Flea Beetle Populations and Their Management on Vegetables in Virginia

James Allen Cole Mason

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Masters in Sciences and Life Sciences

In

Entomology

Thomas P. Kuhar, Chair
Carlyle C. Brewster
James F. Walgenbach

May 4, 2018
Blacksburg, VA

Keywords:
Vegetable pest management, flea beetles, *Epitrix* spp., *Phyllotreta* spp., row covers
Flea Beetle Populations and Their Management on Vegetables in Virginia

James Allen Cole Mason

Abstract

Flea beetles (FB), (Coleoptera: Chrysomelidae), are common pests of cabbage and eggplant, but little is known about the FB populations in Virginia, their impact on yield, or the most effective control methods. This research investigates the FB populations and impact of their feeding injury on cabbage and eggplant in Southwest Virginia, and determines the most efficacious control methods.

In Whitethorne, VA, cabbage and eggplant crops were vacuum sampled weekly throughout two summers. Crucifer flea beetle, *Phyllostreta cruciferae* (Goeze), and striped flea beetle, *Phyllostreta striolata* Fabr. were found on cabbage; whereas, eggplant flea beetle, *Epitrix fucula* (Crotch), and the tobacco flea beetle, *Epitrix hirtipennis* (Melsheimer) were found on eggplant. To evaluate the impact of FB feeding on these plants, insecticides were used to create a range of pest pressure. Flea beetle densities and defoliation was visually assessed weekly and individual plant as well as whole plot yields assessed at harvest. In both crops, as little as 20% defoliation significantly reduced yield, with higher defoliation resulting in lower yield. The efficacy of various insecticides was also evaluated; soil application of the systemic neonicotinoid dinotefuran had the fewest beetles, the least amount of leaf defoliation, and the highest yield in cabbage and eggplant. Lastly, deltamethrin-incorporated mesh row covers were evaluated and shown to provide excellent control of FB compared to an untreated row cover or a control; and comparable to the standard insecticide, dinotefuran. This
research helps vegetable growers to better understand the severity of these pests and how to effectively combat them.
Flea Beetle Populations and Their Management on Vegetables in Virginia

James Allen Cole Mason

Abstract

(General Audience)

Flea beetles are tiny leaf-chewing pests of vegetables, particularly cabbage and eggplant. High populations of FB chewing on leaves can kill plants in early stages of development, and insecticides are the most common defense. Little is known about which FBs are in Virginia, their effect on vegetables grown in the state, or what the best way of controlling these pests. This research investigates FBs to determine the how they affected yield of cabbage and eggplant in Southwest Virginia, as well as determine the best methods for controlling these pests.

Cabbage and eggplant were sampled weekly throughout two seasons, and two species were found on cabbage, the crucifer flea beetle and the striped flea beetle, whereas the eggplant flea beetle and the tobacco flea beetle were found on eggplant. To evaluate FB damage on these plants, defoliation of leaves was evaluated then yield was assessed. In both crops as little as 20% defoliation reduced yield, with higher defoliation resulting in lower yield of surviving plants. Various insecticides were evaluated to determine which treatment and application method were the most effective for controlling FB. A soil-applied systemic insecticide, dinotefuran, had the lowest density of beetles, the least amount of leaf defoliation, and the highest yield in cabbage and eggplant. Lastly, insecticide treated mesh row covers were evaluated and shown to be an effective method for controlling flea beetles on these crops. Treated row covers reduced FB numbers and feeding damage on these crops when compared to an untreated row cover. This research can benefit vegetable growers by helping them...
understand the severity of these pests and by providing effective management strategies to combat them.
Acknowledgements

I want to thank my advisor, Dr. Thomas Kuhar, for encouraging and mentoring me throughout my graduate career. He encouraged me to apply to graduate school in the first place, helped me learn how to be a scientist, guided me through my project even when I didn’t even know where to start, and taught me much about agriculture and entomology. Thank you for all the laughs, sports analogies, and insect facts, I know that we will remain friends and colleagues throughout my career.

I also want to thank the remaining members of my committee, Drs. Carlyle Brewster and James Walgenbach. Both of these individuals helped develop this project, and provided guidance and feedback in their areas of expertise. I could approach them both with questions or concerns and they would make time to address my issues to help me with my project.

