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Yield-Based Economic Thresholds for Grape Berry Moth (Lepidoptera: Tortricidae) in Juice Grapes

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ABSTRACT A 3-yr field study was conducted at commercial juice grape (*Vitis labrusca* L.) vineyards to develop an economic injury level (EIL) for grape berry moth, *Paralobesia viteana* (Clemens) (Lepidoptera: Tortricidae) and to determine patterns of cluster injury. Infestation of grape clusters by *P. viteana* was measured biweekly from bloom until harvest, and fruit was sampled immediately before harvest to determine the yield and level of fruit injury by this pest. Comparison of fruit infestation at each sampling date to that found just before harvest revealed stronger relationships over time, and by early August at least 50% of the variation in preharvest infestation was accounted for by previous infestation. Grape yield declined with increasing infestation by *P. viteana*, allowing calculation of the EIL at which the value of yield lost to infestation equaled the cost of insecticide applications to prevent the infestation. Using two scenarios of pest control programs based on pyrethroid or diamide insecticides, the EILs were calculated to be 9.9 and 17.7% of clusters damaged, respectively. For use in juice grape vineyard integrated pest management programs, we propose using 5 and 10% damaged clusters at harvest as action thresholds for further testing in field trials to evaluate sampling plans and the use of thresholds to guide vineyard pest management decision-making under different insecticide scenarios.

KEY WORDS *Paralobesia viteana*, grape, economic injury level, integrated pest management

Grape berry moth, *Paralobesia viteana* (Clemens) (Lepidoptera: Tortricidae), is a primary pest of cultivated grapes (*Vitis labrusca* L.) in eastern North America (Dennehy et al. 1990, Isaacs et al. 2012b). This moth species has challenged grape growers in this region since the introduction of commercial grape production (Slingerland 1904, Johnson and Hammar 1912). In the past 10 yr, levels of *P. viteana* infestation have increased, in part because of the loss of broad-spectrum insecticides available for its control (Isaacs et al. 2005, 2012b), so new tactics are needed for integration into contemporary integrated pest management (IPM) programs.

Across the Great Lakes region, *P. viteana* adults typically begin to emerge from the overwintering pupal stage in early May. By June, mated females begin to lay eggs on developing flowers or young grape berries (Teixeira et al. 2009) that are then fed upon by the hatching larvae (Johnson and Hammar 1912). Larvae of subsequent generations bore into the developing fruit, infesting multiple berries, and webbing them together (Johnson and Hammar 1912). The number of generations in a growing season varies with geographical location, with two to four possible in Michigan (Tobin et al. 2003, Teixeira et al. 2011). The economic impact of the first generation is minimal, but larvae of later generations can cause significant losses due to contaminated fruit at harvest and reduced yield (Hoffman et al. 1992, Teixeira et al. 2011). Rates of *P. viteana* infestation vary within vineyards, with more egg laying and damage found in border rows adjacent to wooded areas (Hoffman and Dennehy 1987). Larval feeding affects yield by reducing cluster weight and increasing susceptibility to fungal infections, as has been shown for a similar species, European grapevine moth, *Lobesia botrana* (Denis & Schiffermüller) (Fermaud and Le Menn 1989, 1992; Mondy et al. 1998; Ioriatti et al. 2011).

In a typical year, >90% of the Michigan grape crop is processed to make grape juice (USDA–NASS 2011), and there are formal inspections of fruit delivered for processing (USDA–AMS 1943). Before acceptance at the processing plant, a sample of each grape load is inspected to determine the level of *P. viteana* infestation. If >2% of berries by weight contain larvae or have moth injury, the entire load of grapes will be rejected (USDA–AMS 1943), potentially resulting in a significant loss of revenue for the grower. Maintaining populations below this catastrophic level of infestation is obviously a very important goal of grape IPM programs, but preventing yield loss and increasing profitability also should be a priority. Understanding how infestation levels relate to yield is an important step in the development of economic thresholds, and an effective pest sampling plan is required to accurately

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measure the pest and predict yield loss (Pedigo et al. 1986).

