

# Juice Grape Canopy Structure and Cluster Availability Do Not Reduce Middle- and Late-Season Captures of Male *Paralobesia viteana* (Lepidoptera: Tortricidae) in Sex Pheromone Traps

Keith S. Mason<sup>1</sup> and Rufus Isaacs

Department of Entomology, Michigan State University, East Lansing, MI 48824 and <sup>1</sup>Corresponding author, e-mail: [masonk@msu.edu](mailto:masonk@msu.edu)

Subject Editor: Lukasz Stelinski

Received 22 December 2017; Editorial decision 14 March 2018

## Abstract

*Paralobesia viteana* (Clemens) (Lepidoptera: Tortricidae), the grape berry moth, is a major economic pest of cultivated grapes in eastern North America. Although pheromone lures and traps are available for monitoring this pest, male moth captures in these traps decline as the infestation risk increases through the multiple generations that occur during a season. This makes it difficult to use traps to monitor this pest's population dynamics and complicates the timing of pest management activities. To test whether seasonal changes in the plant canopy affect captures of male grape berry moth, we manipulated grapevine fruit density or canopy structure in multiple growing seasons, and measured male captures under these conditions. Removal of either 50 or 100% of the fruit clusters from vineyard plots did not consistently affect captures in pheromone traps. In 2013, significantly more males were captured in traps in plots where clusters were not removed compared to captures in traps in plots where 50 or 100% of clusters were removed, but this effect was not seen in 2014 or 2015. In the first year of a separate experiment, there were no differences in male captures between unaltered canopies and those held open artificially. In subsequent years we detected significant differences in male captures for some sample periods, and there was a prevailing trend of arithmetically more male captures in unaltered than in open canopies. We conclude that fruit presence, fruit density and canopy fullness do not reduce male *P. viteana* captures late in the season, and that other factors are driving this pattern.

**Key words:** monitoring, phenology, *Vitis labrusca*, grape berry moth, pest

The grape berry moth, *Paralobesia viteana* (Clemens) (Lepidoptera: Tortricidae), is a specialist herbivore found in woods and vineyards across eastern North America, feeding primarily on wild and cultivated plants in the genus *Vitis* (Johnson and Hammar 1912). This moth is a primary pest of cultivated grapes (*Vitis labrusca* L. (Rhamnales: Vitaceae) and *Vitis vinifera* L. (Rhamnales: Vitaceae) and their hybrids), and it has challenged grape growers since the beginning of commercial grape production in this region (Johnson and Hammar 1912, Hoffman et al. 1992, Isaacs et al. 2012). There are multiple generations of *P. viteana* in a growing season depending on location and the length of the growing season, with three and sometimes four generations in Michigan (Tobin et al. 2003, Teixeira et al. 2009). First generation adults begin to emerge from overwintering pupae in late April or early May, and mated females start to lay eggs on warm nights in early to mid-June (Clark and Dennehy 1988, Teixeira et al. 2009). After larvae hatch, they feed on multiple adjacent flowers or young berries and produce webbing that encloses the feeding site (Johnson and Hammar 1912).

Larvae of subsequent generations excavate tunnels into the fruit, and web together and infest multiple berries (Johnson and Hammar 1912). The economic impact of the first generation is minimal, but larvae of later generations can cause significant economic losses due to reduced yield, lowered fruit quality or rejection of contaminated fruit by fruit processors (Hoffman et al. 1992, Teixeira et al. 2009, Roubos et al. 2013). Larval feeding by *P. viteana* is similar to that of the closely related European species, *Lobesia botrana* (Denis & Schiffermüller) (Lepidoptera: Tortricidae) that also affects yield and quality by increasing susceptibility to bacterial and fungal infections (Feraud and Le Menn 1992, Mondy et al. 1998, Ioriatti et al. 2011). Because of the risks of direct yield loss, larval contamination of fruit and reduced fruit quality due to pathogens, *P. viteana* is the target of the majority of insecticide applications to vineyards east of the Rocky Mountains (Hoffman et al. 1992, Teixeira et al. 2009).

Flight activity of male grape berry moth can be monitored using traps containing lures baited with synthetic sex pheromone, but the males of this species are only captured in pheromone traps

consistently during the first generation that is active around bloom. The first generation causes little larval feeding damage, but in the second and third generations in the early and late summer, respectively, the level of oviposition on berries, and subsequent larval infestations increase greatly, yet few males are caught in monitoring traps (Snyder et al. 1992, Teixeira et al. 2009—Figure 1, Isaacs et al. 2012). This disconnect between male moth captures and larval infestation at harvest prevents development of action thresholds based on captures of male moths as has been done for other lepidopteran fruit pests (Binns and Nyrop 1992, Bradley et al. 1998, Reddy and Manjunatha 2000, Knight and Light 2005). Exploring factors that affect male captures of this species will inform the development of lures or trapping strategies that improve moth monitoring, potentially allowing for better timing of insecticide applications and improving decision-making about the need for treatments.

