Cicadellidae), and Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae), were not significantly different between programs, and natural enemy captures on yellow sticky traps were also similar. The per hectare cost of insecticides applied in the IPM program was consistently lower than for the Standard program, with a significant difference in the third year of this study. We demonstrate how spatially selective applications of reduced-risk insecticides can provide improved control of grape berry moth at lower cost than standard broad-spectrum insecticide-based programs.

Key words: integrated pest management, methoxyfenozide, chlorantraniliprole, natural enemy, border spray

Noncrop habitats adjacent to agricultural land may harbor alternative hosts for crop pests, and can act as refuges that support unmanaged pest populations (Marshall and Moonen 2002). This can then also increase the likelihood of pest immigration into the crop, resulting in greater pest damage along crop borders (Pickett et al. 1990, Lavallée et al. 1996). In these situations, insecticide may be used to minimize damage and reduce the chance of pest penetration deeper into the crop. Spatially targeting control efforts where pests are present has the potential benefits of reduced environmental impact and effects on nontarget species from decreased pesticide use (Vincent et al. 1997, MacHardy 2000, Leskey et al. 2008) and reduced management costs (Trimble et al. 2001, Weigle and Carroll 2010). Spatially targeting pesticide applications is also expected to reduce negative impacts on natural enemies and improve agricultural worker safety.

Grape berry moth is a monophagous herbivore that is found in woods and vineyards in eastern North America (Johnson and Hammar 1912). It is a specialist on plants in the genus *Vitis*, including several species of wild grape that are common in deciduous woods in this region (Morano and Walker 1995). In cultivated grapes, infestation by this pest is higher in vineyards adjacent to deciduous woods that contain wild grape, and infestation is consistently greater at wooded borders compared to vineyard interiors (Hoffman and Dennehy 1989, Trimble 1993, Botero-Garcés and Isaacs 2003, Roubos et al. 2013). If left unmanaged, grape berry moth can cause 100% infestation of the clusters on vineyard borders by the time of harvest, and larval contamination of the harvested fruit can lead to rejection of the crop by processors or wine makers (Isaacs et al. 2012a). As a result of this risk, grape berry moth is the primary insect pest of grape production in many regions of viticulture in eastern North America, and is the target for the majority of insecticide applications to vineyards across this region (Teixeira et al. 2009).

The passage of the US Food Quality Protection Act in 1996 created the mandate for the US Environmental Protection Agency to review the use of broad spectrum insecticides in food and fiber crops (Anonymous 1996). As a result, there have been restrictions or bans on the use of organophosphate and carbamate insecticides in US grape production over the last decade. During the same period the development and registration of new classes of insecticides has given rise to some effective options for insect management. Insect growth regulators (IGRs), such as the molting hormone agonist methoxyfenozide, are active on lepidopteran eggs and young larvae and must be applied with correct timing to target these susceptible stages (Isaacs et al. 2005). Methoxyfenozide is extremely effective against grape berry moth and other moth pests without disrupting biological control (Carton et al. 2003, Borchert et al. 2004, Schneider et al. 2004, Jenkins and Isaacs 2007, Teixeira et al. 2009). Anthranilic diamides such as chlorantraniliprole interfere with ryanodine receptor function, and are effective against eggs and larvae of moth pests (Hannig et al. 2009, Ioriatti et al. 2009), while also providing selectivity that can support biological control. However, reduced-risk insecticides tend to be more expensive, require different use patterns and are active on a narrower range of insects than conventional insecticides (Ware 2000, Isaacs, et al. 2012b, Roubos et al. 2014), and these factors have limited adoption by grape growers. The challenge is to develop integrated pest management (IPM) programs that can effectively control target pests while also reducing pesticide use and the cost of control programs.

As most reduced risk insecticides are not effective on all life stages of target pests, timing applications for appropriate periods in a pest's phenology is an important part of achieving control. Degree-day based phenological models have been developed for many insect pests, and these models have been incorporated into IPM programs for several important species (Pruess 1983). A model that predicts the start of egglaying by the middle and late-season generations of grape berry moth has been developed and is available online for use by growers and crop consultants (Teixeira et al. 2009). This model uses river-bank grape (*V. riparia* L.) bloom as a biofix, and based on degree-day accumulations (base 8.4°C) at a network of weather stations, the model allows users of the www.enviroweather.msu.edu website to select the nearest location to time the application of insecticides for grape berry moth management. Timing insecticide applications is important for optimizing control, and spatially targeting chemical controls can also reduce pesticide use and associated operating costs (Weigle and Carroll 2010). Targeting pesticide applications to areas with a high risk of infestation would also create unsprayed refuges for natural enemies, and this could indirectly increase biological control in both sprayed and unsprayed areas of the crop. However, untreated refuges may also allow populations of secondary pests to increase over time to economically damaging levels.

