Journal of Integrated Pest Management, (2017) 8(1): 30; 1–7
doi: 10.1093/jipm/pmx027
Profile

OXFORD

Grape Root Borer (Lepidoptera: Sesiidae): An Economic Pest of Commercial Vineyards in the Eastern United States

Jhalendra P. Rijal[1,3] and J. Christopher Bergh[2]

[1]University of California Cooperative Extension & UC Statewide IPM Program, 3800 Cornucopia Way, Ste. A, Modesto, CA 95358, [2]Department of Entomology, Virginia Tech, Alson H. Smith, Jr. Agricultural Research and Extension Center, 595 Laurel Grove Road, Winchester, VA 22602, [3]Corresponding author, e-mail: jrijal@ucdavis.edu

Subject Editor: Danesha Carley

Received 31 August 2017; Editorial decision 4 October 2017

Abstract

Grape root borer, *Vitacea polistiformis* (Harris; Lepidoptera: Sesiidae) is indigenous to the eastern United States and an economically important pest of commercial vineyards much of that region. After eclosion from eggs laid above ground, the oligophagous larvae burrow into the soil and feed on grape roots for 1–3 yr before pupating and emerging as an adult moth. Compared with many other lepidopteran pests of economic crops, the development of IPM tactics for grape root borer has lagged. Indeed, an important ongoing issue is that grape growers often remain unaware of an infestation until the vines show advanced symptoms. While captures of males in sex pheromone-baited traps can be used to determine the initiation, peak, and cessation of adult flight annually, they are not useful to assess the degree of infestation in individual vineyard blocks. Regular sampling of the pupal exuviae left by emerging adults is the optimal method to assess grape root populations in commercial vineyards. The biology and pest status of grape root borer are reviewed and recent developments toward improved monitoring and management tactics for it are discussed.

Key words: *Vitacea polistiformis*, pupal exuviae, monitoring, *Vitis* spp.

Grape root borer, *Vitacea polistiformis* (Harris; Lepidoptera: Sesiidae) is a clearwing moth with edaphic, oligophagous larvae that feed on roots of grape, *Vitis*, and a potentially destructive vineyard pest in portions of the eastern United States (Harris 1854, Brooks 1907, Clark and Enns 1964, Pollet 1975, All and Dutcher 1978). Larvae feed on roots of wild vines, and commercially important *Vitis* species and rootstocks, leading to vine decline and the death of some vines (Clark and Enns 1964, Dutcher and All 1976, All et al. 1987). Grower adoption of monitoring tactics for grape root borer in commercial vineyards is inconsistent, and a chronic problem has been that management decisions for it are typically in response to the detection of infestations that have become severe. Although some recent studies have focused on understanding larval food-finding behavior and the abiotic factors associated with differences in the extent of grape root borer infestations in vineyards, the development, and implementation of coordinated IPM tactics targeting grape root borer has lagged those for other pests. Here, we review the biology and pest status of grape root borer and recent developments that should inform and enhance management decisions by growers.

Geographic Distribution, Life History, and Description of Life Stages

Based on records of grape root borer presence and activity using sex pheromone traps and larval damage to vineyards, its geographic range has been reported to extend from Vermont to Florida and from Minnesota to Texas (Brooks 1918, Pollet 1975, Snow et al. 1991, Taft et al. 1991).

Adults

Grape root borer adults resemble *Polistes* wasps, from which the species name was derived (Harris 1854, Brooks 1907), and are dark to lustrous brown with orange and yellow bands on the abdomen (Brooks 1907, Sorensen 1975) (Fig. 1A–C). Males are characterized by two pairs of orange tufts of scales on the posterior end of the abdomen (Harris 1854, Duckworth and Eichlin 1977) (Fig. 1B).

Adults emerge from the soil around the base of vines between 9:00 and 11:00 a.m. (Brooks 1918, Pearson 1992) and a 1:1 sex ratio has been reported (Dutcher and All 1978b, Townsend and Micinski 1981). Newly emerged moths usually rest on the lower vine trunk while their wings expand and dry, and it is during this period that moths are most easily detected by visual scouting. Females then move to the vine canopy to begin releasing sex pheromone ('calling') in the afternoon of warm, sunny days. Mating usually occurs within 30 min of the onset of calling (Dutcher and All 1979a, Snow et al. 1987, Pearson 1992) and can extend over 4 h (Clark and Enns 1964, Dutcher and All 1978a) (Fig. 1C). Egg-laying may begin soon after mating or on the following day (Brooks 1907, Clark and Enns 1964, Dutcher and All 1979a). Females deposit 350–500 eggs on

