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Profile

Biology and Management of Squash Vine Borer (Lepidoptera: Sesiidae)

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Abstract

Squash vine borer, *Melittia cucurbitae* (Harris) (Lepidoptera: Sesiidae), is a species of clearwing moth native to North and South America which is a pest on members of the cucurbit family during its larval stage. Squash vine borer larvae burrow into cucurbit stems and runners, causing damage and often mortality by girdling the stem. Because they are a sporadic pest and affect home gardens or small-scale diversified farms more often than large-scale operations, research on squash vine borer management is limited. Preventing infestations, often through the use of tillage and sanitation and floating row covers, is a commonly recommended method of control. Perimeter trap cropping is also effective at preventing crop damage. Insecticides such as pyrethroids and spinosad can be applied for control of eggs and young larvae of squash vine borer, with consistent and early scouting and monitoring leading to more effective control. Newer methods of spraying *Bacillus thuringiensis* or entomopathogenic nematodes onto the crop show some promise for both organic and conventional farmers, and prove easier than injecting them into affected cucurbit stems. The use of arthropod natural enemies for biological control has proven ineffective at controlling squash vine borer. Preventing infestations and understanding the biology of this pest are essential to managing squash vine borer effectively for both small-scale and commercial growers.

Key words: squash vine borer, *Melittia cucurbitae*, *Cucurbita*, squash, pumpkin

Squash vine borer, *Melittia cucurbitae* (Harris) (Lepidoptera: Sesiidae), is a diurnal, clearwing moth species which is a pest on members of the cucurbit family. Squash vine borer is native to the Americas and has an extensive geographical range. It is found in the United States and Canada east of the Rocky Mountains, and in much of Central America (Capinera 2008). Squash vine borer has also been reported as far south as Brazil and Argentina (Worthley 1923, Krinski 2015).

Squash vine borer evolved alongside species of cucurbits native to North and South America and is a pest of concern for cultivars that are endemic to the Western Hemisphere (Howe and Rhodes 1973). Species of the genus *Cucurbita* in particular are highly susceptible, with *Cucurbita pepo* (Linnaeus) (Cucurbitales: Cucurbitaceae), and *Cucurbita maxima* (Duchesne) (Cucurbitales: Cucurbitaceae), being especially vulnerable (Howe 1950, Howe and Rhodes 1973). Crop cultivars within *C. pepo* include winter squash, zucchini, and pumpkins (Paris 1989). *C. maxima* consists of buttercup and banana squash, among others. These represent a wide range of economically important crops that can be damaged by squash vine borer.

Only the larvae of squash vine borer cause damage to plants. Larvae burrow into the stems of cucurbits and disrupt the flow of xylem and phloem, causing their host to wilt as water and nutrients are cut off from the rest of the plant (Seaman 2013, Kariuki and Gillett-Kaufman 2017). Individual runners can be infested, or the entire plant can be affected if larvae enter the main stem (Fig. 1; Dellinger and Day 2015). In extreme cases of infestation, larvae can completely sever the stem of their hosts (Howe and Rhodes 1973).

Description of Life Stages

Eggs

Adult female squash vine borers lay eggs on the stems and leaves of cucurbits, usually at the base of the plant or the underside of the stem (Brust 2010). These eggs are small, reddish-brown disks about a millimeter in diameter, and each egg is laid individually (Fig. 2; Capinera 2008). Females can lay anywhere from 150 to 200 eggs in a lifetime (Bauernfeind and Nechols 2005, Capinera 2008). Squash vine borer eggs hatch 6 to 11 d after being laid, or the equivalent of 250–300 base 10°C degree days (Canhilal et al. 2006).

Larvae

Squash vine borer larvae are small, wrinkled, and whitish with a distinct brown head capsule, and grow up to 2.5 cm in length (Fig. 3). Soon after hatching, larvae burrow inside the stem or crown of the plant (Brust 2010). They feed on the surrounding plant tissue, hollowing out a small section. Generally, larvae remain in their host for

Fig. 1. Severe squash vine borer damage at the base of the main stem of a cucurbit. The larva and surrounding frass can be seen. Photo credit: Alton N. Sparks, Jr., University of Georgia, Bugwood.org.