I want to extend thanks to Dr. Timothy Kring, for always offering advice, kind words, and encouragement throughout the time we overlapped in the Entomology department. While I was a student representative to the department we worked well together to help our department grow and I value our working relationship and friendship.

I could not have accomplished many of my achievements or finished my research without the help of my current and former lab mates, and friends in the entomology department. There are too many to name them all, but I wanted to specially thank: James Wilson, Kadie Britt-Byrd, Katlyn Catron, Adam Formella, Hayley Bush, Katlin Mooneyham, Liz Fread, and the many others who helped me with my project and were
true friends throughout my graduate experience. I would not be where I am today without their friendship and support.

I want to thank Aaron Riegel, Bill Carswell, and Rue Cat for all the love, support, laughter, and companionship when I needed it most. Aaron you are my strength and I can think of no better partner to tackle this world with.

I want to thank my parents, Meredith and Chad, and my step parents Andrea and Dave, for believing in me and instilling a powerful desire to be the best that I can be in everything that I do. Thank you Kara, Matthew, and Courtney for being the coolest siblings anyone can ask for, all the animal photos and silly jokes kept me going. I am who I am because of my entire family, thanks for knowing me and surrounding me with love.
Table of Contents

Acknowledgements ........................................................................................................vi

Table of Contents ...........................................................................................................viii

Chapter One: Introduction and Literature Review .........................................................1
  Introduction ..................................................................................................................1
  Biology of and life history of *Phyllotreta* spp .............................................................3
  Biology of and life history of *Epitrix* spp .................................................................6
  Management of flea beetles on vegetables .................................................................9
  Long lasting insecticidal netting (LLIN’s) in agriculture ............................................12
  Research Objectives .................................................................................................13
  References Cited ........................................................................................................15
  Figures .......................................................................................................................18

Chapter Two: Flea beetle (Coleoptera: Chrysomelidae) populations, effects of
  feeding injury, and efficacy of insecticide treatments on eggplant in Virginia ......22
  Introduction ..............................................................................................................22
  Materials and Methods ............................................................................................22
  Results ......................................................................................................................26
  Tables and Figures ....................................................................................................29
  Discussion ................................................................................................................33
  References .................................................................................................................36

Chapter Three: Flea beetle (Coleoptera: Chrysomelidae) populations, effects of
  feeding injury, and efficacy of insecticide treatments on cabbage in Virginia ......38
  Introduction ..............................................................................................................38
  Materials and Methods ............................................................................................39
  Results ......................................................................................................................42
  Tables and Figures ....................................................................................................45
  Discussion ................................................................................................................49
  References .................................................................................................................52

Chapter Four: Deltamethrin-incorporated Screen Row Covers for Flea Beetle
  Control in Vegetables ...............................................................................................54
  Introduction ..............................................................................................................54
  Materials and Methods ............................................................................................55
Results .................................................................59
Tables and Figures ..........................................................62
Discussion .................................................................64
References ..................................................................67
Chapter one

Introduction and Literature Review


*Phyllotreta* spp. flea beetles are specialized to feed on *Brassica* plants throughout the United States and Canada (Capinera 2001, Eastman et al. 2005). These beetles include the crucifer flea beetle, *Phyllotreta cruciferae* (Goeze), the striped flea beetle (Fig. 1.1), *Phyllotreta striolata* Fabr. (Fig. 1.2), and Zimmermann’s flea beetle, *Phyllotreta zimmermanni* (Crotch) (Capinera 2001, Eastman et al. 2005). Each of these insects share similar biology and life history and are often found together competing on the same plants (Feeny et al. 1970, Capinera 2001), and they are commonly found in
the eastern and northeastern part of the U. S. (Capinera 2001, Eastman et al 2005), and could potentially be found on cabbage in Virginia.

*Epitrix* spp. typically attack plants in the nightshade family and their ranges vary based on species in the United States (Capinera 2001). Beetles in this genus include eggplant flea beetle *Epitrix fuscula* (Crotch) (Fig. 1.3), tobacco flea beetle *Epitrix hirtipennis* (Melsheimer) (Fig. 1.4), and potato flea beetle *Epitrix cucumeris* (Harris) (Capinera 2001, Bessin et al. 2005). The *Epitrix* spp. beetles also share similar biology and they compete with each other across their preferred host range (Capinera 2001), and all of the beetles could overlap with eggplant grown in Virginia.