Predicting harvest-time infestation levels will help determine the optimal sampling time to make control decisions during the season. Hoffman et al. (1992) found a strong positive relationship between percent cluster damage during the third week in July and percent cluster damage at harvest; yet, this relationship is not well defined for current viticultural practices. If this relationship can be determined, then infestation prediction may be combined with temperature-based developmental models and reduced-risk insecticides for improved management of *P. viteana.*

Economic injury levels (EILs), the lowest pest population density that will cause sufficient economic loss to justify the cost of control, are a fundamental component of IPM programs (Pedigo et al. 1986). Development and validation of an accurate sampling scheme and EIL can potentially lead to the elimination of excessive and unnecessary insecticide applications (Pedigo et al. 1986). The economic threshold is associated with the EIL, and it is the pest population density at which control measures must be initiated to prevent the pest population from reaching the EIL (Stern et al. 1959). In situations where an EIL has not been developed, subjective economic thresholds are used (Higley and Peterson 2008). Here, we use the term action threshold to refer to subjective thresholds in contrast to economic thresholds based explicitly on EILs.

In New York vineyards, Hoffman and Dennehy (1987) proposed an action threshold of 6% damaged clusters in the third week of July to determine whether treatment for the second generation of *P. viteana* would be required in August. Hoffman et al. (1992) calculated thresholds of 17 and 3% damaged clusters for early- and late-harvested grape varieties, respectively, based on sampling during the third week in July. These thresholds were based on risk assessment and aimed to reduce contamination of harvested fruit; economic factors such as crop value and pest control costs were not taken into consideration.

Legislation such as the Food Quality Protection Act of 1996 and the development of insecticide resistance (Nagarkatti et al. 2002) have changed the availability of previously effective broad-spectrum insecticides used in *P. viteana* management (Isaacs et al. 2005, 2012b). New, effective reduced-risk insecticides have been developed but are more expensive than the products they are replacing and require improved timing and coverage for effective control (Wise et al. 2010). Although mating disruption for *P. viteana* has proven effective in some situations (Dennehy et al. 1991, Trimble et al. 1991, Trimble 1993), growers still rely primarily on insecticides for *P. viteana* control (Jenkins and Isaacs 2007) due to their efficacy, cost, and relative ease of use.

Calculating an EIL and the associated economic threshold for *P. viteana* would improve management of this pest. Thresholds calculated for *P. viteana* in New York (Hoffman and Dennehy 1987, Hoffman et al. 1992) originally led to >50% reduction in the use of insecticides for control of this pest in vineyards (Martinson et al. 1991). However, the types of insecticides available for control of this pest have changed significantly in the past 10 yr, and the published thresholds have increasingly failed to prevent significant infestation by *P. viteana.* These changes may partly be explained by the newer insecticides not having the same combination of longevity and vapor action that previously ensured very high levels of control. The cost of controlling *P. viteana* with insecticides also has increased since the earlier thresholds were developed, and this information can be incorporated into the calculation of EILs (Isaacs et al. 2012a).

As a first important step toward integration of *P. viteana* thresholds into juice grape production, our objectives in this study were to 1) determine at what point during the season grape cluster damage best predicts cluster damage at harvest and 2) develop an empirically derived EIL for *P. viteana* in juice grapes. Development of economically based thresholds that focus on preventing yield loss rather than addressing the contamination of harvested fruit is expected to maintain populations below catastrophic levels.

Materials and Methods

Vineyard Sampling. Assessments of *P. viteana* infestation were made by sampling vineyards in southwestern Michigan (Allegan, Berrien, and Van Buren counties). Sampling was performed at 15 vineyards in 2010, 18 vineyards in 2011, and seven vineyards in 2012. Vineyards varied from 0.8 to 4.5 ha, were comprised of *Vitis labrusca* L. 'Concord' juice grapes, and were chosen to encompass a range of *P. viteana* infestation levels. Growers applied their own insecticide and fungicide programs, including a postbloom application of broad-spectrum insecticides for *P. viteana* control.