Fig. 2. Squash vine borer egg laid singly on the stem of a cucurbit. Photo credit: Alan Eaton, University of New Hampshire Cooperative Extension. Used with permission. This photo was first published in Eaton and Hamilton (2014). Managing Squash Vine Borer Problems in New Hampshire. (https://extension.unh.edu/resources/files/Resource004198_Rep6024.pdf)

Fig. 3. Stem of affected cucurbit cut open to reveal a squash vine borer larva and frass. Photo credit: Jeffrey Hahn, University of Minnesota. Used with permission. This photo was first published in Hahn and Burkness (2007). Squash Vine Borer Management in Home Gardens. (http://www.extension.umn.edu/garden/insects/find/squash-vine-borers/docs/M1209.pdf).

Fig. 4. Adult squash vine borers. The female is on the right, and the male on the left. Photo credit: Jeffrey Hahn, University of Minnesota. Used with permission. This photo was first published in Hahn and Burkness (2007). Squash Vine Borer Management in Home Gardens. (http://www.extension.umn.edu/garden/insects/find/squash-vine-borers/docs/M1209.pdf)

24–27 d (Canhilal et al. 2006), although the amount of time larvae spend feeding is determined by a number of factors. Temperatures exceeding 27°C cause developing larvae to try to escape into the soil (Howe 1950). Similarly, if the stems or fruit that larvae are feeding on begin to rot, larvae will leave their host early (Howe 1950). Larvae develop through four instars, and late-stage larvae drop to the ground to pupate (Britton 1919, Capinera 2008).

Mature larvae burrow several centimeters into the soil surrounding their host plant and spin a silken cocoon to pupate (Capinera 2008). Squash vine borer overwinter in this state, either as mature larvae or pupae in the soil. When temperatures again become warm enough, development continues. Pupae usually take between 750 and 1000 base 10°C degree days to fully mature and emerge as adults (Delahaut 1999, Canhilal et al. 2006).

Adults

Adults are medium-sized moths, with a 2.5- to 4-cm wingspan and have a black or dark blue-green thorax and bright orange coloration on the legs and abdomen (Fig. 4; Fleischer 2001). The forewings are dark and opaque while the hind wings are clear. Adults are diurnal fliers and often resemble wasps due to their rapid movement and a distinctive buzzing sound made while flying (Dellinger and Day 2015, Van Wychen Bennett et al. 2015). After emerging from the soil, adults begin mating at the site of emergence (Pearson 1995). As soon as 3 d after emergence, adult females are ready to oviposit (Capinera 2008). Gravid females search for new host plants on which to lay eggs and can travel distances of up to a mile if suitable hosts are not present nearby (Worthley 1923, Pearson 1995, Eaton and Hamilton 2014). In northern states, adults usually emerge once per year, around June or early July (Britton 1919, Klass 2010). In southern latitudes, there are often two adult emergences during a season, starting as early as May and extending to September or mid October (Britton 1919, Jackson et al. 2005).

Damage and Economic Harm

Cucurbits are of great economic importance in the United States, especially cultivars that are susceptible to squash vine borer like squash and pumpkins. Additionally, the majority of squash and pumpkin production in the United States takes place in states where squash vine borer is present. Respectively, 29,000 and 68,300 acres of each were planted in squash vine borer's geographical range in 2016 and were valued at US$120,428,000 and US$190,898,000 (NASS 2017b). Although squash vine borer is often more damaging to small-acreage farms and home gardens (Pearson 1995, Dellinger and Day 2015), even commercial producers can have up to 25% of plants affected by squash vine borer (Pearson 1995, Bauernfeind and Nechols 2005). Squash vine borer has the potential to cause significant economic losses if left unabated, especially for small, diversified farms.

The damage inflicted on host cucurbits depends both on the number of larvae and the point of entry into the plant. Larvae chewing into runners instead of the main stem will cut off nutrients to that part of the plant, but leave the rest unaffected (Dellinger and Day 2015). When larvae are present in the main stem, more systemic damage will follow. Larvae also occasionally bore into the fruit itself, usually later in the season (Britton 1919, Eaton and Hamilton 2014). In general, the presence of even a single larva will cause loss of yields and only a few larvae are needed to kill a host plant. In pumpkins, one larva can reduce yields up to 4%, three to four will reduce yields >20%, and six or more will kill or severely damage the plant (Brust 2010).