The extent of the damage caused by these insects is not well understood if plants survive feeding during the early stages of development. Control is similar for all flea beetles found on vegetables, with insecticidal control being the most common management tactic to mitigate flea beetle injury (Capinera 2001, McLeod et al. 2002, Walgenbach and Schoof 2010, Mason and Kuhar 2016a, b, ). Other methods of control include a physical barrier in the form of a row cover (Hough-Goldstein 1987), or adjusting plant date to allow the plants to grow past the crucial development period that most flea beetle damage is caused (Capinera 2001).

Long lasting insecticidal netting (LLIN) has been used to control insect disease vectors for quite some time (Hill and Rowland 2006, Martin et al. 2007). Recently the use of LLIN’s in agriculture is being explored to determine its effectiveness at controlling various insect pests while simultaneously reducing the use of traditional insecticides (Dáder et al. 2015, Kuhar et al. 2017). The use of LLIN’s for control of flea beetles could offer another effective tactic for controlling this pest in agriculture.
Biology and life history of *Phyllotreta* spp. Biology of *P. cruciferae*, *P. striolata*, and *P. zimmermanni* was provided by Capinera (2001) unless otherwise noted.

**Distribution.** Records show *P. cruciferae* was first found in North America in 1921 in British Columbia, and then later collected in Ontario and Quebec by 1954. Westdal and Romanow (1972) report the insect was found in Pennsylvania by 1943 and had spread throughout Delaware by 1951. Currently *P. cruciferae* is found throughout southern Canada and the northern United States.

*Phyllotreta striolata* was originally found throughout Europe and Asia and preserved samples of the insect were recovered from Boston, Massachusetts and dated back to the 1700’s making this the earliest instance of *P. striolata* in North America (Bain and LeSage 1998). Today it is widely distributed throughout the United States and Canada being most common in the Canadian Prairie Provinces and northeastern and midwestern U.S.; however, in Canada, *P. striolata* is not as prevalent as *P. cruciferae*. *Phyllotreta zimmermanni* has been recorded in almost every state in the U.S. and most of the Canadian provinces, however its populations have declined since the introduction of the other two *Phyllotreta* species from Europe.

**Host plant range.** All three aforementioned species of *Phyllotreta* are specialized to feed on crucifer plants, though they are also known to feed on other plants containing mustard oils (Feeny et al. 1970, Palaniswamy and Lamb 1992). Many agricultural crops, especially the crucifer vegetables are often attacked by these flea beetles. Preference for certain plant species over others has been noted, for example,
Chinese southern giant mustard (*Brassica juncea* var. *crispifolia*) is a highly preferred species that can even be used for trap cropping for *Phyllotreta* spp. (Grubinger 2005). Palaniswamy and Lamb (1992) report that preference is also dependent on plant stage and leaf type rather than plant preference. It is reported that these insects are not typically found feeding on other plant families.

**Life cycle.** Reports show that *P. cruciferae* has one to two generations per year depending on environmental conditions, and they can complete development from egg to adult in 6-8 weeks (Burgess 1977, Westdal and Romanow 1972). Eggs are laid at the base of host plants and larvae emerge between 11-13 days (Feeny et al. 1970, Westdal and Romanow 1972). After emerging, larvae burrow into the soil and proceed to feed on the roots of the same host plants the adults are feeding on (Feeny et al. 1970, Westdal and Romanow 1972). There are three larval instars during which the insect feeds for 25-30 days before creating a pupal chamber in the soil and entering a prepupal period lasting 3-6 days, then pupate from 7-9 days (Westdal and Romanow 1972). The adult is about 2.2mm long, metallic blue-black, and has enlarged hind femora specialized for jumping (Feeny et al. 1970, Westdal and Romanow 1972, Burgess 1977). Beetles are capable of jumping and flying to disperse and travel from plant to plant. *P. cruciferae* overwinters as an adult in soil, leaf litter, and other potential shelter materials, before emerging in spring (Feeny et al. 1970, Kinoshita et al. 1979). Beetles then disperse, mate, and lay their eggs leading to peak populations in late June then again in late July (Kinoshita et al. 1979).