The overall goal of this study was to determine the utility and economic feasibility of border applications of reduced-risk insecticides for grape berry moth management. The specific objectives were to compare: 1) the efficacy of grape berry moth control when reduced-risk insecticides are applied only to areas of high pest pressure (i.e. vineyard borders) versus a standard management program that uses broad spectrum insecticides applied to the entire vineyard; 2) the abundance of nontarget insects in the two management programs; and 3) the costs of the two management programs.

Materials and Methods

Study Sites

This study was conducted over three seasons at four (2009 and 2011) or five (2010) southwest Michigan juice grape farms. At each farm we chose two 0.8 to 3.6 ha 'Concord' vineyards with similar history of grape berry moth infestation. All vineyards were mature (>10 yr) plantings with 3 m row and 3 m vine spacing and received either a Standard or IPM program for insect control (Table 1), and at each farm the same standard fungicide program was applied to both vineyards. In vineyards that received the IPM program, trellis rows were oriented parallel to an adjacent wooded edge to allow application of insecticides to high pressure areas during routine fungicide sprays. Standard vineyards had rows oriented either parallel or perpendicular to adjacent woods. The Standard program was composed of broad-spectrum insecticides applied to the entire vineyard, whereas in the IPM program, reduced-risk insecticides were applied to areas with the highest insect pressure, i.e. vineyard borders adjacent to woods containing wild grapevines. Vineyard borders ranged from 86 to 239 m in length and were ten rows of vines (27 m) deep, adjacent to woods. This resulted in vineyard border areas that ranged from 0.2 to 0.6 ha. Border sprays were applied to IPM vineyards during routine fungicide applications, by mixing enough fungicide solution to treat the entire IPM vineyard starting with the rows farthest from the woods. When the border area was reached, the correct amount of insecticide was manually added to the spray tank and this was applied to the border area. Grower cooperators applied all pesticides for this study using their own equipment that included airblast, tower and fan-assisted sprayers. Mid-season and late season application timings for both programs were based on predicted first dates of grape berry moth oviposition calculated from the Grape Berry Moth Predictive Model found at the MSU Enviroweather website (Isaacs 2015). In 2009, two growers applied acetamiprid (0.11 kg AI/ha) for control of eastern grape leafhopper or Japanese beetle, and one grower used flubendiamide (0.14 kg AI/ha) in place of chlorantraniliprole in 2011. These applications were included in the per hectare insecticide costs described below.

Damage Assessments

We assessed all vineyards for grape berry moth infestation three times each year based on phenological stages of the grape vines: postbloom (14 June to 7 July), veraison (16 to 30 August) and preharvest (26 August to 29 September). At each sample date, we recorded the number of grape berry moth damaged clusters and the total number of damaged berries on five haphazardly selected clusters on each of 10 vines directly adjacent to woods (50 clusters total). The same number of similarly chosen clusters was assessed on 10 interior vines 50 m from the vineyard border. Sampled vines were separated by at least 30 m and were chosen to include the entire width of the vineyard.

Nontarget Insects

During 2010 and 2011 we compared the effect of the two programs on other economically important grape pests by recording the incidence of those insects. On the same dates and the same vines that we sampled for grape berry moth damage, we recorded the presence or absence of eastern grape leafhopper, *Erythroneura comes* (Say) (Hemiptera: Cicadellidae) on five mature leaves per vine. The presence or absence of Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae) on the whole vine was recorded for the same vines that were sampled for grape berry moth damage (10 vines per location).

Table 1. Insecticide programs compared for their performance against grape berry moth in southwest Michigan vineyards in 2009–2011

Timing[a]	Standard program		IPM Program	
Postbloom	Bifenthrin[b] (0.28 kg/ha AI)	Whole vineyard	Bifenthrin + imidacloprid (0.39 kg/ha AI)	Whole vineyard
Mid-season	Carbaryl (4.5 kg/ha) 500 GDD[c]	Whole vineyard	Methoxyfenozide (0.14 kg/ha AI) 460 GDD[c]	Border[d] only
Preharvest	Phosmet (1.57 kg/ha) 960 GDD[c]	Whole vineyard	Chlorantraniliprole[e] (0.21 kg/ha AI) 900 GDD[c]	Border[d] only

[a] Grape Berry Moth Predictive Model on MSU Enviroweather was used to time applications.