In home gardens or small-scale plots of cucurbits, squash vine borer infestations can destroy all of the susceptible cultivars, due to the concentration of larvae on a small number of plants (Pearson 1995, Bauernfeind and Nechols 2005). Increased crop size appears to mitigate the damage caused by vine borers (Seaman 2013). Traditionally, squash vine borer has been known as a pest that affected home gardeners more than commercial operations. However, with increasing production of varieties of susceptible cucurbits in the past several years, squash vine borer has begun to threaten large-acreage fields as well (Brust 2010). Pumpkin production alone increased from 41,000 to 70,400 acres between 2000 and 2016 (NASS 2017a). When present on large farms, squash vine borer infestations can cause up to 25% yield loss if not properly controlled (Bauernfeind and Nechols 2005).

Warning Signs, Sampling, and Monitoring

Wilting of vines or of the entire plant is the clearest and most recognizable sign of squash vine borer infestation (Welty and Jasinski 2008, Kariuki and Gillett-Kaufman 2017). Wilting in affected plants will appear suddenly and will be most obvious during the heat of the day (Hahn and Burkness 2007). Affected vines also take on a shiny or wet appearance (Hale 2010). Although wilting is often a sign of the presence of squash vine borer, it can also be caused by drought stress, or a number of other diseases such as *Fusarium* or bacterial wilt (Seaman 2013). The main distinguishing characteristic between squash vine borer damage and other causes is the presence of frass inside or around the stem (Fig. 3). Frass will appear near where the larva has tunneled into the plant and resembles wet sawdust (Bauernfeind and Nechols 2005, Hahn and Burkness 2007). Additionally, unlike squash vine borer damage, *Fusarium* wilt leads to reddish or brown discoloration of the vascular tissue of the vine (Zitter 1998). Bacterially wilt is distinct from squash vine borer damage in that the leaves where the bacterium enters the cucurbit will wilt before the rest of the plant, and a stringy ooze can be seen in the vascular tissue if the stem is cut open (Rand and Enlows 1916). It is important to remember that although it is easy to spot, wilting occurs late in an infestation, after a larva has begun disrupting the flow of nutrients and water to the rest of the plant (Kariuki and Gillett-Kaufman 2017). Therefore, monitoring for adults and checking for small amounts of frass early in the season are necessary to identify damage from squash vine borer.

Monitoring crops for adult squash vine borers is the most common way to assess pest populations and set economic thresholds (Jackson et al. 2005, Hahn and Burkness 2007, Van Wychen Bennett et al. 2015). Most thresholds for squash vine borer are based on pheromone trap counts. Many options for pheromone traps are available, but a small wire mesh cone *Heliothis* trap (Scentry *Heliothis* Trap, Gempler's, Madison, Wisconsin) was found to be most effective in a comparative study (Jackson et al. 2005). A standard economic injury level of five adults per pheromone trap per week is common among commercial growers (Rabin 2013, Eaton and Hamilton 2014). For vining-type squash or pumpkins, a higher threshold of 12 adults per trap per week has been suggested (Eaton and Hamilton 2014). However, in a 2010 study, Brust used a more conservative threshold of two adults per trap per 20-m row of pumpkins, although this lower threshold may be due to the fact that Brust used a wingtrap as opposed to a *Heliothis* trap. Additionally, Rabin (2013) suggested that the threshold of five adults per trap per week was too high for many organic growers, and that one adult per trap per week was a more accurate economic injury level. Growers should consider the type of traps they are using, the variety of cucurbits they are growing, and the management options available to them when choosing thresholds for squash vine borer. The accumulation of degree days can be used to target scouting for squash vine borer adults. In general, adults will emerge after 750–1000 base 10°C degree days (Delahaut 1999, Canhilal et al. 2006, Seaman 2013). Brust (2010) found that in Maryland, adults were active and laid eggs from the second week of June to the last week of July. In Minnesota and Wisconsin, the emergence time is similar (Van Wychen Bennett et al. 2015). In southern states like Florida where there can be two emergences per season, adults are present from mid-May to October (Canhilal et al. 2006).