Vineyards were sampled for *P. viteana* infestation every 2 wk from postbloom (early June) to harvest (September). At each visit, visual assessments were conducted on five randomly selected clusters on vines at 0, 6.1, 12.2, 21.3, 33.5, 39.6, 45.7, and 51.8 m (1, 3, 5, 8, 12, 14, 16, and 18 vines) from the vineyard border. Sampled vines were on five transects that were randomly selected at each visit. On each sampling visit, 200 clusters from each vineyard were assessed. The number of *P. viteana* damaged clusters and the number of *P. viteana* damaged berries on each cluster were recorded for each sampled vine.

EIL. Samples of grape clusters were collected at harvest during both years to determine the economic impact of *P. viteana* on grape yield. In each vineyard, 40 clusters were collected using the same scheme as described under Vineyard Sampling (with one cluster sampled per vine instead of five), and clusters brought to the laboratory (Michigan State University, East Lansing, MI) for evaluation. Berries were separated into three groups: *P. viteana*–damaged berries, diseased berries (e.g., phomopsis, black rot, sour rot), or intact berries. The number and weight of berries in each group were recorded for each cluster. Although there is a possible association between *P. viteana* and disease, diseased berries were not included in this analysis unless they also had *P. viteana* injury.

Based on information obtained from National Grape Cooperative's Michigan field office, the number of clusters per hectare for Concord grapes was estimated at 92,643.2 and 150,878.4 (2010 and 2011, respectively), with an average vineyard having 1,360 vines per ha (2.74-m by 2.74-m vine spacing) and 68.12 and 110.94 clusters per vine (2010 and 2011, respectively). The number of clusters per hectare in 2012 was estimated at 80,947.2, with an average vineyard having 1,360 vines per ha and 59.52 clusters per vine based on field observations. Yield was estimated based on the weights of collected clusters. Pesticide use records were provided by the growers, and total cost per insecticide application was calculated as the sum of the cost of each insecticide plus the incidental expenses (e.g., fuel, labor) estimated at an additional $86.49/ha.

The EIL calculation was based on a modified general EIL model: EIL = $C/(V \times D_I \times K)$, where C is cost of management activity (US$ per hectare), V is market value per unit of produce (US$ per metric ton), D_I is yield loss per unit injury (metric tons per percentage of clusters with *P. viteana* damage), and K is proportionate reduction of the insect population (Pedigo et al. 1986, Higley and Pedigo 1996). The relationship between yield and *P. viteana* damage (D_I) was determined using linear regression. The slopes of the regression lines were used to provide the value of D_I in EIL calculations (Higley and Pedigo 1996).

For values of C, the management cost, two insecticides were selected from products labeled for *P. viteana* control in vineyards. Bifenthrin (Brigade 2 EC, FMC Corp., Philadelphia, PA) represents a low-cost, broad-spectrum insecticide used for control of *P. viteana* as well as for control of leafhoppers and Japanese beetle (*Popillia japonica* Newman), but it has relatively short residual control during hot, summer weather conditions. In contrast, rynaxypyr (Altacor, DuPont, Wilmington, DE) is a more costly reduced-risk insecticide that is highly active on *P. viteana*, with some activity on beetle pests, and it provides long residual control. These products were selected to show the range of EIL values for *P. viteana* with different insecticides. Crop value (V) was based on information obtained from National Grape Cooperative's Michigan field office. Proportional efficacy (K) for each product was based on field trials conducted in 2010 (Wise et al. 2011).