Volatile host plant chemicals can influence host-finding in some key crop pests (Bruce et al. 2005, Leskey et al. 2008, Piñero and Dorn 2009, Saveer et al. 2012). Most previous studies in this area have focused on the behavior of females, but either sex can respond to host plant volatiles in the laboratory or field (Stelinski et al. 2003, Light and Knight 2005, Faraone et al. 2013). Within species, odorant receptors and neural pathways are also similar between sexes (Jordan et al. 2009, Varela et al. 2011). Female codling moth, *Cydia pomonella* L. (Lepidoptera: Tortricidae), are attracted to apple odor, and show increased oviposition and flight response in laboratory studies (Wearing et al. 1973, Yan et al. 1999, Coracini et al. 2004). In addition, *C. pomonella* males are attracted to compounds derived from pear, and these can be used in monitoring traps resulting in higher captures than with pheromone alone (Light et al. 2001, Knight et al. 2005, Il'ichev et al. 2009). In the oriental fruit moth, *Grapholitha molesta* (Busck) (Lepidoptera: Tortricidae), females are attracted to a combination of green leaf volatiles and other aromatic compounds that are derived from peach shoots (Piñero and Dorn 2007). In addition, male and female *G. molesta* are attracted to monitoring traps baited with volatiles derived from peach and pear (Lu et al. 2012). Female European grapevine moth (*L. botrana*), consistently flew upwind and landed on unripe grape clusters in wind tunnel tests (Tasin et al. 2006). In subsequent studies, *L. botrana* females were also attracted to a four-component blend of volatile compounds collected from the headspace around confined grapes clusters, and females were attracted to synthetic grape volatiles in field studies (Tasin et al. 2010). In similar studies, *P. viteana* females oriented toward grapevine structures in wind tunnel tests, and this response was stronger for shoot tips and mature leaves than that for flowers, unripe berries or mature fruit (Cha et al. 2008a). In further tests using wind tunnels, females consistently flew to lures loaded with blends of grape shoot volatiles that were collected from the headspace around grape shoots (Cha et al. 2008b). Male *P. viteana* were also attracted to this blend as males were captured in traps baited with the same volatile blends in field tests (Cha et al. 2008b, Loeb et al. 2011). These latter studies show that grape shoot volatiles are important and attractive cues for both male and female *P. viteana*, and they also suggest that the volatile-rich grape canopy may influence the interaction between male *P. viteana* and monitoring traps.

The size and chemical composition of grape clusters and the vine canopy change considerably during seasonal growth and development (Hrazdina et al. 1984, Mullins et al. 1992, Schultz 1995). Early in the season, few leaves and only small flower or berry clusters are present on vines. As the growing season proceeds, the clusters increase in weight 100-fold, and as the berries soften and become ripe, physiological changes lead to increased soluble solids, lower organic acids (e.g., tartaric, malic and citric), and depending on

grape variety, an increase in pH to a final value between 2.8 and 3.7 at harvest (Hrazdina et al. 1984, Jackson and Lombard 1993). The concurrent increase in phenolic compounds, such as flavonoids and anthocyanins, can impart distinctive odors and flavors to ripening grape clusters (Singleton and Trousdale 1983), and volatile terpenes that increase greatly after veraison (fruit coloring) also change the aroma and flavor characteristics of grapes (Dimitriadis and Williams 1984, Rosillo et al. 1999). These physiological transformations contribute to an odor landscape that varies consistently through the growing season, and these changing host plant cues may provide information that *P. viteana* could use to orient to its host plant, and find potential mates and oviposition sites. If *P. viteana* mating occurs on the grape clusters, or if females spend the majority of their time on clusters, males would have an increased chance of finding females, and mating successfully, if they can detect and orient toward the volatiles produced by grape clusters. This could lead to a 'competition' between clusters and traps that might lead to a reduction in the number of male captures in traps. In addition, the combination of grape volatiles and sex pheromone may be more attractive to male *P. viteana* than sex pheromone alone, as has been shown for *C. pomonella* (Light et al. 2001). This preference could result in reduced *P. viteana* male captures in pheromone traps because the amount of grape cluster volatiles increases during the season due to the increase in cluster size and the ripening of the crop.

In addition to changes that occur as clusters develop, the physical structure of the juice grapevine canopy is also transformed through each season. In varieties that are bred and managed to maximize crop yield, such as juice grapes (*V. labrusca*, cvs. Concord and Niagara), the vines are typically cane-pruned and trained to a single wire top-cordon system. The resulting trailing habit of shoot growth causes the canopy to become increasingly dense, and it creates a thick matrix of shoots and leaves as the season progresses (Smart et al. 1982, Miller and Howell 1998, Dry 2000, Bates 2008). The quantity and quality of grape shoot and leaf volatiles that are present in a vineyard change as the canopy grows and becomes more dense (Tasin et al. 2005). The dense canopy imposes challenges on disease and insect management by forming an impediment to air flow and reducing spray coverage (Wise et al. 2010). The increase in canopy density may also affect monitoring *P. viteana* with pheromone traps by altering trap findability (Miller et al. 2006), making it less likely that male moths find traps. The canopy could physically block males from reaching traps, it may disrupt the structure of the pheromone plumes from lures, or the naturally occurring grape shoot volatiles may draw moths away from traps.

To better understand the observed phenology of *P. viteana* in vineyards, this study explored the interaction between *P. viteana* and two host plant characteristics, cluster density and canopy structure. We determined if these factors reduce moth captures in pheromone traps by testing two hypotheses: 1) grape clusters reduce captures of *P. viteana* males in pheromone traps, and 2) the juice grape canopy reduces male *P. viteana* moth captures in pheromone traps.

## Materials and Methods

Field trials measured the effect of the presence and density of grape clusters on captures of male *P. viteana* at six (2013) or five (2014 and 2015) commercial juice grape vineyards (cv 'Concord') in Van Buren and Berrien counties in southwest Michigan (42.25 to 41.75°N, 86.5 to 85.75°W). All vineyards were grown on a 1.8 m (6 ft) tall trellis with a single-wire, top-cordon training system, and vineyards were cane pruned to ~75 buds per vine. At each vineyard, three 15 × 15 m plots (5 rows × 5 vines), separated by at least 15 m, were

setup on the vineyard border adjacent to a woodlot containing wild grape (*Vitis* spp). Plots received one of the following randomized treatments: 100% of the clusters removed, 50% of the clusters removed or 0% of the clusters removed (control). Pruning shears were used to remove clusters between the 26 May and 18 June, before the end of bloom in all 3 yr.