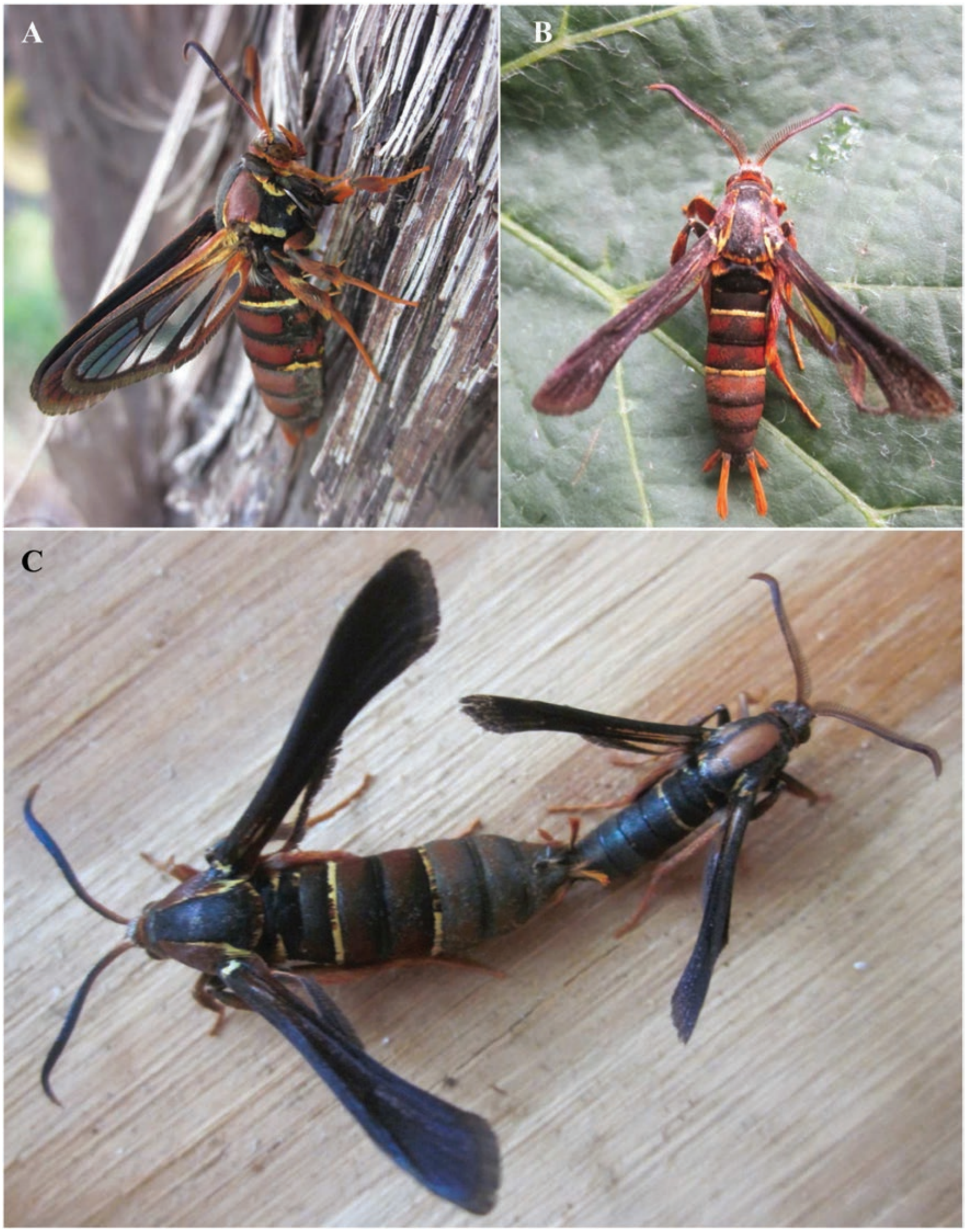

Fig. 1. Grape root borer adults (A) newly emerged female on the trunk of a grape vine, (B) male, (C) and pair *in copula*.

grapevines and weeds in the vine row over 7–8 d (Brooks 1907, Sorensen 1975, Dutcher and All 1979a), although ~50% of their egg complement is laid during the first 1–2 d (Clark and Enns 1964, Dutcher and All 1979a). Brooks (1918) observed that females lay single eggs at intervals of a few inches along the vine over a distance of ~3 m.

Eggs

Eggs are 1.05–1.10 mm long and 0.70–0.75 wide, dark brown and elliptical in shape with a reticulated dorsal surface and a longitudinal groove on the ventral surface (Fig. 2A) (Brooks 1918, Bambara and Neunzig 1977). They are thought to be easily dislodged from plant surfaces, and many may drop to the soil (Brooks 1907, Wylie and Johnson 1978) before eclosing in about 15 d at 30°C (Dutcher and All 1978a). Newly eclosed larvae are about 2.4 mm in length, cream in color with a brown head capsule (Bambara and Neunzig 1977) (Fig. 2B) and almost immediately burrow into the soil to search for roots (Brooks 1918, Clark and Enns 1964). Larvae have been reported moving to soil depths of up to 120 cm (Brooks 1907, 1918; Rijal and Bergh 2016), which likely depends on soil type, texture, and moisture content.

Larvae

Larval developmental duration ranges from 1 to 3 yr across its geographic range (reviewed in Bergh 2012), with the shortest and longest periods in southern (e.g., Florida, Georgia) and northern regions (e.g., Ohio), respectively. Based on a potted vine study in Florida, Webb and Mortensen (1990) reported larval development in 1 yr. Following their initial establishment on roots, larvae eventually bore into the root cortex and create diagnostic feeding channels packed with reddish frass that increase in diameter as larvae mature (Dutcher and All 1979a) (Fig. 2C and D). Younger larvae are distributed uniformly throughout the root system but tend to move toward the crown of the vine during their development (Clark

Fig. 2. Grape root borer (A) egg, (B) freshly eclosed larva, (C) larva feeding on root, (D) larval damage on grape root showing feeding channel packed with diagnostic reddish frass, (E) pupal exuviae protruding from soil at the vine base, and (F) pupal exuviae lying on the soil surface.

and Enns 1964, Sarai 1972, Dutcher and All 1979a). Although larvae spend 1–3 yr inside roots depending on geographic location, feeding may cease during winter (Brooks 1918, All et al. 1987). The number of instars has not been determined, but larvae are ~29 mm long and 6 mm wide at the end of their feeding period (Bambara and Neunzig 1977).