Statistical Analysis. Averages for the number of berries per cluster and cluster weight were compared among years by using one-way analysis of variance (ANOVA) (PROC MIXED) with least significant difference (LSD) means separation tests (SAS Institute 2009). Data were square root transformed to correct for heterogeneity of variances. The average number of *P. viteana* damaged berries per cluster at different levels of cluster injury was compared among years by using one-way ANOVA with LSD means separation tests. These data were $\log_{10}(x + 1)$ transformed to meet model assumptions. Untransformed data are presented in the figures. Correlation analysis was used to determine the relationship between the level of infestation at sampling dates during the season and the level of infestation at harvest. Total numbers of damaged clusters at each sample time were analyzed using PROC CORR (SAS Institute 2009). Regression equations for EILs were calculated using simple linear regression (PROC REG, SAS Institute 2009) with percentage of damaged clusters as the independent variable and yield per hectare as the dependent variable.

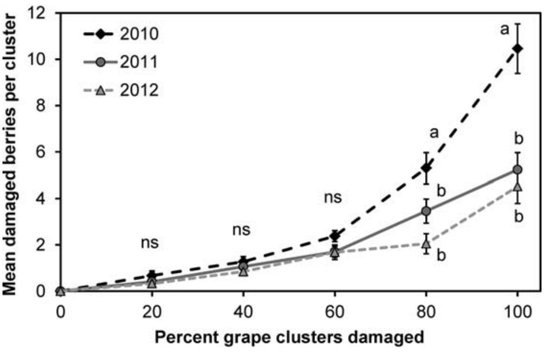

Fig. 1. Number (mean ± SE) of grape berries with injury by grape berry moth as a function of the percentage of clusters damaged. Means with the same letter are not significantly different among years at $P < 0.05$ (ns, not significant).

Results

Incidence of *P. viteana* injury differed greatly between the 2 yr of this study. Early season frost damage in 2010 and 2012 led growers to abandon vineyard pest management programs at many of the sites, resulting in higher pest pressure compared with 2011. The average number of berries per cluster varied by year ($F = 118.2$; df = 2, 1,567; $P < 0.001$) and consequently, average cluster weight varied by year ($F = 53.76$; df = 2, 1,567; $P < 0.001$) (highest in 2011, lowest in 2012). The number of *P. viteana*–damaged berries per cluster was significantly higher in 2010 compared with 2011 and 2012 ($F = 186.1$; df = 2, 1,567; $P < 0.001$). There were also significant differences among years in the number of damaged berries per cluster at high levels of cluster infestation (Fig. 1). Percent cluster damage at key sampling periods for all vineyards combined is shown in Fig. 2. The average number of damaged grape clusters per vineyard ($n = 200$) at preharvest ranged from 0.5 to 17.1% in 2010, from 0.4 to 11.8% in 2011, and from 2.3 to 8.3% in 2012. The average cluster damage for all vineyards was twice as severe at harvest in 2010 compared with 2011 (Fig. 2).

Vineyard Sampling. Grape cluster injury was assessed at seven sample periods each season. Coefficients of determination of grape cluster damage for each sample period in relation to the preharvest samples are shown in Fig. 3. In 2010, r^2 values were higher

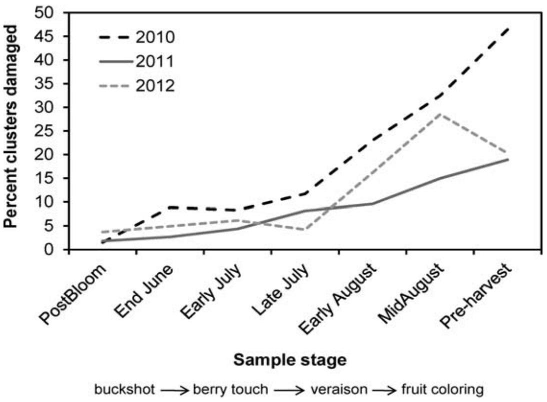

Fig. 2. Percentage of grape clusters with injury by grape berry moth over the 2010, 2011, and 2012 growing seasons.

initially but decreased until early August, coinciding with onset of berry ripening (veraison), increasing thereafter as harvest approached. In 2011, r^2 values increased over the entire season and were higher than 2010 values from early July to harvest (Fig. 3). In 2012, r^2 values increased until early August, but unlike in 2010 and 2011 they decreased in mid-August.