Management Options

Cultural and Mechanical Control

Cultural and mechanical control options are some of the most reliable and commonly used tactics to control squash vine borer. Individually, these methods may lack the efficacy of insecticidal sprays, but a combination of techniques can provide comparable degrees of protection or prevent infestations entirely. Because of this, prevention and mechanical control remain the best line of defense for growers dealing with squash vine borer.

Crop Rotation

Crop rotation is an important first step to preventing squash vine borer infestations. Larvae overwinter in the soil, so planting squash on squash increases the likelihood of future problems (Britton 1919). Crop rotation is most effective if fields are far apart, as squash vine borer adults are strong fliers and have been known to locate fields up to a mile from where cucurbits were grown the previous year (Worthley 1923, Eaton and Hamilton 2014). If a grower is limited by space and cannot grow cucurbits in a separate area, waiting a year between plantings can achieve a similar effect (Eaton and Hamilton 2014).

Host Plant Resistance

Planting cultivars of cucurbits that are more resistant to squash vine borer is a viable option to prevent infestations, albeit not always practical for growers trying to meet consumer demands (Adam 2006). Table 1 shows a range of squash varieties and types, along with their attractiveness to squash vine borer. Butternut squash (*Cucurbita moschata* Duchesne (Cucurbitales: Cucurbitaceae)) is an example of a cultivar that is more resistant to squash vine borer larvae (Gould 1958). In a comparative study, cultivars of *C. moschata* experienced

Table 1. Attractiveness of cucurbit varieties

Variety	Attractiveness	Species
Blue Hubbard	5	*C. maxima*
Boston Marrow	4	*C. maxima*
Golden Delicious	4	*C. maxima*
Connecticut Field Pumpkin	4	*C. pepo*
Small Sugar Pumpkin	4	*C. pepo*
White Bush Scallop	3	*C. pepo*
Acorn	3	*C. pepo*
Summer Crookneck	2	*C. pepo*
Dickinson Pumpkin	2	*C. moschata*
Green Striped Cushaw	1	*C. argyrosperma*
Butternut	1	*C. moschata*

Attractiveness of different varieties of commonly grown cucurbits to female squash vine borer.

5 = most attractive; 1 = least attractive. Adapted from (Seaman 2013 and Grupp n.d).

less damage from squash vine borer, and larvae had greater difficulty establishing within the stem when compared with *C. pepo* and *C. maxima* (Howe and Rhodes 1973). Cultivars of *Cucurbita argyrosperma* (Koch) (Cucurbitales: Cucurbitaceae), a less frequently grown species of pumpkin, are also resilient to squash vine borer, possibly due to their tougher stems (Howe and Rhodes 1973). In general, squash vine borer prefer softer, wider stemmed cucurbits, so planting cultivars with narrower, woodier stems may provide less protection or nutrition for developing larvae (Gould 1958, Howe and Rhodes, 1973). Additionally, bush-type varieties tend to be more susceptible than vine-type varieties. This is because vine types often root at their nodes, thereby decreasing the likelihood that larvae can cut off the supply of nutrients to any part of the plant (Eaton and Hamilton 2014).

Sanitation and Tilling

Field sanitation and tillage are commonly recommended control strategies. Destroying squash vine borer larvae in the soil or in the remains of old crops will prevent a buildup of the pest and can mitigate future outbreaks. Plants that are killed by squash vine borer during the growing season should be removed immediately and discarded (Kariuki and Gillett-Kaufman 2017). After harvest, collecting and destroying old vines can significantly reduce squash vine borer numbers (Egel et al. 2016). Burning the vines is effective (Britton 1919, Bauernfeind and Nechols 2005), but other sources suggest simply tilling or disking the old crop into the soil (Adam 2006, Hale 2010, Welty 2017). This will destroy larvae in the old vines as well as mature larvae and pupae in the soil. Individuals that are not killed outright will often be buried too deep to survive, or will be brought to the surface where they are more vulnerable to predators (Bauernfeind and Nechols 2005). Tilling should reach a depth of at least 5 cm as larvae burrow 2.5–5 cm into the soil to pupate and overwinter (Canhilal et al. 2006). Sanitation and tilling are particularly useful for cucurbit crops with successive plantings in a season, such as zucchini and summer squash (Seaman 2013). It is important to note that tilling does have drawbacks and limitations. During heavy infestations, tilling may not appreciably lower crop damage even if it kills many larvae (Eaton and Hamilton 2014) and has been shown to reduce threefold the abundance of important pollinators like ground-dwelling squash bees (Shuler et al. 2005).