Upon completing development, larvae move to within ~5 cm of the soil surface to pupate within cocoons of soil, frass, and silk (Pollet 1975, Dutcher and All 1979a). Pupae are 19 mm long and 5.4 mm wide and vary in color from yellowish brown to dark brown (Bambara and Neunzig 1977), and the average duration of male and female pupal development is 29 and 33 d, respectively (Dutcher and All 1979a). Pupae use spiral body movements to move to the soil surface, where adult moths emerge (Dutcher and All 1979a), leaving the copper-colored exuviae lying on or protruding through the soil surface (Pollet 1975, Dutcher and All 1979a) (Fig. 2E and F). The majority of pupal exuviae are found within a 35 cm radius from the vine base (Clark and Enns 1964, Dutcher and All 1978c).

Seasonal Phenology

The adult flight period varies with latitude, ranging from 2 mo in the northern portions of its range to 6 mo in central and south Florida (Pfeiffer et al. 1990, Snow et al. 1991, Webb et al. 1992, Bergh et al. 2005, Weihman and Liburd 2007, Said et al. 2015). In Virginia, adults emerge from about late June until about early September, with peak emergence between late July and early August (Pfeiffer et al. 1990, Rijal et al. 2014b). In Florida, adult activity begins between early May and early August and extends into December, with peak activity varying from mid-August to early October in different parts of that State (Snow et al. 1991, Webb et al. 1992, Weihman and Liburd 2007). The onset and duration of adult emergence are affected by variations in annual temperature and rainfall (Clark and Enns 1964, Sarai 1972, Webb et al. 1992); higher temperatures can trigger an earlier onset of emergence while high rainfall can extend the duration of the emergence period.

Pest Status

Vineyards in the eastern United States are often planted near forested areas containing wild grape and their infestation by grape root borer is thought to originate via populations that immigrate from wild vines (Brooks 1907, All et al. 1987, Snow et al. 1991, Bergh 2006). At least ten species of native *Vitis* have been recorded in southeastern States (Massey 1945), but their relative suitability for larval development is unknown. The earliest reports of infestations in commercial plantings were from vineyards in Kentucky, Missouri, North Carolina, and Ohio (Harris 1854, Walsh 1868). In the 1870s, a severe infestation was reported from Albemarle, North Carolina, involving the loss of ~5000 vines from 107 cultivars of *Vitis vinifera* imported from France (reviewed in Brooks 1918). Pollet (1975) reported that the pest destroyed ~300–350 acres of bunch grapes, *Vitis labrusca*, in South Carolina between 1967 and 1975 and that many growers in that State had ceased grape production as a result.

Grape root borer has caused widespread damage to wine and table grape species, including *V. vinifera, V. labrusca*, and *Vitis rotundifolia* Michx. (Johnson et al. 1981, Webb and Mortensen 1990, Olien et al. 1993), and is considered as a pest of all commercially important grape cultivars (Harris et al. 1994). Larval feeding can completely destroy smaller roots (<1.5 cm diameter), but the girdling that results from larval feeding at the crown can have a significant impact. It has been suggested that a single larva may kill a vine (Sarai 1972, Pollet 1975), while Dutcher and All (1976) mentioned that nine larvae are enough to girdle and kill a grape vine with an 8″ base circumference. Twenty-five or more larvae have been reported on the root system of individual vines (Brooks 1907, Clark and Enns 1964), and Rijal (2014) recorded 38 larvae on just the exposed portion of the root system of a vine that was pulled from a severely infested vineyard in Virginia. Wylie and Johnson (1978) noted that larval densities were reduced on heavily damaged vine roots and suggested that this may have been due to resource depletion or to higher numbers of natural enemies in the vineyard.

Vineyard managers are often unaware that grape root borer has become established until the cumulative effects of feeding injury over several years have become apparent (Brooks 1907, Dutcher and All 1979b). This is largely due to a chronic lack of monitoring and scouting by growers (Bergh 2012) and to the lack of diagnostic symptoms on the aboveground parts of vines that can be ascribed unequivocally to the effects of larval feeding on the root system (Brooks 1918, All et al. 1987). Although indistinguishable from the symptoms that can be caused by other conditions, symptoms associated with grape root borer infestations are discolored and smaller leaves, reduced shoot growth, fewer and smaller berries, and vine wilting (Sorensen 1975, All et al. 1987), collectively known as 'slow vine decline' (All et al. 1987). All et al. (1987) noted that infested vines usually began to show symptoms after 5–10 yr of feeding and declined progressively over 3 to 5 yr, although Pollet (1975) suggested that larval feeding may affect vine health and berry yield in the second year of infestation. Brooks (1918) observed that infested vines under proper pruning, fertilization, and cultural management produced a satisfactory crop for at least 10 yr, while neglected vines died over several years (Brooks 1918).