These correlations were combined with the *P. viteana* temperature developmental model (Tobin et al. 2003) to determine whether sample periods lined up with predicted moth development. The temperature developmental model with base 8.41°C (Tobin et al. 2001) and wild grape bloom as biofix predicts egglaying of the second and third generations to start at 450 and 900 growing degree-days (GDD), respectively (Isaacs et al. 2012b). Using an online GDD calculator (www.enviroweather.msu.edu), we determined that 450 GDD coincided with the early July sample, where $r^2 = 0.27$ in 2010, 0.29 in 2011, and 0.32 in 2012; and 900 GDD coincided with the early August sample, where $r^2 = 0.34$ in 2010, and 0.55 in 2011, and 0.74 in 2012.

EIL. The values used in the general EIL model and resulting EILs, given in terms of percentage of damaged clusters and number of damaged clusters per vine, for *P. viteana* in 'Concord' grapes are reported in Table 1. EILs for rynaxypyr, the more expensive insecticide, were on average 9% higher than those calculated for bifenthrin. Regression analysis results are shown in Fig. 4. There was a linear relationship between percent cluster damage and estimated yield in 2010 ($F = 7.38$, df = 29, $P = 0.011$) and 2012 ($F = 17.97$, df = 13, $P = 0.001$), but the slope of the regression line in 2011 was not statistically different from zero ($F = 2.48$, df = 35, $P = 0.125$). Variation in the amount of grape injury caused by *P. viteana* among years was indicated by the different slopes of the regression lines (Fig. 4) and number of damaged berries per cluster (Fig. 1).

Table 1. Values of variables and resulting EILs for infestation by grape berry moth in juice grapes

Year	Insecticide	D_I: yield reduced (ton per % damage)	EIL[a] (% clusters damaged)	EIL (damaged clusters per vine)
2010	Bifenthrin[b]	0.0259	11.8	8.0
	Rynaxypyr[c]	0.0259	21.1	14.4
2011	Bifenthrin	0.0228	13.4	14.9
	Rynaxypyr	0.0228	24.0	26.6
2012	Bifenthrin	0.0308	9.9	5.9
	Rynaxypyr	0.0308	17.8	10.6

[a] EIL = $C/(V \times D_I \times K)$, where C is cost of application (US$ per hectare): $93.91 for bifenthrin and $171.59 rynaxypyr; V is crop value (US$ per metric ton) was $313.50; and K is proportional efficacy: 0.98 for bifenthrin and 1.0 for rynaxypyr.

[b] Bifenthrin (Brigade 2EC) applied at rate of 233.8 ml/ha (3.2 U.S. fl oz/acre).

[c] Rynaxypyr (Altacor) applied at rate of 219.2 ml/ha (3.0 U.S. fl oz/acre).

Discussion

P. viteana infestation reduced yields of juice grapes during the 3 yr of this study, showing that vineyard pest managers should be concerned about this pest for its direct feeding injury to the fruit, as well as for

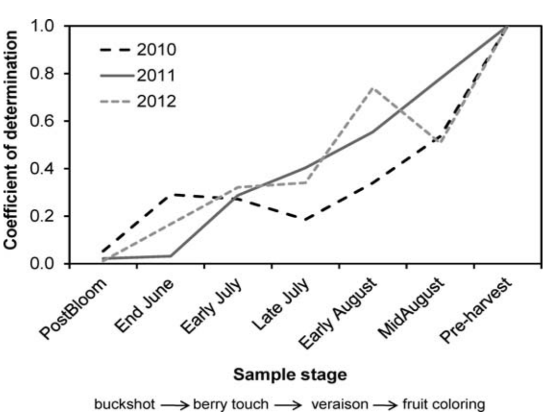

Fig. 3. Correlations of percentage of grape clusters with grape berry moth injury at different sample times in relation to the level of injury in preharvest samples.