One Pherocon VI monitoring trap baited with a sex pheromone lure (Trece Inc, Adair, OK) was hung inside the grape canopy with the long axis of the trap parallel to the row. Traps were attached to the trellis wire in the middle row of each plot between the third and fourth vines in the row when clusters were removed in late May or early June. Captures of males were recorded weekly until the end of the experiment. For each season, lures from a single lot were used, and lures were changed every 6 wk to coincide with the start of each generation. Sticky trap liners were changed every 2 to 4 wk when they became water-logged or excessively soiled. *P. viteana* generations were determined using the MSU Enviroweather grape berry moth model (Isaacs 2017) that employs an egg to adult development time of 423.9 DD<sub>8.41°C</sub> and local bloom of wild grape (*Vitis riparia* (Michx.) (Rhamnales:Vitaceae)) as the biofix (Tobin et al. 2001, Teixeira et al. 2009). Using this model, moths that emerged from overwintering pupae and were caught in May and June were classified as the first generation, those caught in July through mid-August comprised the second generation, and the third generation consisted of moths that were captured from mid-August until harvest in late September. In each year, the total number of males captured during each of three generations and the total number captured per season were square root transformed before analysis to stabilize error variance in order to meet the normality assumptions of the analysis of variance. Captures were then compared among treatments with analysis of variance using vineyard as a random variable and plots as replicates followed by means separation using Tukey's HSD test (JMP Pro ver 13.1.0, SAS Institute Inc 2016).

To determine whether mid and late-season *P. viteana* male captures are reduced by a dense juice grape canopy, a field trial was established during the spring of 2012 at a commercial Concord vineyard in Lawton, MI (42.15°N, 85.83°W). This experiment was

repeated in 2014 and 2015 in a vineyard (cv Niagara) at the Trevor Nichols Research Center in Fennville, MI (42.58°N, 86.14°W). Ten 15 × 15 m plots (5 rows × 5 vines) were marked on the edge of the vineyard adjacent to a woodlot containing wild grape (*Vitis* spp.). The vineyard was grown on a 1.8 m (6 ft) tall trellis and trained to a single-wire, top-cordon system, and vines were cane pruned to ~75 buds per vine. We did not collect canopy measurements such as shoot length, cluster density leaf density, etc., as our study only included two levels of canopy density, 'Open' or 'Unaltered'. Treatments were arranged in blocked pairs with the two different treatments applied in adjacent plots that were separated by at least 9 m. In the center row of one randomly chosen plot in each pair, we used bamboo stakes, snow fence and zip ties to hold the canopy open by constructing a 15-m-long triangular tunnel (0.5 m on a side) that was open at the bottom (Fig. 1), and this treatment was designated as 'Open'. The second plot in the pair was left unaltered, and this treatment was referred to as 'Unaltered', and was used as a control. Treatments were re-randomized each year to reduce location effects. In mid-May of each year, a monitoring trap as described above was hung on the trellis wire with the long axis of the trap parallel to the row and between the third and fourth vines in the middle row of each plot. Traps were within the canopy in 'Unaltered' plots, or inside the tunnel in 'Open' plots. The number of *P. viteana* males captured was recorded each week from mid-May through September. Each year, lures came from a single lot and were changed every 6 wk to coincide with the start of each generation. Sticky trap liners were changed at least every 4 wk when they became waterlogged or soiled with insects. Generations were determined as described above, and the total number of males captured during each generation and the total captured in a season were compared between treatments with analysis of variance using square-root transformed data and included blocked pairs as a random variable and vineyards as replicates (JMP Pro 13.1.0, SAS Institute Inc 2016). In 2015, data transformation did not satisfy the normality assumptions for analysis of variance, so these data were not transformed and were compared between treatments using a Wilcoxon Test of summed ranks (JMP Pro 13.1.0, SAS Institute Inc 2016).



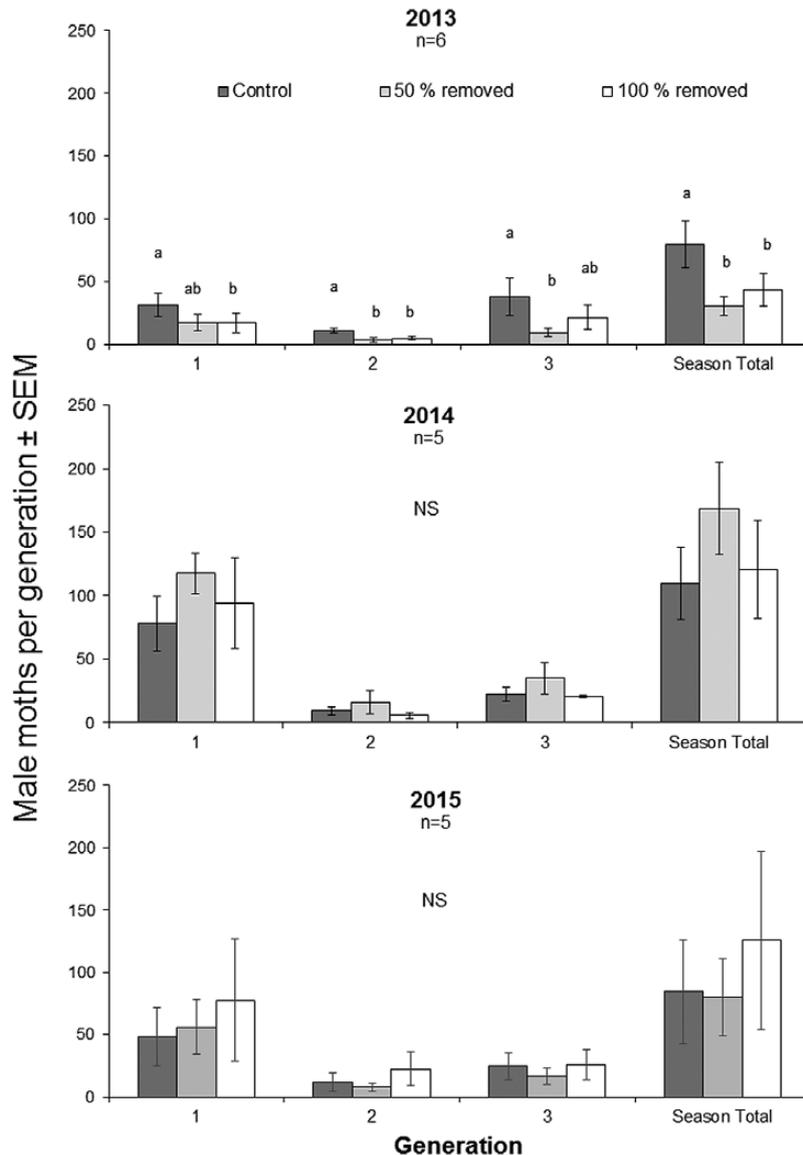
Fig. 1. Vineyard plot containing a triangular tunnel designed to keep grape canopy open. Photograph was taken early in the season before the canopy was fully developed.