Trap Cropping

Depending on the cultivar of squash being grown, trap cropping can be used as a method of control. Squash vine borer can be lured away from crops by planting more attractive cultivars either surrounding the crop in a perimeter or simply close to the main crop. Squash vine borers lay eggs on the trap crop, thereby sparing the less susceptible cultivars from damage. The trap crop is treated with insecticides or destroyed after infestation to kill the larvae (Seaman 2013). As a general rule, trap crops should take up 10% of the total cropping area, although this varies depending on pest pressure and crop type (Hokkanen 1991, Shelton and Badenes-Perez 2006), and there are currently no specific recommendations for trap crop size regarding squash vine borer. To be effective, the trap crop must be significantly more desirable to the pest than the main crop being grown. Blue Hubbard squash, *C. maxima*, is one of the most susceptible cultivars of squash available and will be readily attacked by squash vine borer (Howe and Rhodes 1973). It is therefore one of the most desirable cucurbits to use as a trap crop (Boucher and Durgy 2003, Grupp n.d). When a perimeter of Blue Hubbard squash was used as a trap crop around summer squash, Boucher and Durgy (2003) found that squash vine borer infestations were decreased by 88% in the main crop. Blue Hubbard squash should be planted about 2 wk before the main cash crop. This ensures that the trap crop is better established and more attractive to squash vine borer adults (Pinero 2017).

Blue Hubbard squash can be effective as a trap crop for many cultivars, but not for other cultivars of Hubbard squash which, although less susceptible, are too similar to Blue Hubbard squash for squash vine borer to differentiate between them (Howe and Rhodes 1973, Seaman 2013). Trap cropping can fail if squash vine borers fail to discriminate between cultivars, even those of very different desirability. Howe and Rhodes (1973) found that older females often laid eggs on less desirable hosts, including some that larvae could not survive on such as cucumber or melon. This effect was more pronounced when plantings were mixed and vines of different cultivars grew and became intertwined. Keeping trap crops spatially separate may help prevent such confusion.

Timing of Planting

Depending on the location, either early or late-planted cucurbits will experience more damage from squash vine borer. In intermediate or more northern latitudes, early plantings experience greater damage. In Connecticut and Ohio, early-planted squash experienced greater injury from squash vine borer (Britton 1919, McFarland and Welty 2017). Similar results are found in Minnesota, where squash planted later experienced less damage (Hahn and Burkness 2007). This is because squash planted late in the season mature after adult squash vine borers have laid all of their eggs (Hahn and Burkness 2007). Conversely, in Florida, squash planted early in the season experienced less damage (Capinera 2008). This is probably because squash can be planted much earlier in the season in Florida, so it is an option to grow a complete crop before squash vine borers emerge. In all but the most southern states, it seems that late-planted cucurbits will be safer from squash vine borer.

Early-planted cucurbits will be more heavily infested in most cases and can be used as trap crops. Additionally, not harvesting fruit appears to make individual plants more attractive to squash vine borer. McFarland and Welty (2017) found that zucchini planted early in the season and left unharvested could make effective trap crops for a cash crop of summer squash planted later. A previous study supported the fact that unharvested squash are more prone to infestation; finding unharvested zucchini had a 53% rate of infestation, whereas harvested zucchini had a 14.6% rate of infestation (Welty and Jasinski 2008). Britton (1919) also suggests planting a trap crop of squash early in the season and destroying them once squash vine borers lay their eggs. Cucurbits planted early and left unharvested can be used as trap crops, and planting later in the season and harvesting ripe squash on a regular basis can lessen damage to the main crop.