Monitoring and Infestation Assessment

Methods to monitor and assess grape root borer populations in vineyards include inspecting the roots of vines that have been removed from the soil, deploying pheromone-baited traps, and scouting for pupal exuviae.

Root Inspection

Root examination for grape root borer larvae and feeding sites can provide an approximation of the current and past infestation status of individual vines and has been employed in previous studies (Brooks 1918, Sarai 1972, Dutcher and All 1979b, Jubb 1982, Harris et al. 1994, Johnson et al. 2013). However, this rather crude and destructive sampling approach is not a pragmatic option in any but extreme circumstances, and likely underestimates the extent of infestation, since only a portion of the root system is exposed when vines are pulled from the ground.

Pheromone Traps

Male grape root borers are strong and swift fliers and their response to a sex pheromone lure is very rapid; it is quite common to observe them orienting to the lure even before a baited trap has been placed on the trellis. Thus, pheromone traps are very efficient and sensitive for monitoring the onset, peak, and duration of its flight activity in vineyards (Johnson et al. 1986, Alm et al. 1989, Johnson et al. 1991, Snow et al. 1991, Webb et al. 1992, Harris et al. 1994, Weihman and Liburd 2007). However, while never specifically measured, it appears likely that male grape root borer responds to traps over a considerable distance. Because males originating from wild vines and/or nearby vineyards or vineyard blocks are also captured, the numbers of moths in traps do not necessarily reflect the infestation status of individual blocks (Snow et al. 1991, Webb et al. 1992, Bergh 2006). Rijal (2014) concluded that weekly captures of male moths in pheromone-baited traps deployed in individual blocks were not a reliable predictor of weekly numbers of pupal exuviae in the same blocks, somewhat limiting the utility of captures in pheromone traps for population assessment.

Pupal Exuviae Sampling

Recording the number of pupal exuviae around the base of vines at regular intervals during the adult emergence period is only the unequivocal, nondestructive indicator of the infestation status of individual vines and vineyard blocks. Pupal exuviae sampling has been used to measure the effects of cultural practices on infestations (Townsend 1991), to determine the distribution of pupae around the vine base (Dutcher and All 1978c), and to assess the effects of control measures (Johnson et al. 1991, Pearson 1992, Johnson et al. 2013). To measure pupal exuviae density most accurately, an area of about 1 m diameter around the base of each sample vine should be cleaned to the soil surface prior to the onset of sampling and maintained free of vegetation for the duration of the sampling period. This is easily accomplished using a 'weedwacker' and raking and enables observers to find exuviae readily, as the shiny, copper colored exuviae are easily seen against a bare soil background. Typically, a trained observer can conduct this sampling in <1 min per vine. Rijal et al. (2014a) used weekly pupal exuviae sampling throughout the adult emergence period in Virginia to characterize the spatial distribution of grape root borer infestations in vineyards and reported that 73.6% of all pupal exuviae were found during the period between the second week of July and first week of August. In addition, they developed a sampling scheme based on the spatial distribution of exuviae, involving weekly collections from a grid of sample vines during the 3–4 wk period of peak moth emergence. Because the pupal exuviae collected from individual vineyard blocks tended to show 'hot spots' within which they were aggregated, Rijal et al. (2014a) calculated that independent sampling can be achieved by spacing the sample vines at 9 m intervals.

Rijal et al. (2014b) showed that 50 commercial vineyards in Virginia varied considerably in the extent to which they were infested by grape root borer; some vineyards or individual blocks supported damaging populations while others were relatively unaffected. Reports from North Carolina support this finding (Burrack, pers. comm.). Ultimately, grape root borer infestations are dependent upon the survivorship of the eggs and successful establishment of young larvae on roots. Dutcher and All (1978b) reported that the majority of grape root borer mortality was during the egg and early larval stages. Sarai (1972) concluded that soil moisture likely influences the survivorship of first instars; dry soil causes larval desiccation and higher mortality than soil with a higher moisture content. However, Townsend's (1991) multi-year examination of the effects of several ground cover treatments and irrigation regimens on infestations in vineyards in Missouri showed in no differences in pupal exuviae counts or adult emergence among the treatments after 2 yr. Using data from season-long pupal exuviae sampling in Virginia vineyards and 18 potential horticultural, cultural, and environmental risk factors, Rijal et al. (2014b) examined the association between these biotic and abiotic factors and grape root borer density. They concluded that two abiotic factors, soil clay/sand ratio and water holding capacity were most strongly associated with differences among the vineyards in the level of pest infestation. These two factors were used to develop a risk prediction model to enable growers to predict the relative risk that newly established blocks might become heavily infested and/or to assess the probability that established plantings are likely to be more or less heavily infested. In turn, this information may guide grower decisions about appropriate levels of monitoring this pest in their vineyards.

Grape Root Borer Management

Cultural Practices

Historically, cultural practices were used to manage grape root borer infestations in vineyards. Brooks (1907) suggested that soil cultivation near the vine base to expose pupae or bury them deeply during the period of pupation and adult emergence would reduce future infestations. A laboratory study by Sarai (1969) resulted in >93% mortality of pupae buried in soil to a depth of ≥2.5 cm. A 15–25 cm deep mound under vines reduced adult emergence by ~85 to 90% (Sarai 1969, Wylie 1972) and 25–30 cm deep mounds around the vine base at about 90% pupation revitalized a South Carolina vineyard after 2 yr (Pollet 1975). However, soil mounding is labor-intensive in regions where larvae develop over 2 yr, since mounds must be created and removed annually for at least for two consecutive seasons and may cause soil erosion on sloped terrain. Polyethylene sheets in vine rows have been used to create a mechanical barrier to adult emergence (Attwood and Wylie 1963), although this may not be a pragmatic or cost-effective solution option on large acreage (Yonce 1995).