## Results

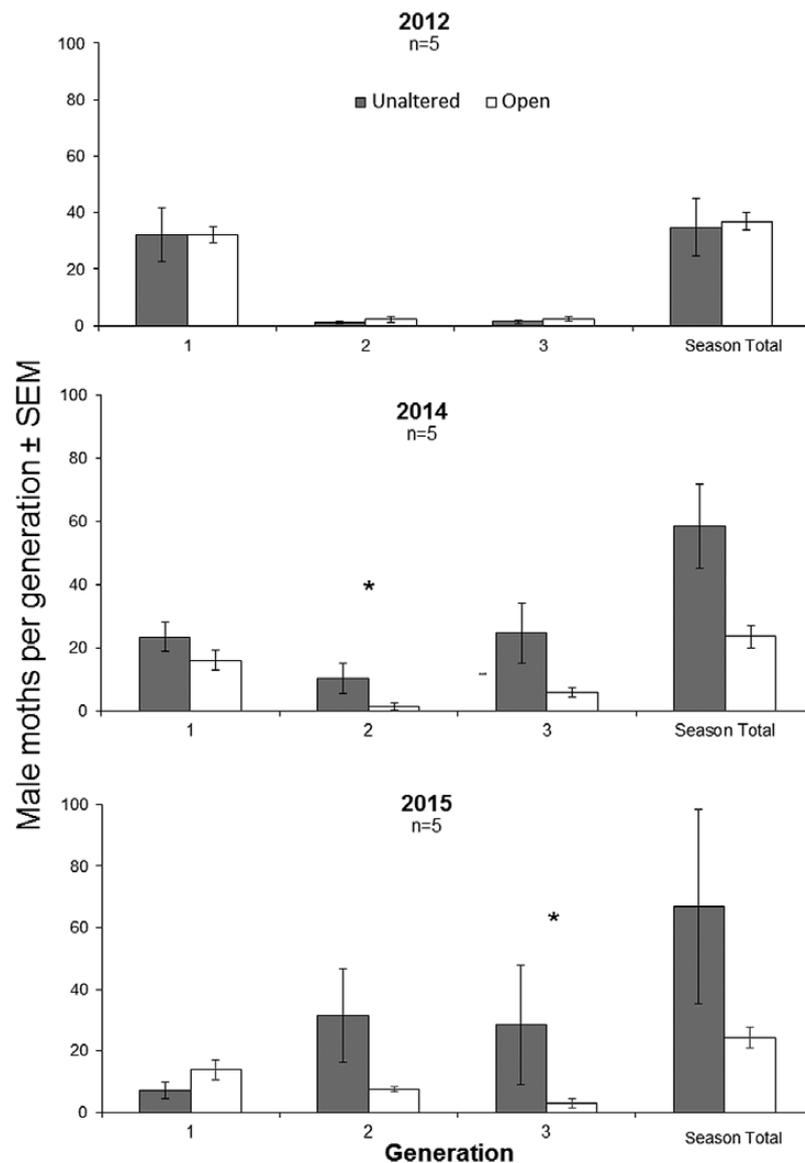
In 2013, significantly more *P. viteana* males were caught in traps in plots where clusters were retained compared to plots where they were removed. This was true for the number of moths trapped during each generation (Generation 1:  $F_{2,10} = 4.67$ ,  $P < 0.037$ ; Generation 2  $F_{2,10} = 7.48$ ,  $P < 0.01$ ; Generation 3:  $F_{2,10} = 7.73$ ,  $P < 0.01$ ), and for the total captured during the entire season ( $F_{2,10} = 9.04$ ,  $P < 0.006$ ; Fig. 2). However, in 2014 and in 2015 after experimental plots were re-randomized, no significant differences were detected among cluster removal treatments in the total number of male *P. viteana* captured during the entire season ( $F_{2,8} = 2.53$ ,  $P > 0.14$ , Fig. 2). There was also no difference in the number of males captured during any of the three generations in 2014 ( $F_{2,8} < 2.52$ ,  $P > 0.14$ ), or 2015 ( $F_{2,8} < 0.86$ ,  $P > 0.45$ ). The contrasting results between the first year and subsequent years indicate there was a confounding location effect in 2013, most likely because our control plots were inadvertently situated in areas of high grape berry moth pressure.

No significant differences were found between male captures in plots where all of the clusters were removed compared to captures in plots where 50% of the clusters were removed. The absence of a cluster removal rate effect suggests that removing clusters triggered vegetative growth, and this may have led to a similar increase in leaf volatiles in the canopy in the 50 and 100% cluster removal treatments. This may have led to similar male moth captures between those treatments.

The number of male moths captured in open canopies was similar to moth capture in unaltered canopies in 2012 (Fig. 3). No significant differences in total number of male moths captured during the entire season were detected between canopy treatments in 2012 ( $F_{1,4} = 0.22$ ,  $P > 0.65$ ). Similarly, there were no significant differences between treatments in the number of moths caught during any of the three generations in 2012 (Generation 1:  $F_{1,4} = 0.05$ ,  $P > 0.84$ ; Generation 2:  $F_{1,4} = 0.65$ ,  $P > 0.46$ ; Generation 3:  $F_{1,4} = 0.12$ ,  $P > 0.74$ ). In 2014, significantly more male moths were captured in unaltered canopies than in open canopies during the second generation ( $F_{1,4} = 15.22$ ,  $P < 0.018$ ; Fig. 3). However, we found no significant



**Fig. 2.** Effect of cluster removal on capture of male *P. viteana*. Captures of male *P. viteana* in plots with 0, 50, or 100% of clusters removed in 2013, 2014, and 2015. Columns with the same letter are not significantly different; 'NS' indicates no significant differences were found among treatments,  $P > 0.05$ .