Row Covers

Row covers consist of lightweight permeable cloth placed over crop plants. They exclude insects, but still allow light and water to pass through. Row covers can be used to prevent squash vine borer from laying eggs on the crop and should be attached firmly to the ground to prevent any larvae or adults from crawling underneath (Hahn and Burkness 2007, Van Wychen Bennett et al. 2015). If correctly implemented, row covers have been shown to eliminate the need for insecticides to control squash vine borer and reduced damage caused by the pest overall (Minter and Bessin 2014, Tillman et al. 2015). Although effective at preventing damage, row covers must be removed in order to facilitate pollination once flowers form (Seaman 2013). Squash vine borer is active at the same time as many pollinators, so removing row covers to allow pollinators access may expose the crop to squash vine borer as well. Careful timing and effective monitoring can help reduce risk (Eaton and Hamilton 2014). Tillman et al. (2015) delayed row cover removal until 50% of the female squash plants had flowers, and suffered no negative impact on yield. Another option is to remove row covers in the evening and replace them in the morning, allowing native squash bees to pollinate the crop during times when squash vine borer are not active (Minter and Bessin 2014). If cucurbit crops were planted in the same area and were affected by squash vine borer the previous year, it is not advisable to install row covers. Larvae and pupae from the previous season may be present in the soil and will be trapped under the cover and remain on the crop once they emerge as adults (Hahn and Burkness 2007). Unless thorough sanitation and tilling were implemented, covering crops run the risk of starting an infestation the next season.

Removing Larvae and Burying Stems

Physically killing larvae and eggs is time consuming and difficult. Eggs are laid singly by females (Canhilal et al. 2006) and therefore have to be individually removed. This is impractical for production of any size greater than a home garden and for all but the most detail-oriented growers. Killing larvae is a more practical method, but still labor intensive. Once an infected plant has been discovered, slitting open the stem and removing the larva will prevent further damage (Britton 1919). Difficult though this is, it is a commonly recommended option for home growers (Hahn and Burkness 2007, Hale 2010, Van Wychen Bennett et al. 2015). The chance of saving the plant or runner is small, but the grower does not have much to lose at this point as the plant has already been heavily damaged by the larva (Hahn and Burkness 2007).

After the larvae have been removed, burying the stem joints of affected cucurbits or heaping moist soil over the nodes encourages new roots to form at the joint and may allow the plant to survive (Hale 2010). Burying nodes can also be used prophylactically, in the hope that roots will form and supply the plant with nutrients if larvae later enter the vine and cut it off from the main stem (Kariuki and Gillett-Kaufman 2017). However, success is far from certain with these methods, and they are only realistic for small-scale cucurbit plots (Hahn and Burkness 2007).

Chemical Control

Applying foliar insecticides is a very common and effective method for controlling squash vine borer. Insecticides are usually applied every 5 to 7 d for 3 to 5 wk, beginning when eggs are being laid and before they hatch (Hale 2010, Saha et al. 2016). Timing is critical to achieve effective control as larvae will not be effected by insecticides once they are inside the stems (Fleischer 2001, Klass 2010, Dellinger and Day 2015). Insecticides should be applied to the base of plants where eggs and larvae are most commonly found (Rabin 2013, Dellinger and Day 2015).

Applying insecticides can adversely affect pollinators that visit cucurbit flowers. Spraying in the late evening or early morning when pollinators like honeybees are less active can help mitigate unintentional harm (Eaton and Hamilton 2014, Cloyd and Nechols 2016). However, native pollinator species can still be affected even with these precautions. Native squash bees have been found to be one of the most abundant and important pollinators of squash and pumpkin (Shuler et al. 2005, Minter and Bessin 2014, Egel et al. 2016) and tend to rest inside squash flowers at night (Eaton and Hamilton 2014). Selectively spraying only the base of stems can help avoid harming these native bees (Eaton and Hamilton 2014).

Although multiple insecticides may be useful for controlling squash vine borer, there are relatively few studies directly testing their efficacy. The current-recommended insecticides and dosages for conventional growers are listed in Table 2, and case studies of particular insecticides and methods are listed below.