[b] In 2011 zeta-cypermethrin + bifenthrin (0.39 kg/ha AI) was used in place of bifenthrin in the Standard Program.

[c] Growing Degree Days (GDD) from wild grape (Vitis riparia) bloom using a base temperature of 8.41°C.

[d] Border = 0.6 to 1.5 ha of vineyard adjacent to a woodlot (~10 rows).

[e] One grower used flubendiamide in place of chlorantraniliprole in 2011.

To determine the effect of the insecticide programs on natural enemy populations, four 28 by 46cm yellow sticky traps (Great Lakes IPM, Vestaburg, MI) were placed at least 50 m apart in each vineyard. Two traps were hung from the trellis wire on the vineyard border and two in the field interior, following the methods of Jenkins and Isaacs (2007). Yellow sticky traps were replaced every two weeks from early May to the end of September, for a total of eight samples per season. Collected traps were returned to the lab, stored in a freezer (−5°C) and assessed during the fall and winter of each year. Natural enemies captured on traps were identified to order or family using basic keys for insect identification (Borror and White 1970, Dunn 1996) and the number of insects per trap from each taxon was recorded.

Insecticide Costs

Data on insecticide use was obtained for each vineyard from the growers' pesticide application records. Insecticide costs were derived by averaging prices obtained each year from agrichemical distributors in southwest Michigan. These data were used to calculate a per-hectare cost of insecticide for each vineyard by taking the total cost of all insecticides applied to that vineyard divided by the area of the vineyard. For the spatially-targeted IPM program this resulted in the cost of insecticide being spread across the whole area of the vineyard that was treated only on the border.

Data Analysis

All statistical analyses were performed using SYSTAT version 12.02 (SYSTAT 2007, San Jose, CA). The number of grape berry moth infested berries per 100 clusters was square root transformed to stabilize variance and compared between programs using one-way analysis of variance. Due to the well-documented evidence of the difference between grape berry moth infestation at wooded borders compared to infestation in vineyard interiors (Hoffman and Dennehy 1989, Trimble 1993, Botero-Garcés and Isaacs 2003, Roubos et al. 2013) we chose to compare grape berry moth infestation between programs at border and interior locations separately at each damage assessment. In addition, to determine whether vineyard row orientation affected grape berry moth infestation, we pooled data from Standard vineyards over the three years of this study, and compared infestation in vineyards with rows oriented parallel to the adjacent wooded edge to that in vineyards with rows perpendicular to the wooded edge using one-way analysis of variance, with vineyards as replicates. The total number of each natural enemy group trapped was square root transformed and compared each season between programs using one-way ANOVA. Due to the nonnormality of the data, the presence of nontarget pests was compared between programs with a Kruskal-Wallis test. Per hectare insecticide costs for each season were compared between programs with one-way ANOVA using square root transformed data.

Results

Grape Berry Moth Damage and Infestation

Over the three years of this study and at each damage assessment on vineyard borders, the number of grape berry moth damaged berries was lower in vineyards treated with the IPM program compared to vineyards treated with the Standard program (Fig. 1). In 2009 this difference was statistically significant at the preharvest assessment ($F = 7.0$; df = 1, 6; $P = 0.04$). In 2010, the number of GBM damaged berries was significantly lower at veraison ($F = 9.5$; df = 1, 8; $P = 0.02$) and preharvest timings ($F = 4.9$; df = 1,8; $P = 0.05$). Similarly, in 2011 grape berry moth berry damage was significantly lower in the IPM-treated vineyards at the veraison ($F = 10.2$; df = 1, 6; $P = 0.02$) and preharvest samples ($F = 5.8$; df = 1, 6; $P = 0.05$). Inside vineyards, damage from grape berry moth was considerably lower than at borders regardless of treatment program (Fig. 1), and there were no significant differences between the programs at any of the assessment timings. Row orientation did not significantly affect grape berry moth infestation; damage at either border or interior locations in Standard vineyards with rows oriented parallel to adjacent woods was similar to that in Standard vineyards with rows perpendicular to adjacent woods (Border: $F < 0.54$; df = 1, 11; $P > 0.48$; Interior: $F < 1.43$; df = 1, 11; $P > 0.27$).