**Fig. 3.** Effect of manipulating canopy structure on captures of male *P. viteana*. Male captures in plots with unaltered, dense juice grape canopies (Unaltered) or canopies held open with a triangular tunnel (Open) in 2012, 2014, and 2015. Asterisks indicate treatments were significantly different ( $P < 0.05$ ). This experiment was run in a Concord vineyard in 2012, and in a Niagara vineyard in 2014 and 2015.

differences in the number of male moths captured between canopy treatments during the first ( $F_{1,4} = 5.74$ ,  $P > 0.07$ ) or third generation ( $F_{1,4} = 3.59$ ,  $P > 0.13$ ). The sum of moth captures over the entire season was also similar between canopy treatments ( $F_{1,4} = 5.72$ ,  $P > 0.07$ ). Moth captures in unaltered canopies were significantly greater than captures in open canopies only during the third generation in 2015 (Fig. 3; Generation 3:  $X^2 = 5.12$ ,  $df = 1$ ,  $P < 0.03$ ). Although the average number of males captured in unaltered canopies was arithmetically greater than captures in open canopies in the second generation, these differences were not statistically significant because of considerable variability within treatments (Generation 1:  $X^2 = 2.45$ ,  $df = 1$ ,  $P > 0.11$ ; Generation 2:  $X^2 = 3.55$ ,  $df = 1$ ,  $P < 0.06$ ). Similarly, total captures for the season were not different between canopy treatments (Fig. 3). Season total:  $X^2 = 0.53$ ,  $df = 1$ ,  $P > 0.46$ ). The consistent pattern of numerically higher male captures in unaltered canopies during the second and third generations shows the canopy does not reduce moth capture, and it suggests that shoots and leaves may be used by males to find traps or calling females.

## Discussion

These experiments show that captures of male *P. viteana* are not consistently affected by cluster density or by the vine canopy structure in juice grape (cv Concord and cv Niagara) vineyards. When we did observe treatment effects on moth captures, the results did not help to explain the previously documented reduction in male *P. viteana* captures in monitoring traps in the middle and late season.

In the cluster density experiment in 2013, we caught significantly more males in plots where clusters were left intact than in plots with 50 or 100% of the clusters removed. This effect was not present in the following years when treatment locations were re-randomized, as there were no significant differences between cluster removal treatments in 2014 or 2015. We interpret this as evidence of a location effect in 2013, likely because by chance our control plots were near areas of high male moth activity/density. The results from all 3 yr of our study falsified our original hypothesis that cluster density reduces male *P. viteana* capture in traps. Therefore, the presence or density

of fruit does not cause the reduction of male captures of *P. viteana* in pheromone traps that occurs during the second and third generations (Snyder et al. 1992, Teixeira et al. 2009). Even though clusters increase greatly in size and the volatile chemicals produced by fruit clusters change markedly through the season, it appears they are not a critical cue used by male *P. viteana*. This contrasts the behavior of some other fruit feeding tortricids such as *L. botrana*, *C. pomonella*, and *G. molesta* that are attracted to volatiles derived from fruit (Knight and Light 2005, Piñero and Dorn 2007, Tasin et al. 2010). However, these three species all feed on multiple hosts, so we cannot rule out some contribution of diet breadth to the difference between these pests and the specialist, *P. viteana*. A meta-analysis comparing the responses of males of different species to host plant volatiles derived from fruit to those present in shoots may help explain these differences, but that is beyond the scope of the present work. Our results are also consistent with previous research that shows fruit is less attractive than grape shoot tips and leaves to *P. viteana* (Cha et al. 2008a,b). Males are strongly attracted to shoot tips and leaves in addition to sex pheromone, and we saw that a change in the density of fruit does not affect male moth capture. We would expect an increase in vegetative growth when clusters are removed, and this presumably would lead to an increase in the amount of leaf volatiles in areas where clusters are removed. It is conceivable that an increase in leaf volatiles could draw more males into the cluster removal plots, but these males may be attracted to leaves and not to traps. Unfortunately, we did not measure vegetative growth or leaf volatile titers in our research plots, so we cannot directly assess the effect these factors had on male capture.

In 2 of the 3 yr of our canopy structure study, we found consistent arithmetical differences between male captures in vineyard plots with an unaltered canopy and those that were opened using an artificial tunnel. In 2012, the effects of these treatments did not differ, whereas in the second generation in 2014 and in the third generation in 2015, the number of males captured in unaltered canopies was significantly higher than in open canopies. These results show that the canopy does not impede the movement of male moths to traps. Captures of *P. viteana* in dense, unaltered grape canopies were higher than in open canopies, which highlights the possible importance of shoots and leaves in male trap finding behavior. As volatile compounds are attractive to male *P. viteana*, (Cha et al. 2008a,b), we may have caught more males in unaltered canopies because traps were in closer proximity to leaves in the unaltered versus open treatments. We were unable to assess the effect of the seasonal increase in leaf volatile titer on male captures because we did not manipulate the amount of leaf area in experimental plots with pruning, leaf removal, etc., but we expect the titer of leaf volatiles would have been similar between treatments. Still the results of our experiment refute the hypothesis that canopy structure reduces male moth capture, and does not support the prediction that low captures of male *P. viteana* in traps at the end of the season are due to physical interference from the canopy.

It may be advantageous for a grape specialist such as *P. viteana* to respond more strongly to leaf volatiles than to fruit volatiles due to the climbing, spreading growth of grapevines in a natural setting. The total area of leaves of a grapevine is much greater than the area of the fruiting zone, and growing shoots may be several meters away from fruit clusters, particularly in uncultivated habitats (Mullins 1992). We would therefore argue that *P. viteana* moving through wooded areas are more likely to encounter leaves than fruit, so detecting leaf volatiles may be the optimal strategy for finding host plants within the dense deciduous habitats of eastern North America.