Pyrethroids

Pyrethroids are the most common classes of insecticides used to control squash vine borer (Saha et al. 2016). A number of these chemicals are effective against squash vine borer including permethrin, bifenthrin, esfenvalerate, and zeta-cypermethrin (Hahn and Burkness 2007, Saha et al. 2016). Cucurbit mortality due to squash vine borer was lowered from an average of 14% in untreated fields, to an average of 1.5% in fields treated with esfenvalerate weekly during a growing season (Brust 2010). A mixture of bifenthrin and zeta-cypermethrin was found to reduce squash vine borer infestation rates from 14.6 to 0% (Welty and Jasinski 2008). Ambush, a

Table 2. Recommended insecticides for squash vine borer

Brand name	Common name	Application (fluid oz per acre)	Seasonal limit (fluid oz per acre)	Efficacy
Asana XL	Esfenvalerate	5.8–9.6	48	Effective
Belt 2 SC	Flubendiamide	1.5	4.5	Effective
Brigade 2 EC	Bifenthrin	2.6–6.4	19.2	Very Effective
Mustang Max	Zeta cypermethrin	1.28–4	24	Very Effective
Permethrin 3.2 EC	Permethrin	4–8	64	Very Effective
Warrior II	Lambda cyhalothrin	1.28–1.92	11.5	Very Effective

Adapted from (Saha et al. 2016).

permethrin based insecticide, reduced squash vine borer densities from an average of 1.24 larvae per plant to 0.2 larvae per plant (Boucher and Durgy 2002). Studies on another insecticide that contains pyrethrins plus piperonyl butoxide, Evergreen, found that it reduced squash vine borer infestations slightly, although low infestation rates overall make these results suspect (Welty 2006, McFarland and Welty 2017).

Spinosad

Spinosad can be utilized in both conventional and organic agriculture, although not in all concentrations or formulations for the latter. Spinosad was shown to be effective in controlling squash vine borer, using a formulation not allowed in organic agriculture (Seaman 2013). At 4 oz of formulation per acre, Spinosad-treated plots had an average of 0.16 vine borers per plant compared with 1.24 vine borers in untreated plots (Boucher and Durgy 2002). No specific data are available for organic formulations such as Entrust, but it has been recommended for organic growers (Rabin 2013). Spinosad can be as effective as some pyrethroids to control squash vine borer under conventional management (Boucher and Durgy 2002) and has the potential to be used in organic applications as well.

Carbaryl

Carbaryl has been shown to reduce squash vine borer numbers to levels comparable with pyrethroids, but does not seem to be as consistently effective. Treatment with carbaryl reduced the percentage of plants damaged by squash vine borer from 14.6 to 3.3% in one study, on par with the results from a mixture of bifenthrin and zeta-cypermethrin (Welty and Jasinski 2008). In an earlier study, however, the yields of cucurbits treated with carbaryl were not significantly higher than those of untreated cucurbits (Welty 2006). Additionally, in the 2016–2017 Vegetable Production Guide for Commercial Growers, carbaryl is listed as only somewhat effective for controlling squash vine borer (Saha et al. 2016).

Kaolin Clay and Alternative Insecticides

There are a variety of alternative chemical treatments that can be used against squash vine borer, many of which are classified as organic. Examples include neem, neem oil, geraniol, thyme oil, and kaolin clay (Seaman 2013). There are few current studies on the efficacy of these insecticides on squash vine borer, and those that do exist suggest minimal success. Neem has been described as weak on squash vine borer and is unlikely to control the pest well (Eaton and Hamilton 2014). Kaolin clay is labeled for use against squash vine borer in home gardens (Klass 2010), but studies do not show good efficacy. In field trials, kaolin clay was not found to significantly reduce squash vine borer numbers or increase yield (Delate 2003, Delate et al. 2005). Currently these methods do not seem promising, but could potentially prove useful to organic farmers upon further study (Seaman 2013).