Nontarget Insects

In 2010 and 2011, the number of leaves with grape leafhoppers present was lower in IPM-treated vineyards, but not significantly different from vineyards treated with the Standard program (Table 2). In addition, there were no significant differences in the number of vines with Japanese beetles between IPM and Standard programs in any of the sampling years (Table 3).

Insects in nine natural enemy groups were caught on yellow sticky traps in all three seasons. Parasitic wasps that included members of the Braconidae, Ichnuemonidae, and Chalcidae, comprised the most abundant group trapped in all three years. There were no statistical differences detected between programs in the abundance of any natural enemy group (Table 4), indicating similar effects of the two programs on beneficial insects (Kruskal Wallis; df = 1; $P > 0.05$ for all groups).

Insecticide Costs

All insecticides that were applied to the study vineyards were included in this analysis. In all three years and at all except one farm in 2009, the per-hectare insecticide cost in vineyards that received the IPM Program was lower than that for the Standard Program

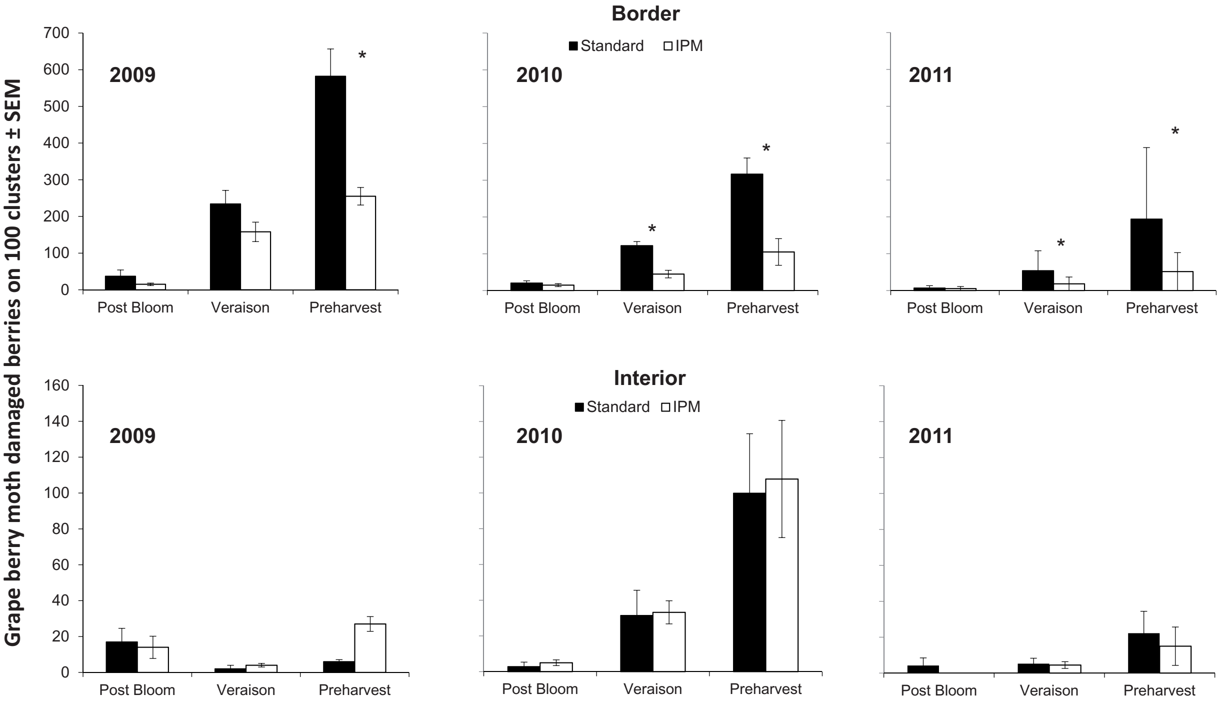

Fig. 1. Grape berry moth damage in three years at border and interior locations in southwest Michigan vineyards treated with an IPM or standard insecticide program. Asterisks denote mean values that are significantly different ($P < 0.05$). No significant differences were detected between programs in vineyard interiors in any sample.