*P. striolata* shares many of the same characteristics as *P. cruciferae*, though there are some differences. The beetle has one generation per year in most areas
though it can complete its life cycle in as little as one month, about half the time it takes for _P. cruciferae_ (Burgess 1977). Eggs are laid in the same manner as _P. cruciferae_, hatching in about five days, while the larvae also have three instars it is not reported exactly how long they remain larvae or pupa in the soil before emerging as adults (Burgess 1977). The adult _P. striolata_ range from 2.0-2.4 mm, are mostly brownish-black with a distinct irregular yellow stripe on each elytra, this band can sometimes be discontinuous (Feeny et al. 1970, Burgess 1977). Other characteristics, behavior, and overwintering methods are similar to _P. cruciferae_, however, _P. striolata_ is known to emerge about two weeks earlier.

Compared to _P. cruciferae_ and _P. striolata_, less information is available on _P. zimmermanni_; this could be in part due to diminishing populations, or it can be easily mistaken for _P. striolata_. _P. zimmermanni_ shares many of the same traits as the other two flea beetles. It also has a single generation per year in most areas, requiring 30 days to complete its life cycle. The egg and larval stages of this insect differ from the other _Phyllotreta_ spp. previously mentioned. The adults lay their eggs on the upper surface of leaves on their host plants, the larvae then emerge and feed as leaf miners burrowing in between the upper and lower leaf epidermis. It is not described how long the insects stay in each of these stages, and although it is known that pupation occurs in the soil, the pupal stage is otherwise undescribed. The adults are almost identical to _P. striolata_, however, they are a little larger, ranging from 2.0-3.0 mm long, and the fifth antennal segment on males is about three times as large as the sixth segment, whereas in _P. striolata_, it is only about twice the size of the sixth segment. All other characteristics are similar to _P. striolata_.

**Feeding injury and its impact.** All three of these species of flea beetle feed on plants by chewing small holes in the foliage, however, they do not chew through the entire leaf, leaving the lower epidermis intact (Burgess 1977, Soroka and Pritchard 1987). The lower epidermis then dries out falling from the plant, leaving the characteristic flea beetle feeding injury (Burgess 1977). When this defoliation occurs at a high rate, it can dry surrounding leaf tissues near the feeding holes which can kill young seedlings (Feeny et al. 1970, Burgess 1977). Capinera (2001) indicates that this effect and seedling mortality can be more dramatic in spring when the weather is hot and dry. Little is known about the yield effects of surviving seedlings for a majority of crops, however, on broccoli it is shown that surviving plants may experience reduced growth, and direct feeding on florets greatly reduces yield (Soroka and Pritchard 1987). In canola, rape, and yellow mustard, *Phyllotreta* spp. feeding during the first few weeks after emergence, caused high seedling mortality, stunted plant growth, and reduced yield (Lamb 1984). In the same experiments flea beetle feeding had less of an impact on a later planting of the same crops (Lamb 1984).

Larval feeding is typically less of a concern, the larvae usually feed on root hairs of the host plants in the case of *P. cruciferae* and *P. striolata*, and this feeding injury can reduce the marketability of root crops (Kinoshita et al. 1978). *P. zimmermanni* larvae feed on the plant foliage of weeds surrounding crops unlike their adults.

**Biology and life history of *Epitrix* spp.** Biology of *E. fuscula*, *E. hirtipennis*, and *E. cucumeris*, was provided by Capinera (2001) unless otherwise noted.
**Distribution.** *E. fuscula* is a native North American flea beetle found throughout the U. S. from coast to coast, excluding northern areas and is not known as a pest in Canada. *E. hirtipennis* is found throughout much of the U. S. ranging as far north as Maryland and Michigan, and it is commonly found in the southeast. Populations of *E. cucumeris* range from South Carolina northward in the U. S., and have been known to be a problem on the Eastern Shore of Virginia (Anderson and Walker 1934).

**Host plant range.** The plants fed on by *E. fuscula* are not well known, however, it is well known to attack eggplant and potato and its host range is likely similar to the range of *E. cucumeris* (Bessin et al. 2005). *E. cucumeris* is often found attacking most Solanaceous plants including weeds and vegetables. Vegetables that are particularly attractive to *E. cucumeris* include potato, eggplant, tomato, and pepper (Bessin et al. 2005). *E. hirtipennis* is widely known for attacking tobacco (Dominick 1967), but it is also found to attack many other Solanaceous plants (Gentile and Stoner 1968). Some records show this beetle attacking plants outside of the nightshade family, however, its larvae cannot develop feeding on other plants.