*P. viteana* has limited capacity for long flights and it seems well adapted to movement within the dense vegetation of its natural habitat (Botero-Garcés and Isaacs 2004). A series of short flights between shoots may be advantageous for an organism like *P. viteana* that must find mates and food resources in a structurally complex environment such as a contiguous forest or vineyard canopy. If *P. viteana* uses short flights between shoots to move around its environment, we would expect to see lower numbers of males in traps in open canopies, because the trap is outside of the space where the moths are moving. Movement in the canopy was not addressed in our study, but it could be explored using video recordings (Grieshop et al. 2012) in open and unaltered canopies to compare the movement behavior of moths in relation to varying habitat structure.

Some possible confounding factors may have influenced the canopy experiment, but it is unclear how important these were for our results. The experiment was performed at two different locations over 3 yr, and two closely related grape varieties were used. In 2012, the trial was performed in a commercial vineyard (*V. labrusca* L. cv ‘Concord’) in Lawton Michigan, while in 2014 and 2015, we used a *V. labrusca* L. (cv ‘Niagara’) vineyard 80 km away at the Trevor Nichols Research Center in Fennville, MI. High temperatures (25–30°C) in the spring of 2012 led to an early start of growth, and made this one of the warmest years on record for the region. Subsequent spring freezes reduced the crop load by 30–40% in the section of the vineyard we used, and the owner of the vineyard reduced his disease and insect management program, as is common practice in freeze years. The 2014 and 2015 growing seasons did not have a major freeze event, but they were some of the coolest seasons in the previous 20 yr, and the experimental vineyard did not receive insecticide in 2014 or 2015. In any given year, all of the treated plots were exposed to these factors to the same degree, so we conclude that there were no confounding effects from weather, location, or variety.

The fencing material that we used to construct the tunnels to create open canopies may have produced repellent odors, or created a visual pattern that could have deterred male moths from entering plots that contained the tunnels. Although we did not directly test for the effect of the fencing on male moth captures, our data suggest there was not a repellent effect. There were no significant differences in captures between plots with fencing (Open) and plots without this material (Unaltered) in the first generation. During this period, the grape canopy was not fully grown and the tunnels were visible and any odors from the fencing would also be present (Fig. 1). Our results show the juice grape canopy affects captures of male grape berry moth, but the observed effect does not explain the previously reported reduction of male *P. viteana* captures in pheromone traps during the second and third generations (Teixeira et al. 2009, Isaacs et al. 2012). We postulated that the unaltered juice grape canopy interferes with a male’s ability to find traps. However, we caught more males in traps that we placed in unaltered as opposed to open canopies, and from this, we propose that the canopy is an important component of trap and presumably mate finding. Surprisingly, fruit cluster presence or density did not consistently affect male captures, so we conclude that any effect the fruit may have does not contribute to the reduction of male captures during the middle and late season generations. There remains a need to explore the factors that cause reduced moth captures at the time when oviposition by *P. viteana* is increasing, and this could help to improve monitoring of this key vineyard pest. Additional studies that examine the reduction of captures during the second and third generation flights when oviposition and infestation increase will be reported later as separate publications. Other areas of research focus on testing the effects of temperature on some important aspects of mating behavior such as: female calling/receptivity to

mating; male diurnal activity; the timing and frequency of mating; the duration of the mating period; moth longevity; and oviposition. We are also testing the effect of seasonal temperature changes on the release rate of sex pheromone lures to determine if second and third generation males are repelled by monitoring traps due to higher pheromone release rate at high temperatures.

## Acknowledgments

We thank the Michigan grape growers who allowed us to work in their vineyards: Rick Brown, Bryan Cronenwett, Ed Oxley, and Bob Pagel. Thanks to Jordan Brandel, Hayley Sisson, Laura Bizzarri, Ian McCririe, Matt Hiles, Dan Pickard, the Trevor Nichols Research Center crew and the Isaacs' lab field assistants for technical assistance during this project. Funding was provided by Project GREEN (GR15-079-ISAACS-ENT), the National Grape Cooperative and the Ray and Bernice Hutson Memorial Entomology Endowment Fund.