Table 2. Mean (± SEM) number of eastern grape leafhopper infested leaves (per 150 leaf sample) in two years at border and interior locations in southwest Michigan vineyards treated with an IPM or standard insecticide program

Location	2010		2011	
	Standard	IPM	Standard	IPM
Border	1.6 ± 0.7	1.2 ± 1.0	5.0 ± 5.0	0.0 ± 0.0
Interior	0.6 ± 0.4	0.2 ± 0.2	0.5 ± 0.3	0.3 ± 0.2

No significant differences were detected between programs in either year (Kruskal–Wallis test, df = 1, $P > 0.05$).

Table 3. Mean (± SEM) number of vines with Japanese beetle present (per 30 vine sample) in two years at border and interior locations in southwest Michigan vineyards treated with an IPM or standard insecticide program

Location	2010		2011	
	Standard	IPM	Standard	IPM
Border	8.2 ± 3.5	4.8 ± 2.3	1.0 ± 0.7	4.5 ± 2.5
Interior	3.8 ± 2.6	3.8 ± 2.2	1.0 ± 0.4	4.3 ± 2.7

No significant differences were detected between programs in either year (Kruskal–Wallis test, df = 1, $P > 0.05$).

(Table 5). As the project progressed, the average per hectare savings by using the IPM Program became progressively larger, with these costs being $51.68 lower in the IPM Program by the third year. When data from all three years were pooled, the average insecticide cost was $42.17 per hectare lower for the IPM program ($F = 6.3$; df = 1, 24; $P = 0.02$).

Discussion

This study shows the improved control and economic advantage of selectively applying reduced-risk insecticides to areas of vineyards where there is high pressure from grape berry moth, i. e. borders adjacent to wooded areas. Vineyard borders that received the IPM program for insect management had lower levels of grape berry moth damage than the borders of Standard vineyards. The superior performance of the IPM program is in part due to the increased efficacy and longer residual activity of the compounds in that program. In vineyard interiors, we found comparable levels of infestation by grape berry moth in vineyards managed with either program, even though IPM vineyard interiors were not treated with insecticide after the postbloom period for three seasons. We documented a substantial cost saving per vineyard hectare that grew from $27.15 in 2009 to $51.68 in 2011 in vineyards that received the IPM program. This was realized with the added benefit of superior or comparable grape berry moth control in IPM vineyards compared to that in Standard vineyards, which would also have provided greater yield (Roubos et al. 2013). We expect that the combination of economic and pest infestation results will increase the chance of such an approach being adopted by grape growers in Michigan and elsewhere that grape berry moth is a pest.

In addition to cost advantages, the consistent, high level of control in the IPM vineyards in this study represents an improvement over the control that was reported previously for vineyards in the same region managed using insect growth regulator insecticides (Jenkins and Isaacs 2007). The IPM program in Jenkins and Isaacs (2007) used weekly scouting to identify the presence of *P. viteana* eggs, and this was used to time two to three applications of methoxyfenozide in the mid and late season. The current study employed one application of methoxyfenozide and one of chlorantraniliprole that were timed using a degree day model. It is likely that the

Table 4. Natural enemies captured on yellow sticky traps in three years in southwest Michigan vineyards treated with an IPM or standard insecticide program

Natural enemy group	2009		2010		2011	
	Standard	IPM	Standard	IPM	Standard	IPM
Parasitic wasps (multiple families)	1,658	1,176	2,803	2,647	1,626	1,194
Ground beetles (Carabidae)	164	156	148	152	46	37
Ants (Formicidae)	81	130	100	145	16	50
Syrphid flies (Syrphidae)	75	48	190	156	26	22
Lacewings (Chyrsopidae, Hemerobiidae)	19	31	30	43	5	6
Spiders (Araneae)	19	27	59	60	20	25
Lady beetles (Coccinellidae)	18	17	59	54	14	8
Social wasps (Vespidae)	7	5	3	1	5	2
Robber flies (Asilidae)	2	4	0	1	1	0
Other	7	17	105	93	5	4
Total	2,050	1,611	3,497	3,352	1,764	1,348

No differences were detected between programs for any natural enemy group, in any year (Kruskal–Wallis; df $= 1$; $P < 0.05$).