Host Plant Resistance

There have been attempts to examine the potential resistance of some *Vitis* spp. to grape root borer infestation. Walsh (1868) reported that southern fox grape, *Vitis vulpina*, was potentially resistant and some growers used vines grafted on *V. vulpina* rootstock during the late 1860s. Engelhardt (1946) reported that a well-established planting of fox grape, *V. labrusca*, on Staten Island, New York was infested. Brooks (1907) stated that *V. rotundifolia* was resistant to grape root borer larvae, but later studies did not support that conclusion (Wylie 1972, Wylie and Johnson 1978, Johnson et al. 1981). Webb and Mortensen (1990) measured less damage by larvae on roots of cultivars having the native leatherleaf grape, *Vitis shuttleworthii* House, in their parentage. Rijal et al. (2014b) reported no differences in infestation among various grape rootstocks, but Rijal (unpublished data) observed one instance of a heavily-infested block of Chardonnay vines next to a block of the native, *Vitis aestivalis* Michx., (cv. 'Norton') on its own roots that yielded no pupal exuviae. However, there is no evidence of resistance to grape root borer in commercially important grape cultivars or rootstocks.

Natural Enemies

Natural enemies of grape root borer include fungal pathogens, entomopathogenic nematodes (Dutcher and All 1978b; All et al. 1981; Saunders and All 1985; Williams et al. 2002, 2010), a parasitoid, (Brooks 1907), predatory firefly larvae, birds and other vertebrate predators (Clark and Enns 1964, Taylor 1965, Sarai 1972, Sorensen 1975). Although there may be opportunities to exploit a broader range of these natural enemies for grape root borer biological control, research to date has focused on the effects of entomopathogenic nematodes (reviewed in Bergh 2012). The nematode, *Steinernema carpocapsae* (Wiser), was effective against grape root borer larvae in laboratory studies (All et al. 1981, Saunders and All 1985), but not in greenhouse or field trials (All et al. 1981, Saunders and All 1985). Williams et al. (2002) tested several strains of nematodes in the laboratory and greenhouse and selected *Heterorhabditis bacteriophora* Poinar (GPS11 strain) and *Heterorhabditis zealandica* Poinar (X1 strain) for further evaluation in the field. Later, Williams et al. (2010) reported that the native nematode, *H. bacteriophera*, effectively reduced grape root borer infestations in the field and that it showed higher persistence in soil than the non-native, *H. zealandica*. Recently, two commercially available nematode species, *H. bacteriophora*, and *Heterorhabditis megidis* Poinar, Jackson & Klein were found to be as effective as the insecticide, chlorpyrifos, treatment for reducing a grape root borer infestation (Said et al. 2015). Despite the success of these nematodes in research trials, their adoption on a commercial scale is limited or perhaps nonexistent, possibly due to a lack of grower education.

Chemical Control

Currently, chlorpyrifos is the only insecticide labeled for use against grape root borer, applied as a soil drench around the base of vines as a toxic barrier to the movement of neonates to roots. The residual activity of chlorpyrifos against larvae in soil is about 4 wk (All et al. 1985), and such applications provide better efficacy when vine rows are free of vegetation (All et al. 1987). Its 35-d pre-harvest interval in grapes is problematic for early maturing cultivars and for use in southern states, where harvest coincides with peak eclosion of grape root borer eggs (Pritchard 2004, Bergh 2012). As well, many wine grape growers are reluctant to use chlorpyrifos in this manner, based on their perceptions of its negative impacts on soil biodiversity and associated effects on vine health, berry quality, and ultimately, wine quality (Bergh 2012).

Mating Disruption

Early assessments of the potential utility of sex pheromone-based mating disruption for grape root borer management showed a significant reduction in the number of male moths attracted to a caged virgin female in treated plots (Johnson et al. 1981). Trials using the minor pheromone component, (Z, Z)-3,13-ODDA, the major component [(E, Z)-2,13-ODDA], or both components together, resulted in significant reductions in captures in traps or infestations in commercial vineyards (Johnson et al. 1986, Johnson et al. 1991, Pearson 1992). Weihman and Liburd (2006) used dispensers containing 95% (E, Z)-2,13-ODDA (95%) and (E, Z)-3,13-octadecadien-1-ol (5%) and reported that captures in pheromone-baited traps were eliminated. Pfeiffer et al. (2010) reported reduced pupal exuviae counts in disrupted vineyard blocks in Virginia and Sanders et al. (2011) showed that a wax-based 'Specialized Pheromone and Lure Application Technology' (SPLAT) was also effective. Johnson et al. (2013) deployed three densities (127, 370, 494 or 741 dispensers/ha) of Isonet-Z dispensers, a new sex pheromone blend of the leopard moth, *Zeuzera pyrina*, consisting of a 95:5 blend of

(E, Z)-2,13-ODDA and (E, Z)-3,13-ODDA, and reported complete trap shutdown in the disrupted plots. Currently, Isomate-GRB, a 99:1 blend of (E, Z)-2, 13-ODDA and (Z, Z)-3,13-ODDA is commercially available and the preferred management option for grape root borer management. The minimum vineyard size recommended for this tactic is 5 acres (~2 ha). These hand-placed dispensers (commonly called 'twist-ties') may be attached to the lower trellis wires, trellis support posts, or in the mid-canopy of vines at a density of 100 dispensers per acre. Dispensers should be deployed at the onset of moth emergence and flight in a given area annually. Depending on the area under mating disruption, one or more pheromone-baited traps should be deployed per treated block and monitored weekly for male captures. The effect of mating disruption should be manifest as an elimination or a drastic reduction of captures.