## References Cited

- Bates, T. 2008. Pruning level affects growth and yield of New York concord on two training systems. *Am. J. Enol. Vitic.* 59: 276–286.
- Binns, M. R., and J. P. Nyrop. 1992. Sampling insect populations for the purpose of IPM decision making. *Annu. Rev. Entomol.* 37: 427–53.
- Botero-Garcés, N., and R. Isaacs. 2004. Movement of the grape berry moth, *Endopiza viteana*: displacement distance and direction. *Physiol. Entomol.* 29: 443–452.
- Bradley, S. J., J. T. S. Walker, C. H. Wearing, P. W. Shaw and A. J. Hodson. 1998. The use of pheromone traps for leafroller action thresholds in pip-fruit. *Proc. 51st N.Z. Plant Protection Conf.* 1998: 173–178.
- Bruce, T. J., L. J. Wadhams, and C. M. Woodcock. 2005. Insect host location: a volatile situation. *Trends Plant Sci.* 10: 269–274.
- Cha, D. H., S. P. Hesler, C. L. Moser, S. Nojima, C. E. Linn, Jr, W. L. Roelofs, and G. M. Loeb. 2008a. Flight tunnel responses of female grape berry moth (*Paralobesia viteana*) to host plants. *J. Chem. Ecol.* 34: 622–627.
- Cha, D. H., S. Nojima, S. P. Hesler, A. Zhang, C. E. Linn, Jr, W. L. Roelofs, and G. M. Loeb. 2008b. Identification and field evaluation of grape shoot volatiles attractive to female grape berry moth (*Paralobesia viteana*). *J. Chem. Ecol.* 34: 1180–1189.
- Clark, L. G., and T. J. Dennehy. 1988. Oviposition behavior of grape berry moth. *Entomol. Exp. Appl.* 47: 223–230.
- Coracini, M., M. Bengtsson, I. Liblikas, and P. Witzgall. 2004. Attraction of codling moth males to apple volatiles. *Entomol. Exp. Appl.* 110: 1–10.
- Dimitriadis, E., and P. J. Williams. 1984. The development and use of a rapid analytical technique for estimation of free and potentially volatile monoterpene flavorants of grapes. *Am. J. Enol. Vitic.* 35: 66–71.
- Dry, P. R. 2000. Canopy management for fruitfulness. *Aust. J. Grape Wine Res.* 6: 109–115.
- Faraone, N., G. D'Errico, V. Caleca, A. D. Cristofaro, and R. M. Trimble. 2013. Electrophysiological and behavioral responses of oriental fruit moth to the monoterpene citral alone and in combination with sex pheromone. *Environ. Entomol.* 42: 314–322.
- Fermaud, M., and R. Le Menn. 1992. Transmission of *Botrytis cinerea* to grapes by grape berry moth larvae. *Phytopathology.* 82: 1393–1398.
- Griehop, M. J., B. Werling, K. Buehrer, J. Perrone, R. Isaacs, and D. Landis. 2012. Big brother is watching: studying insect predation in the age of digital surveillance. *Am. Entomol.* 58: 172–182.
- Hoffman, C. J., T. J. Dennehy, and J. P. Nyrop. 1992. Phenology, monitoring, and control decision components of the grape berry moth (Lepidoptera: Tortricidae) risk assessment program in New York. *J. Econ. Entomol.* 85: 2218–2227.
- Hrazdina, G., G. F. Parsons, and L. R. Mattick. 1984. Physiological and biochemical events during development and maturation of grape berries. *Am. J. Enol. Vitic.* 35: 220–227.
- Il'ichev, A. L., S. Kugimiya, D. G. Williams, and J. Takabayashi. 2009. Volatile compounds from young peach shoots attract males of oriental fruit moth in the field. *J. Plant Interact.* 4: 289–294.
- Ioriatti, C., G. Anfora, M. Tasin, A. De Cristofaro, P. Witzgall, and A. Luchi. 2011. Chemical ecology and management of *Lobesia botrana* (Lepidoptera: Tortricidae). *J. Econ. Entomol.* 104: 1125–1137.
- Isaacs, R. 2017. MSU Enviroweather. [http://enviroweather.msu.edu/run.php?mc=138&stn=law&mod=f\\_gbm&da1=2&mo1=5&da2=16&mo2=5&yr=2015&ds=cd](http://enviroweather.msu.edu/run.php?mc=138&stn=law&mod=f_gbm&da1=2&mo1=5&da2=16&mo2=5&yr=2015&ds=cd), accessed December 22, 2017.
- Isaacs, R., L. A. F. Teixeira, P. E. Jenkins, N. Botero Neerdaels, G. M. Loeb, and M. C. Saunders. 2012. Biology and management of grape berry moth in North American vineyard ecosystems, pp. 361–381. *In* N. J. Bostanian, R. Isaacs, C. Vincent (eds.), *Arthropod management in vineyards: pests, approaches and future directions*. Springer, New York, NY.
- Jackson, D. I., and P. B. Lombard. 1993. Environmental and management practices affecting grape composition and wine quality - a review. *Am. J. Enol. Vitic.* 44: 409–430.
- JMP Pro 13.1.0. 2016. SAS Institute Inc. Cary, NC.
- Johnson, F., and A. G. Hammar. 1912. The grape berry moth. U.S. Department of Agriculture Bulletin 116: 15–71. US Department of Agriculture. Washington, DC.
- Jordan, M. D., A. Anderson, D. Begum, C. Carraher, A. Authier, S. D. Marshall, A. Kiely, L. N. Gatehouse, D. R. Greenwood, D. L. Christie, et al. 2009. Odorant receptors from the light brown apple moth (*Epiphyas postvittana*) recognize important volatile compounds produced by plants. *Chem. Senses.* 34: 383–394.
- Knight, A. L., and D. M. Light. 2005. Developing action thresholds for codling moth (Lepidoptera: Tortricidae) with pear-ester and codlemone-baited traps in apple orchards treated with sex pheromone mating disruption. *Can. Entomol.* 137: 739–747.
- Knight, A. L., R. Hilton, and D. M. Light. 2005. Monitoring codling moth (Lepidoptera: Tortricidae) in apple with blends of ethyl (E, Z)-2, 4-decadienoate and codlemone. *Environ. Entomol.* 34: 598–603.
- Leskey, T. C., J. C. Piñero, and R. J. Prokopy. 2008. Odor-baited trap trees: a novel management tool for plum curculio (Coleoptera: Curculionidae). *J. Econ. Entomol.* 101: 1302–1309.
- Light, D. M., and A. Knight. 2005. Specificity of codling moth (Lepidoptera: Tortricidae) for the host plant kairomone, ethyl (2E,4Z)-2,4-decadienoate: field bioassays with pome fruit volatiles, analogue, and isomeric compounds. *J. Agric. Food Chem.* 53: 4046–4053.
- Light, D. M., A. L. Knight, C. A. Henrick, D. Rajapaska, B. Lingren, J. C. Dickens, K. M. Reynolds, R. G. Buttery, G. Merrill, J. Roitman, et al. 2001. A pear-derived kairomone with pheromonal potency that attracts male and female codling moth, *Cydia pomonella* (L.). *Naturwissenschaften.* 88: 333–338.
- Loeb, G. M., D. H. Cha, S. P. Hesler, C. E. Linn, Jr, A. Zhang, P. E. Teal, and W. L. Roelofs. 2011. Monitoring grape berry moth (*Paralobesia viteana*: Lepidoptera) in commercial vineyards using a host plant based synthetic lure. *Environ. Entomol.* 40: 1511–1522.
- Lu, P. F., L. Q. Huang, and C. Z. Wang. 2012. Identification and field evaluation of pear fruit volatiles attractive to the oriental fruit moth, *Cydia molesta*. *J. Chem. Ecol.* 38: 1003–1016.
- Miller, D. P., and G. S. Howell. 1998. Influence of vine capacity and crop load on canopy development, morphology, and dry matter partitioning in concord grapevines. *Am. J. Enol. Vitic.* 49: 183–190.
- Miller, J. R., L. J. Gut, F. M. de Lame, and L. L. Stelinski. 2006. Differentiation of competitive vs. non-competitive mechanisms mediating disruption of moth sexual communication by point sources of sex pheromone (part 2): case studies. *J. Chem. Ecol.* 32: 2115–2143.
- Mondy, N., B. Charrier, M. Fermaud, P. Pracros, and M. F. Corio-Costet. 1998. Mutualism between a phytopathogenic fungus (*Botrytis cinerea*) and a vineyard pest (*Lobesia botrana*). Positive effects on insect development and oviposition behaviour. *Life Sci.* 321: 665–671.
- Mullins, M. G., A. Bouquet, and L. E. Williams. 1992. *Biology of the grapevine*. Cambridge University Press. Cambridge, United Kingdom.
- Piñero, J. C., and S. Dorn. 2007. Synergism between aromatic compounds and green leaf volatiles derived from the host plant underlies female attraction in the oriental fruit moth. *Entomol. Exp. Appl.* 125: 185–194.
- Piñero, J. C., and S. Dorn. 2009. Response of female oriental fruit moth to volatiles from apple and peach trees at three phenological stages. *Entomol. Exp. Appl.* 131: 67–74.