Application of Insecticides Combined with Scouting

The standard method of applying foliar insecticides consistently for several weeks is often effective, but can waste insecticide and have detrimental effects on nontarget organisms like pollinators (Brust 2010, Eaton and Hamilton 2014). By monitoring the presence of adults, more efficient application methods can be used (Eaton and Hamilton 2014, Cloyd and Nechols 2016). When implemented correctly, scouting combined with spraying was shown to reduce insecticide use and to increase control of squash vine borer. Brust (2010) found that cucurbit mortality due to squash vine borer was lowered from an average of 14% in untreated fields to an average of less than 1% in fields that were scouted and treated with esfenvalerate accordingly. This method was significantly more effective than spraying without scouting and reduced insecticide use and costs for the grower (Brust 2010).

Biological Control

Natural Biological Control

There are few arthropod biological control agents that have been investigated for controlling squash vine borer, and none that are commercially available (Dellinger and Day 2015). Parasitic wasps of the family Scelionidae have been found to parasitize squash vine borer eggs, occasionally to a high degree (Worthley 1923), although most years the wasps do not destroy a significant number of eggs (Hale 2010). Several species of ground beetle have been observed to attack squash vine borer larvae and robber flies occasionally attack adults, but neither appear to significantly reduce pest populations (Worthley 1923). As it stands, natural biological control of squash vine borer is marginal (Hale 2010).

Entomopathogenic Nematodes

Another form of biological control that shows more promise is the application of entomopathogenic nematodes. In a 3-yr study, Canhilal and Carner (2006) tested the efficacy of multiple varieties of nematodes known to cause mortality in species of clearwing moths. The efficacy of several species of steinernematid nematodes to control squash vine borer was compared with a treatment of endosulfan. At the same time, endosulfan was a standard insecticide used against squash vine borer, although it has since been phased out (Canhilal and Carner 2006, UNEP 2011). Multiple species of nematode were shown to provide as much protection against squash vine borers as endosulfan, and both sprays and injections of nematodes into the stems were found to enact some measure of control, although never caused greater than 40% larval mortality in field tests (Canhilal and Carner 2006). Nematodes may be a viable option for use in organic agriculture when other insecticides cannot be utilized (Canhilal and Carner 2006).

Bacillus thuringiensis Sprays and Injections

Bacillus thuringiensis (Bt) has been used extensively to control arthropod pests and has proven highly toxic to many different pest taxa (Schnepf et al. 1998). A commercial formulation of Bt was found to be roughly as effective at controlling squash vine borer as the previous industry standard of endosulfan, often preventing infestations entirely (Canhilal and Carner 2007). Bt can be applied in a foliar spray or via injection directly into the stem of the infested cucurbit. Foliar sprays were found to be more effective and are less time consuming than stem injections (Canhilal and Carner 2007). Bt sprays and injections show promise as a control option for organic and conventional cucurbit growers (Canhilal and Carner 2007, Seaman 2013).

Conclusion

The wide range of control options available for managing squash vine borer demonstrates the importance of developing an integrated pest management plan that is based on sound knowledge of the pest, and the needs and preferences of the grower. Consistent and early monitoring with pheromone traps is important to assess squash vine borer populations and implement effective control before economic losses occur. Cultural control options can keep squash vine borer populations low or nonexistent and carefully timed applications of insecticide can stop outbreaks from damaging the crop. By understanding host plant susceptibility and resistance, growers can use trap crops to great effect or plant-resistant varieties to prevent infestations.

However, additional research is still needed on effective methods to control squash vine borer, especially on small farms where this pest is often most damaging. Many of the currently recommended control options like weekly insecticide applications and physically removing larvae are time intensive, wasteful, or have off-target effects. Methods that show promise such as trap cropping and insecticide treatments combined with scouting still need further research and study in order to determine how to make them most useful to growers. Researchers should also focus on studying the synergistic effects of multiple management techniques on controlling squash vine borer, especially prophylactic techniques. Preventing this unpredictable pest from becoming a problem in the first place is the most reliable way of avoiding damage to crops, and using several prophylactic measures simultaneously may prove to be highly effective. Additionally, growers will likely employ multiple methods to control this pest, and research on what combination of control options is most effective would be both useful and timely. Although more research is needed, and although squash vine borer can be a damaging pest, the sources reviewed here offer many different management options to enact effective control for growers on both a large and small scale.

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