Conclusion

Grape growers must remain vigilant about this insidious, below-ground pest to avoid repeating the common mistake of being unaware of a developing infestation until the problem becomes severe. For reasons that are not yet completely understood, vineyards vary widely in the extent to which they become infested by grape root borer; some may require intervention while others may not. Thus, IPM-based management of grape root borer must begin with monitoring using pheromone traps and record-keeping of captures. Traps will yield important information about background levels of grape root borer pressure, whether from the vineyard or surrounding habitat. While there is not an established, trap-based threshold for grape root borer, the numbers of moths captured should provide guidance about the need for additional monitoring or intervention. If captures in traps indicate this need, pupal exuviae sampling from vines in individual vineyard blocks is warranted, using the protocols described previously. Pupal exuviae sampling will provide a more accurate assessment of vineyard infestation status and guide management decisions. In Georgia vineyards with Concord grapes (*V. labrusca*), Dutcher and All (1979b) reported an economic threshold of 0.074 larvae per vine or 73 larvae per ha, although *vinifera* grapes in other parts of the eastern United States can support larger populations than this without showing apparent adverse effects (Rijal et al. 2014b). Consequently, the decision to apply control measures will be subjective to some extent. Pheromone traps also provide timely information about the onset, peak, and cessation of annual moth activity that can guide the timing of grape root borer control tactics. For example, chlorpyrifos should be applied just prior to peak oviposition, which will be reflected to a large extent by increasing captures within each season, and mating disruption dispensers should be deployed just before or at the onset of adult captures. In regions where this pest has a 2- or 3-yr life cycle, any management tactic employed must be repeated over that period, since larvae from overlapping generations may be present simultaneously on roots. The use of one or two pheromone traps per block under mating disruption will confirm that the treatment is having the intended effect on moth behavior (i.e., reducing or eliminating captures). Pupal exuviae sampling, in combination with record-keeping, may be used to evaluate the effectiveness of any long and short-term control measures.

References Cited

All, J. N., and J. D. Dutcher. 1978. Current status of grape root borer infestations in Georgia: promising chemical control methods. Georgia Agriculture Research 19: 17–20.

All, J. N., M. C. Saunders, J. D. Dutcher, and A. M. Javid. 1981. Susceptibility of grape root borer larvae, *Vitacea polistiformis* (Lepidoptera: Sesiidae) to *Neoaplectana carpocapsae* (Nemotoda: Rhabditida): potential of host kairomones for enhancement of nematode activity in grape vineyards. Miscellaneous Publication of Entomological Society of America 12: 9–14.

All, J. N., J. D. Dutcher, M. C. Saunders, and U. E. Brady. 1985. Prevention strategies for grape root borer (Lepidoptera: Sesiidae) infestations in Concord grape vineyards. J. Econ. Entomol. 78: 666–670.

All, J. N., J. D. Dutcher, and M. C. Saunders. 1987. Control program for the grape root borer in grape vineyards of the eastern United States. Down Earth 43: 10–12.

Alm, S. R., R. N. Williams, D. M. Pavuk, J. W. Snow, and M. A. Heinlein. 1989. Distribution and seasonal flight activity of male grape root borers (Lepidoptera: Sesiidae) in Ohio. J. Econ. Entomol. 82: 1604–1608.

Attwood, V. G., and W. D. Wylie. 1963. Grape root borer threatens vineyards. Arkansas Farm Research 12: 6–12.

Bambara, S. B., and H. H. Neunzig. 1977. Descriptions of immature stages of the grape root borer, *Vitacea polistiformis* (Lepidoptera: Sesiidae). Ann. Entomol. Soc. Am. 70: 871–875.

Bergh, J. C. 2006. Trapping grape root borer (Lepidoptera: Sesiidae) in vineyard and non-vineyard habitats in Virginia. J Entomol Sci 41: 253–256.

Bergh, J. C. 2012. Grape root borer, pp. 383–402. In N. J. Bostanian, C. Vincent, and R. Isaacs (eds.), Arthropod management in vineyards. Springer, Dordrecht, Netherlands.

Bergh, J. C., D. G. Pfeiffer, and K. P. Love. 2005. Survey of grape root borer, *Vitacea polistiformis* (Harris), using pheromone traps in Virginia vineyards. J. Entomol. Sci. 40: 337–342.

Brooks, F. E. 1907. The grapevine root borer. West Virginia Agriculture Experiment Station Bulletin 110: 20–30.

Brooks, F. E. 1918. Grape root borer. US Department of Agriculture Bulletin 730: 21–28.

Clark, G. N., and W. R. Enns. 1964. Life history studies of the grape root borer (Lepidoptera: Aegeriidae) in Missouri. J. Kans. Entomol. Soc. 37: 56–63.