- Reddy, G. V. P., and M. Manjunatha. 2000. Laboratory and field studies on the integrated pest management of *Helicoverpa armigera* (Hübner) in cotton, based on pheromone trap catch and threshold level. *J. Appl. Ent.* 124: 213–221.
- Rosillo, L., M. R. Salinas, J. Garijo, and G. L. Alonso. 1999. Study of volatiles in grapes by dynamic headspace analysis: application to the differentiation of some *Vitis vinifera* varieties. *J. Agric. Food Chem.* 47: 155–159.
- Roubos, C. R., K. Mason, L. A. F. Teixeira, and R. Isaacs. 2013. Yield-based economic thresholds for grape berry moth (Lepidoptera: Tortricidae) in juice grapes. *J. Econ. Entomol.* 106: 905–911.
- Savee, A. M., S. H. Kromann, G. Birgersson, M. Bengtsson, T. Lindblom, A. Balkenius, B. S. Hansson, P. Witzgall, P. G. Becher, and R. Ignell. 2012. Floral to green: mating switches moth olfactory coding and preference. *Proc. Biol. Sci.* 279: 2314–2322.
- Schultz, H. R. 1995. Grape canopy structure, light microclimate and photosynthesis 1. A two-dimensional model of the spatial distribution of surface area densities and leaf ages in two canopy systems. *Vitis*. 34: 211–215.
- Singleton, V. L., and E. Trousdale. 1983. White wine phenolics: varietal and processing differences as shown by HPLC. *Am. J. Enol. Vitic.* 34: 27–34.
- Smart, R. E., N. J. Shaulis, and E. R. Lemon. 1982. The Effect of Concord vineyard microclimate on yield. Yield I. The effects of pruning, training and shoot positioning on radiation microclimate. *Am. J. Enol. Vitic.* 33: 99–108.
- Snyder, D. P., T. H. Weigle, and G. B. White. 1992. Economics of integrated pest management practices for insects in grape production. College of Agriculture and Life Sciences Bulletin 92-1. Cornell University, Ithaca, NY.
- Stelinski, L. L., J. R. Miller, N. E. Ressa, and L. J. Gut. 2003. Increased EAG responses of tortricid moths after prolonged exposure to plant volatiles: evidence for octopamine-mediated sensitization. *J. Insect Physiol.* 49: 845–856.
- Tasin, M., G. Anfora, C. Ioriatti, S. Carlin, A. De Cristofaro, S. Schmidt, M. Bengtsson, G. Versini, and P. Witzgall. 2005. Antennal and behavioral responses of grapevine moth *Lobesia botrana* females to volatiles from grapevine. *J. Chem. Ecol.* 31: 77–87.
- Tasin, M., A. C. Bäckman, M. Bengtsson, C. Ioriatti, and P. Witzgall. 2006. Essential host plant cues in the grapevine moth. *Naturwissenschaften*. 93: 141–144.
- Tasin, M., A. C. Bäckman, G. Anfora, S. Carlin, C. Ioriatti, and P. Witzgall. 2010. Attraction of female grapevine moth to common and specific olfactory cues from 2 host plants. *Chem. Senses*. 35: 57–64.
- Teixeira, L. A., K. Mason, and R. Isaacs. 2009. Control of grape berry moth (Lepidoptera: Tortricidae) in relation to oviposition phenology. *J. Econ. Entomol.* 102: 692–698.
- Tobin, P. C., S. Nagarkatti, and M. C. Saunders. 2001. Modeling development in grape berry moth (Lepidoptera: Tortricidae). *Environ. Entomol.* 30: 692–699.
- Tobin, P. C., S. Nagarkatti, and M. C. Saunders. 2003. Phenology of grape berry moth (Lepidoptera: Tortricidae) in cultivated grape at selected geographic locations. *Environ. Entomol.* 32: 340–346.
- Varela, N., J. Avilla, C. Gemenio, and S. Anton. 2011. Ordinary glomeruli in the antennal lobe of male and female tortricid moth *Grapholita molesta* (Busck) (Lepidoptera: Tortricidae) process sex pheromone and host-plant volatiles. *J. Exp. Biol.* 214: 637–645.
- Wearing, C. H., P. J. Connor, and K. D. Ambler. 1973. Olfactory stimulation of oviposition and flight activity of the codling moth *Laspeyresia pomonella*, using apples in an automated olfactometer. *N. Z. J. Sci.* 16: 687–710.
- Wise, J. C., P. E. Jenkins, A. M. Schilder, C. Vandervoort, and R. Isaacs. 2010. Sprayer type and water volume influence pesticide deposition and control of insect pests and diseases in juice grapes. *Crop Prot.* 29: 378–385.
- Yan, F., M. Bengtsson, and P. Witzgall. 1999. Behavioral response of female codling moths, *Cydia pomonella*, to apple volatiles. *J. Chem. Ecol.* 25: 1343–1351.