**Life cycle.** *E. fuscula* is reported to have two generations per year, and is estimated to require 30-45 days to go from egg to adult. Eggs are laid just beneath the soil at the base of host plants and hatch within 6-8 days. The larvae of *E. fuscula* have three instars and a varying development time, between 17-25 days, Capinera (2001) reports that weather is the major cause of this variability. When the larvae prepares to pupate it creates a pupal cell in the soil, afterward the pupal stage lasts for 4-8 days. The adult flea beetle is 2 mm long on average, with a black body that is covered in short hairs, whereas the antennae and legs are reddish-yellow except the enlarged hind
femur, which is black. This is similar to *E. cucumeris* except *E. fuscula* is more densely covered in hair and its fore and middle femora are black. Like many other flea beetles, *E. fuscula* overwinters as an adult in the surrounding leaf litter and soil, it then emerges in the spring from April to May and begins searching for suitable host plants (Bessin et al. 2005).

*E. hirtipennis* unlike the other *Epitrix* spp. can have 2-5 generations per year depending on location and climate, where the warmer the climate the more generations per year, in Virginia these beetles have 3-4 generations. The egg stage lasts for 6-8 days, and adults lay eggs at the base of host plants preferring moist soil. The larval stage of this beetle lasts from 16-20 days and like *E. fuscula*, is dependent on weather, uniquely their larvae are cannibalistic. Like *E. fuscula*, the larvae then create a pupal cell and spend 4-5 days in the pupal stage. As adults these flea beetles can be smaller than most ranging between 1.4-2.2 mm long, have a reddish-yellow body with similarly color legs excluding the darker femora, and have an irregular brown band that crosses the elytra horizontally. Overwintering strategies are similar to *E. fuscula*, except in southern regions this beetle may remain active throughout the winter (Bessin et al. 2005).

Throughout its northern range, *E. cucumeris* has one generation per year, in more southern regions the beetle can have two generations per year requiring between 30-50 days to complete their life cycle (Anderson and Walker 1934). The eggs are laid in the soil with females preferring moist soil to lay eggs, the eggs then hatch after 6-8 days (Anderson and Walker 1934). The larval stage varies in length with Capinera (2001) reporting between 13-45 days before pupation, whereas, Anderson and Walker
(1934) report it taking between 13-15 days in Virginia. These two sources report the pupal stage lasting from 6-13 days (though it can be longer), and both detail the larvae’s creation of a pupal chamber before pupation. The adult is described above and is quite similar to *E. fuscula*.

**Feeding injury and its impact.** Each of the aforementioned *Epitrix* spp. flea beetles injure Solanaceous plants the same way by chewing small pits in leaves riddling them with holes (Anderson and Walker 1934, Semtner 1984, Bessin et al. 2005). This feeding can severely dry leaves causing them to take on a burned appearance as leaf tissue surrounding the holes dries and dies. Adult feeding has been shown to kill seedlings, retard plant growth, and reduce yield in tomato (Chalfant et al. 1979), tobacco (Semtner 1984), and in potato (Anderson and Walker 1934). It is not well known how this feeding affects eggplant though it likely has a similar effect.

The larvae of these insects can also be damaging to some crops, especially vegetables. *E. hirtipennis* larvae has been responsible for yield reduction and root destruction in tobacco (Semtner 1984), and in tomato plants (Gentile and Stoner 1968). The larvae of *E. cucumeris* causes direct damage to potato tubers and can reduce the marketability of these tubers (Anderson and Walker 1934). Capinera (2001) reports that both *E. cucumeris* and *E. fuscula* can cause pitting and roughening on these tubers, and severe root pruning can occur in other host plants.

**Management of flea beetles on vegetables.**

**Insecticidal control.** Insecticides are the most commonly used method for controlling flea beetles on vegetables. From arsenicals used to successfully control flea
beetles in tobacco (Jewett 1937), and potato (Anderson and Walker 1934), to carbamates to control flea beetles in kale (Reed and Byers 1981) and broccoli (Soroka and Pritchard 1987), insecticides used to control flea beetles have evolved over time.