Duckworth, W. T., and T. D. Eichlin. 1977. A classification of the Sesiidae of America north of Mexico (Lepidoptera: Sesidoidea). California Department of Food and Agriculture Occasional Paper 26: 1–54.

Dutcher, J. D., and J. N. All. 1976. Beware the grape root borer. Journal of American Fruit Grower 96: 18–19.

Dutcher, J. D., and J. N. All. 1978a. Reproductive behavior of *Vitacea polistiformis* Harris. Journal of Georgia Entomological Science 13: 59–62.

Dutcher, J. D., and J. N. All. 1978b. Survivorship of the grape root borer in commercial grape vineyards with contrasting cultural practices. J. Econ. Entomol. 71: 451–454.

Dutcher, J. D., and J. N. All. 1978c. Models of the distribution of subterranean stages of *Vitacea polistiformis* in Concord grape vineyards. Environ. Entomol. 7: 461–465.

Dutcher, J. D., and J. N. All. 1979a. Biology and control of the grape root borer in Concord grape vineyards. Georgia Agriculture Experiment Station Research Bulletin 232: 1–18.

Dutcher, J. D., and J. N. All. 1979b. Damage impact of larval feeding by the grape root borer in a commercial Concord grape vineyard. J. Econ. Entomol. 72: 159–161.

Engelhardt, G. P. 1946. The North American clearwing moths of the family Aegeriidae, pp. 222. US Natural Museum Bulletin, Smithsonian Institute, Washington, DC.

Harris, T. W. 1854. Report on some of the diseases and insects affecting fruit trees and vines, pp. 210–217. In Proceedings, 3rd session of the American Pomological Society, 13–15 September 1854, Boston, MA. Franklin Printing House, Boston, MA.

Harris, J. P., B. J. Smith, and W. C. Olien. 1994. Activity of grape root borer (Lepidopetera: Sesiidae) in southern Mississippi. J. Econ. Entomol. 87: 1058–1061.

Johnson, D. T., R. L. Mayes, and P. A. Gray. 1981. Status of grape root borer, *Vitacea polistiformis* (Lepidoptera: Sesiidae) management and feasibility of control by disruption of mating communication. Miscellaneous Publication of Entomological Society of America 12: 1–7.

Johnson, D. T., J. R. Meyer, and R. L. Mayes. 1986. Evaluation of Hercon laminated dispensers baited with Z,Z-3,13-octadecadien-1-ol acetate for suppression of the grape root borer, *Vitacea polistiformis* (Harris) (Lepidoptera: Sesiidae), populations in grapes. J. Entomol. Sci. 21: 231–236.

Johnson, D. T., B. A. Lewis, and J. W. Snow. 1991. Control of grape root borer (Lepidoptera: Sesiidae) by mating disruption with two synthetic sex pheromone compounds. Environ. Entomol. 20: 930–934.

Johnson, D. T., C. R. Roubos, T. W. Nyoike, L. L. Stelinski, and O. E. Liburd. 2013. Lures, mating disruption and mass trapping of the grape root borer. Acta Horticulture (ISHS) 1001: 129–137. http://www.actahort.org/books/1001/1001_13.htm.

Jubb, G. L. 1982. Occurrence of the grape root borer, *Vitacea polistiformis*, in Pennsylvania. Meisheimer Entomol. Ser. 32: 20–24.

Massey, A. B. 1945. Native grapes and their wildlife values. Bulletin of Virginia Polytechnic Institute 38: 1–20.

Olien, W. C., B. J. Smith, and C. P. Hegwood. 1993. Grape root borer: a review of the life cycle and strategies for integrated control. HortScience 28: 1154–1156.

Pearson, G. 1992. Pheromone effects on mating success and female behavior in the grape root borer. Ph.D. dissertation. North Carolina State University, Raleigh, NC.

Pfeiffer, D. G., T. J. Boucher, M. W. Lachance, and J. C. Killian. 1990. Entomological research in Virginia vineyards, pp. 45–61. In N. J. Bostanium, L. T. Wilson and T. J. Denneehy (eds.), Monitoring and management of arthropod pests of small fruit crops. Intercept, Andover, UK.

Pfeiffer, D. G., C. A. Luab, T. A. Jordan, A. K. Wallingford, and M. Cassell. 2010. Control of grape root borer using mating disruption–2009, pp. 35–36. In Proceedings, 85th Cumberland-Shenandoah Fruit Workers Conference, 19–20 November 2009, Winchester, VA.

Pollet, D. K. 1975. The grape root borer in South Carolina, pp. 7. Clemson University Extension Service Circular. Clemson University Extension Service, Clemson, SC.

Pritchard, P. M. 2004. Reproductive capacity of grape root borer, *Vitacea polistiformis* (Harris) and implications for pheromone based management. Ph.D. Dissertation. North Carolina State University, Raleigh, NC.

Rijal, J. P. 2014. Environmental and behavioral factors associated with the infestation of vineyards by larvae of grape root borer. Ph.D dissertation. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Rijal, J. P., and J. C. Bergh. 2016. Food-finding capability of grape root borer (Lepidoptera: Sesiidae) neonates in soil column bioassays. J. Entomol. Sci. 51: 54–68.