Table 5. Per hectare insecticide costs (in $U.S.) for IPM or Standard insecticide programs tested in Michigan vineyards during three growing seasons

Farm	2009		2010		2011	
	Standard	IPM	Standard	IPM	Standard	IPM
1	112.00	77.94	112.00	111.31	112.00	48.91
2	112.00	51.78	112.00	40.17	112.00	40.17
3	97.75	70.92	75.64	65.37	118.51	95.25
4	112.00	124.45	216.56	90.67	159.53	110.99
5			216.56	192.55		
Average	108.44	81.29	146.56	100.00	125.52	73.84
SEM	3.56	15.42	29.33	26.04	11.44	17.30

Values in the IPM Program represent the cost of the insecticide applied, distributed across the whole area of the vineyard.

difference in the relative efficacy of these programs across studies was influenced by a combination of the more precise targeting of insecticide applications that are afforded by using the Grape Berry Moth Predictive Model (Isaacs 2015) and the greater efficacy of chlorantraniliprole.

The marked difference in the amount of damage between border and interior locations in this study is consistent with previous reports (Hoffman and Dennehy 1989, Trimble 1993, Botero-Garcés and Isaacs 2003, Teixeira et al. 2009, Roubos et al. 2013). The much lower levels of pest pressure in vineyard interiors highlights the potential for focusing insecticide applications targeted only to high pressure areas while omitting insecticide applications in vineyard interiors. The present study also suggests controlling grape berry moth on the vineyard border will help to limit the buildup of infestation in the vineyard interior. However, for a more complete answer, a comparison of these vineyards with control vineyards that are not treated with insecticide would be valuable, though inclusion of such a treatment was not possible in this study due to grower unwillingness to leave an entire vineyard unprotected.

Secondary pest outbreaks have been documented in other crop systems when management programs based on broad spectrum insecticides are transitioned to reduced-risk insecticides, particularly if natural enemies of the pest are not present in sufficient densities for effective control (Grafton-Cardwell et al. 2005). The abundance of two key vineyard pests, eastern grape leafhopper and Japanese beetle, were similar in the two programs tested in this study. Growers applied a bifenthrin + imidacloprid premixed insecticide to the entire vineyard in the IPM program during the postbloom period, and it is likely that this application was sufficient for season-long control of leafhoppers. It is also conceivable that the unsprayed vineyard interiors acted as a refuge for leafhopper natural enemies such as *Anagrus* spp. (Hymenoptera: Mymaridae) during the later portion of the season (Williams et al. 2000), and this may have contributed to low leafhopper abundance in IPM vineyards. Two growers chose to apply acetamiprid for leafhopper or Japanese beetle control in 2009, and it is likely this reduced the abundance of these secondary pests. Acetamiprid is a neonicotinoid insecticide, and although some compounds in this chemical class have shown some activity against moth pests of fruit (Van Timmeren et al. 2011), we expect there was little effect of these applications on the conclusions of the present study.

Natural enemy abundance was similar between programs. This is in agreement with the results of Jenkins and Isaacs (2007) in the same system, but other studies have observed increases in natural enemies in response to a transition from broad-spectrum to reduced risk or organic insecticides. For example, in apple orchards in Washington and Oregon, pitfall trapping showed that some ground dwelling natural enemies were more abundant in orchards treated with reduced-risk insecticides than in orchards that were managed with conventional broad spectrum insecticides (Epstein et al. 2000). Similarly, using sweep net samples and visual observation, more soybean aphid natural enemies were found in soybean plots that received reduced risk insecticides than in plots that were treated with broad spectrum compounds (Ohnesorg et al. 2009). However, in the same study no differences in natural enemy abundance were seen when yellow sticky traps were used to monitor natural enemies. Our results suggest that natural enemies were drawn from adjacent areas to traps in IPM and Standard with similar frequency. This may indicate that natural enemy populations are not affected at the single vineyard scale, and a larger area-wide approach may be needed to see changes in natural enemy abundance in response to reduced insecticide use.

This study demonstrates an economically viable strategy for growers to help counteract the relatively high cost of reduced risk insecticides with the incorporation of precisely timed and spatially targeted applications, without the proliferation of secondary pests. However, the orientation of the vineyard rows relative to adjacent woods represents a potential obstacle for widespread adoption of the targeted reduced-risk application approach. This is because grapes are grown on a fixed trellis, and when the rows are oriented perpendicular to the woods, the sprayer cannot travel parallel to woods to selectively treat the areas of highest insect pressure. Insecticide injection application systems are being developed that enable insecticide to be metered into the spray lines and added to a broadcast fungicide application only when the sprayer is moving through an area of high insect pest pressure. This approach could be used to apply treatments for other pest and weed species with clumped distributions. We therefore expect that technical limitations can be overcome to allow widespread adoption of targeted applications that will facilitate further transition to IPM programs integrating reduced risk insecticides for use in eastern North American vineyards.

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