Today, pyrethroids and neonicotinoids are the most commonly used classes of insecticides for flea beetle control. *P. cruciferae* and *P. striolata* have been controlled using bifenthrin foliar sprays reducing flea beetle densities, defoliation, and increasing yield on cabbage (Mason and Kuhar 2016 a, Shelton and Wilsey 1996, Walgenbach and Schoof 2011). These same beetles have also been controlled successfully using systemic neonicotinoids, such as clothianidin and thiamethoxam in canola (Tansey et al 2008), and imidaclorpid and dinotefuran in cabbage (Mason and Kuhar 2016 a, Walgenbach and Schoof 2011, 2016).

These same insecticides have also been used successfully in controlling *E. fuscula* and *E. hirtipennis* on solanaceous vegetables. Bifenthrin sprays have been particularly effective in controlling *E. fuscula* on eggplant by reducing flea beetle densities and defoliation (Mason and Kuhar 2016 b, McLeod and Diaz 2000). The systemic neonicotinoids, thiamethoxam (McLeod et al. 2002), imidaclorpid, and dinotefuran (Mason and Kuhar 2016 b) effectively control the beetles in eggplant.

**Cultural control.** The use of cultural control for flea beetles has had varying success and the most effective method is to adjust plant date. By planting before large numbers of beetles emerge from overwintering, or planting later in the season after peak beetle populations occurring in June and July have begun to decline, growers can dodge a crucial period where high beetle populations coincide with vulnerable stages of plant growth (Milbrath et al 1995, Capinera 2001, Knodel et al 2008).
Trap cropping has also been investigated as a method for controlling flea beetles found on collards grown in Virginia. Chinese southern giant mustard (*Brassica juncea* var. *crispifolia*) is an example of a trap crop that has been used effectively in the United States to protect crucifer crops from *Phyllotreta* spp. (Grubinger 2005). Other trap crop studies have achieved mixed results where collards planted next to nonhost plants reduced the numbers of beetles and defoliation found on collards, but yield was not increased due to collard competition with the other plants (Latheef and Ortiz 1984). Living mulches have also been used in an attempt to reduce flea beetle densities in cabbage, where flea beetle density was reduced on cabbage with living mulch cabbage yield was also reduced due to the plant competing with the mulch (Andow et al. 1986).

**Row covers.** The use of row covers can be effective for controlling flea beetles on various vegetable crops. Row covers made of polyester screen can act as a physical barrier preventing adult flea beetles from attacking vegetable crops and laying their eggs at the base of these plants (Capinera 2001). A similar row cover was used to reduce flea beetle populations and increase yield in cabbage grown in Delaware (Hough-Goldstein 1987). It is important to note that these barriers are not always effective against flea beetles. If the beetle populations were present on or around the plants prior to applying the row cover, these covers can be completely ineffective as they are able to circumvent barrier and avoid potential natural enemies or adverse environmental conditions (Capinera 2001, Parker and Snyder 2017).

**Biological control and natural enemies.** There are few effective natural enemies able to feed on flea beetles. Generalist predators are sometimes observed feeding on flea beetles, however, they have little to no impact on flea beetle populations
A parasitoid wasp *Microctonus vittatae* (Muesebeck) (Hymenoptera: Braconidae) is reported to parasitize *P. cruciferae* and *P. striolata* in Canada, though rate of parasitism may only be 30-50% and more work needs to be done to assess its effectiveness at controlling flea beetles (Wylie 1982, Capinera 2001).

**Long lasting insecticidal netting (LLIN’s) in agriculture.**

The primary use of LLIN’s is to protect humans from biting Diptera that vector certain diseases, such as malaria (Hill and Rowland 2006, Martin et al. 2007). These nets are typically treated with a pyrethroid insecticide that repel, incapacitate, or kill biting Diptera that come in contact with them (Hill and Rowland 2006). This netting has insecticide woven around or incorporated into the fibers that continually moves to the surface over time replacing the residue that may have been removed by washing or wear (Martin et al. 2007). This technology allows for long residual efficacy of the nets, making them perfect for use over many years (Martin et al. 2007).