Rijal, J. P., C. C. Brewster, and J. C. Bergh. 2014a. Spatial distribution of grape root borer (Lepidoptera: Sesiidae) infestations in Virginia vineyards and implications for sampling. Environ. Entomol. 43: 716–728.

Rijal, J. P., C. C. Brewster, and J. C. Bergh. 2014b. Effects of biotic and abiotic factors on grape root borer (Lepidoptera: Sesiidae) infestations in commercial vineyards in Virginia. Environ. Entomol. 43: 1198–1208.

Said, R., R. L. Hix, and S. Reitz. 2015. Biological control of grape root borer (Lepidoptera: Sesiidae) with commercially available entomopathogenic nematodes in Florida muscadine and 'Cynthiana grapes'. J. Entomol. Sci. 50: 150–156.

Sanders, W. R., O. E. Liburd, R. W. Mankin, W. L. Meyer, and L. L. Stelinski. 2011. Applications and mechanisms of wax-based semiochemical dispenser technology for disruption of grape root borer mating. J. Econ. Entomol. 104: 939–946.

Sarai, D. S. 1969. Effect of burial of grape root borer pupae on adult emergence. J. Econ. Entomol. 62: 1507–1508.

Sarai, D. S. 1972. Seasonal history and effect of soil moisture on mortality of newly hatched larvae of the grape root borer in southern Missouri. J. Econ. Entomol. 65: 182–184.

Saunders, M. C., and J. N. All. 1985. Association of entomophilic rhabditoid nematode populations with natural control of first-instar larvae of the grape root borer, *Vitacea polistiformis* in Concord grape vineyards. J. Invertebr. Pathol. 45: 147–151.

Snow, W. J., M. Schwarz, and J. A. Klun. 1987. The attraction of the grape root borer, *Vitacea polistiformis* (Harris) (Lepidoptera: Sesiidae) to (*E, Z*)-2, 13-octadecadienyl acetate and the effects of related isomers on attraction. J. Entomol. Sci. 22: 371–374.

Snow, W. J., D. T. Johnson, and J. R. Meyer. 1991. The seasonal occurrence of the grape root borer (Lepidoptera: Sesiidae) in the eastern United States. J. Entomol. Sci. 26: 157–168.

Sorensen, K. A. 1975. The grape vine root borer: present status of research and control. Vinifera Wine Growers Journal 2: 24–30.

Taft, W., D. Smitley, and J. W. Snow. 1991. A guide to the clearwing borers (Sesiidae) of the north central United States. North Central Regional Publication No. 394.

Taylor, R. 1965. A progress and status report on the grape root borer. Proceedings of Arkansas State Horticultural Society 86: 26–27.

Townsend, H. G. 1991. The effect of drip irrigation and ground cover on the grape root borer, pp. 60–65. Missouri Fruit Experiment Station Annual Report, Southwest Missouri State University, Mountain Grove, MO.

Townsend, H. G., and S. Micinski. 1981. Grape root borer research. Proceedings of Arkansas State Horticultural Society 102: 154–157.

Walsh, B. D. 1868. First annual report on the noxious insects of the state of Illinois, pp. 24–27. Prairie Farmer Company Steam Print, Chicago, IL.

Webb, S. E., and J. A. Mortensen. 1990. Evaluation of bunch grape rootstocks and muscadine varieties for resistance to grape root borer. Proceeding of Florida State Horticultural Society 103: 310–313.

Webb, S. E., R. K. Sprenkel, and J. L. Sharp. 1992. Seasonal flight activity of grape root borer (Lepidoptera: Sesiidae) in Florida. J. Econ. Entomol. 85: 2161–2169.

Weihman, S. W., and O. E. Liburd. 2006. Mating disruption and attract-and-kill as reduced-risk strategies for control of grape root borer, *Vitacea polistiformis* (Lepidoptera: Sesiidae) in Florida vineyards. Fla. Entomol. 89: 245–250.

Weihman, S. W., and O. E. Liburd. 2007. Seasonal distribution and evaluation of two trap types for monitoring grape root borer *Vitacea polistiformis* (Lepidoptera: Sesiidae) in Florida vineyards. Fla. Entomol. 90: 480–487.

Williams, R. N., D. S. Fickle, P. S. Grewal, and J. R. Meyer. 2002. Assessing the potential of entomopathogenic nematodes to control the grape root borer, *Vitacea polistiformis* (Lepidoptera: Sesiidae) through laboratory and greenhouse bioassays. Biocontrol Sci Technol 12: 35–42.

Williams, R. N., D. S. Fickle, P. S. Grewal, and J. Dutcher. 2010. Field efficacy against the grape root borer, *Vitacea polistiformis* (Lepidoptera: Sesiidae) and persistence of *Heterorhabditis zealandica* and *H. bacteriophora* (Nematoda: Heterorhabditidae) in vineyards. Biol. Control 53: 86–91.

Wylie, W. D. 1972. Grape root borer control. Proceedings of Arkansas State Horticultural Society 90: 71–73.

Wylie, W. D. and D. T. Johnson. 1978. Summary of grape root borer and scale research. Proceedings of Arkansas State Horticultural Society 99: 108–110.

Yonce, C. E. 1995. Physical barriers as a means to reduce grape root borer, *Vitacea polistiformis* (Harris) infestations in vineyards and in greenhouse muscadine plants. J. Entomol. Sci. 30: 237–242.