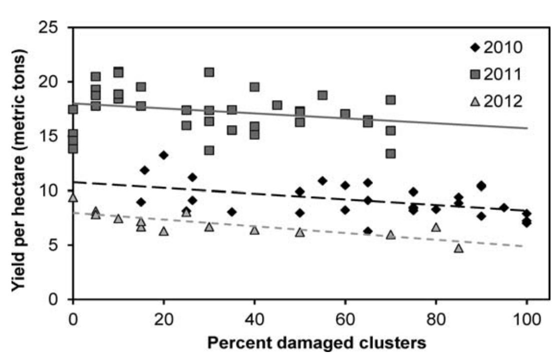

Fig. 4. Regression of grape yield per hectare as a function of percentage of grape clusters damaged by grape berry moth. 2010: $y = -0.0259x + 10.76$, $r^2 = 0.209$, root mean square error (RMSE) = 1.39. 2011: $y = -0.0228x + 18.00$, $r^2 = 0.068$, RMSE = 1.98. 2012: $y = -0.0308x + 7.96$, $r^2 = 0.600$, RMSE = 0.75.

potential contamination of harvested berries. Calculation of economic thresholds based on the value of yield lost and the cost of protecting the fruit provide updated thresholds that can be integrated into vineyard pest management programs, with the ability to focus management inputs only when needed.

We did not include vineyard position in the analysis even though *P. viteana* infestation is known to be concentrated mostly in vineyard borders (Hoffman and Dennehy 1989, Botero-Garcés and Isaacs 2003). The distinction between border and interior samples was disregarded to keep the model simple and develop an EIL that is applicable across the entire vineyard. To address spatial differences in infestation, a sampling system similar to the one developed for New York could be used (Hoffman and Dennehy 1987). This system would allow growers to target sprays into vineyard regions where the cost of treatment was warranted.

Grape cluster injury by *P. viteana* varied among years in this study, in part because of frost damage to vineyards in 2010 and 2012 that resulted in less grower investment in crop protection. Although this situation resulted in higher infestation, it also provided a view of the full potential range of infestation that can occur, and the potential reduction in yield. Higher overall infestation rates in 2010 and 2012 and the steeper regression slopes shown in Fig. 4 emphasize the importance of controlling this pest. The differences in infestation among years affected the correlation of percent cluster injury at various sample times during the season to injury at harvest. This made it harder to predict injury at harvest in 2010 because percentage of injury increased at a higher rate than in 2011 (Fig. 2). Percentage of injury in 2012 increased at a similar rate to 2010 except for a decrease in the final sample at preharvest. Infestation increased at a slower rate over the 2011 season due to the concerted effort of growers to manage *P. viteana.*

The difference in percent cluster injury among years in this study resulted in different yield reduction estimates (D_I). However, the slope of the line from 2011 was not statistically different from zero, so the estimation of D_I based on these data are not reliable. The 2010 and 2012 data are more appropriate for these calculations; based on these data, a conservative EIL for *P. viteana* in Concord juice grapes is 9.9–11.8% of clusters damaged by this pest. This provisional EIL is similar to that developed previously in New York vineyards for sampling in July (Hoffman and Dennehy 1987, Hoffman et al. 1992), but their system also had a higher threshold later in the season. In this case, we recommend that growers implement management programs to maintain their cluster infestation levels below 10% at harvest. This threshold based on yield loss needs to be validated under field conditions over multiple seasons to determine how well it performs for guiding investment in pest management activities, and it may require an action threshold of 5% cluster damage to be effective. Using percentage of berries with *P. viteana* feeding injury instead of percentage of clusters would have likely resulted in more accurate EIL calculations, but growers and crop scouts typically use clusters as their sampling unit. EIL calculations based on clusters are therefore more practical and likely to be adopted.

Development of this action threshold now moves the focus of management of this pest from control to maintenance below the EIL. Further investigation is needed to develop a system that can work in commercial vineyards with the available pest control options to prevent infestation exceeding this threshold at harvest. This system may be accomplished using the available insecticides, including reduced-risk insecticides such as the insect growth regulator methoxyfenozide and the diamides rynaxypyr and flubendiamide that have excellent efficacy against *P. viteana* (Bostanian et al. 2012). Although these reduced-risk insecticides are more expensive than conventional pyrethroid insecticides, they have many positive attributes, including longer residual (Isaacs et al. 2005) and lower negative side effects on natural enemies (Jenkins and Isaacs 2007), but they also have a more restricted spectrum of activity that may not be ideal for conditions where *P. viteana* co-occurs with leafhoppers or other nonlepidopteran pests.

Factors other than *P. viteana* feeding may have contributed to variability observed in the yield data. These factors include a range of cluster sizes (6–79, 11–108, and 9–56 berries per cluster in 2010, 2011, and 2012, respectively) and cluster weight reduction due to disease. Diseased berries without obvious *P. viteana* larval infestation were not counted in the yield loss estimates, even though berry moth infestation may have contributed to disease increase. Although these factors likely contributed to the weak fit of the linear regression analysis, it reflects the reality of vineyard conditions in that there is significant variability in levels of cluster infestation among farms within the state and among vineyards within farms.

Sampling for *P. viteana* moth injury at key periods indicated by the GDD model will provide data useful for predicting potential loss at harvest. Pheromone traps are useful for trapping *P. viteana* males early in the season, but they are not reliable indicators of grape cluster infestation later in the season (Hoffman et al. 1992, Botero-Garcés and Isaacs 2004). Temperature-based developmental models have proven useful for predicting the onset of each generation (Tobin et al. 2001, 2003); so, degree-day–based models are being developed using wild grape (*Vitis* spp.) bloom as a biofix. Although this approach provides improved timing for crop protection, it does not forecast yield loss incurred by *P. viteana* infestation or determine whether crop protection is necessary and economically advantageous. Hoffman et al. (1992) found that percent cluster damage during the third week of July was strongly correlated ($r^2 = 0.61$) with damage at harvest for early-harvested grapes and weakly correlated ($r^2 = 0.11$) for late-harvested grapes. In Michigan, grapes are harvested in September and October, corresponding to the late-harvested grapes described by Hoffman et al. (1992). *P. viteana* infestation in late July was more strongly correlated with damage at harvest in our study than observed in New York. This difference may be explained by variation in management because the vineyards used by Hoffman et al. (1992) had not been treated with insecticides throughout the experiment, whereas those sampled in Michigan in 2011 received active management (one to three sprays for this pest). However, the late-July timing did not correspond to second generation *P. viteana* egglaying as predicted by the GDD model; therefore, the timing of sampling will need to be adjusted to early July to overlap the egglaying period.

Oviposition periods for each generation of *P. viteana* overlap (Teixeira et al. 2011), and the reduction of yield at harvest is the result of cumulative damage over the growing season. Timing these samples around the GDD model will be useful because the model is already available and is being used by some growers. In all 3 yr of this study, egglaying by the third generation coincided with the veraison sample period (early August). The sample timing with the highest predictive power co-occurs with the emergence of the third generation and provides an optimal time to sample vineyards to determine the need to control this pest in advance of harvest. Sampling at veraison will still provide enough time for growers to assess risk of *P. viteana* damage before harvest, with time for intervention if needed.

Pest management in high value fruit crops is challenging due to stringent quality standards and the high per-acre value of the crop. Pest injury can reduce yield and also lead to downgrading or rejection of harvested fruit. The EILs calculated here based on vineyard data are an important step toward developing a contemporary IPM program in grapes, and we expect that implementation of this action threshold within IPM programs will lead to significant cost savings and improved fruit yields.

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