**Agricultural research using LLIN’s.** The potential use of these nets in agriculture could add another valuable pest management tool for growers. In Europe these pyrethroid-incorporated nets have been used as a floating row cover to control various lepidopteran and hemipteran pests of vegetables (Martin et al. 2006, Licciardi et al. 2008, Dáder et al. 2015). The toxicity of this netting was evaluated and shown to have a mortality effect on the brown marmorated stink bug *Halyomorpha halys* (Stål), alluding to its potential impact against the insect in a field setting (Kuhar et al. 2017). These nets are considered to be cost-effective because they control multiple pests, last
multiple years, and due to the mesh size can reduce disease and plant growth inhibiting factors from covering plants (Dáder et al. 2015).

**Research Objectives**

The goal of my research is to gain a better understanding of flea beetles attacking vegetables in Virginia and to determine the most effective methods for controlling them on cabbage and eggplant. Specifically, my research objectives were as follows:

**Objective 1: Species complex and population dynamics of flea beetles attacking vegetables in Virginia.**

Evaluate which species of flea beetles are found feeding on cabbage and eggplant in Southwest Virginia to determine the dominant species on each crop, and draw conclusions about population dynamics for each species.

**Objective 2: Impact of flea beetle feeding injury on cabbage and eggplant.**

Determine the effects of flea beetle feeding on yield of cabbage and eggplant that survive the initial defoliation. Plants will be evaluated on an individual plant and per plot basis, to better understand how these beetles impact these vegetables.

**Objective 3: Efficacy of different insecticides for controlling flea beetles.**

Determine which of the recommended insecticides show the greatest efficacy for controlling flea beetles on cabbage and eggplant, and determine if application method plays a role in insecticidal efficacy.
Objective 4: Efficacy of deltamethrin incorporated screen row covers for
controlling flea beetles in cabbage and eggplant.

Determine if deltamethrin incorporated screen row covers are an effective
method for controlling flea beetles in cabbage and eggplant, and determine if these row
covers are as effective as untreated row covers or traditional insecticides for controlling
flea beetles.
References


**Dominick, C. B., 1967.** Systemic insecticides applied to the soil for control of the tobacco flea beetle on tobacco. J. Econ. Entomol. 60: 1468-1469


McLeod, P., F. J. Diaz, and D. T. Johnson. 2002. Toxicity, persistence, and efficacy of spinosad, chlorfenapyr, and thiamethoxam on eggplant when applied against the
eggplant flea beetle (Coleoptera: Chrysomelidae). J. Econ. Entomol. 95: 331-335.


Fig 1.1 Crucifer flea beetle *Phyllotreta cruciferae*
Fig 1.2 Striped flea beetle *Phyllotreta striolata*
Fig 1.3 Eggplant flea beetle *Epitrix fuscula*
Fig 1.4 Tobacco flea beetle *Epitrix hirtipennis*
Chapter two

Flea beetle (Coleoptera: Chrysomelidae) populations, effects of feeding injury, and efficacy of insecticide treatments on eggplant in Virginia

Introduction

Eggplant, *Solanum melongena* L. Solanaceae, is grown throughout the United States and is attacked by a number of different arthropod pests (Bessin et al. 2005). In most regions of North America, the most prominent pests of eggplant seedlings are flea beetles (Coleoptera: Chrysomelidae), including eggplant flea beetle, *Epitrix fuscula* (Crotch), tobacco flea beetle, *Epitrix hirtipes* (Melsheimer), and potato flea beetle, *Epitrix cucumeris* (Harris) (Capinera 2001, Bessin et al. 2005). Flea beetle adults feed on leaves resulting in characteristic “shot-hole” appearances (McLeod et al. 2002). High densities of these insects can completely riddle leaves with holes. In tomato this injury can retard plant growth, reduce yield, and potentially kill seedlings (Chalfant et al. 1979). Very little is known regarding the species complex of flea beetles attacking eggplant in Virginia, or on the impact of their feeding injury as well as efficacy and yield benefit of various insecticide controls. Herein, we investigated the flea beetle species complex attacking eggplant in Virginia, assessed the impact of their feeding injury on the crop yield, and evaluated various insecticide treatments for efficacy at controlling this pest group.

Materials and Methods

**Field Plots.** Small plots of eggplant were established at Virginia Tech’s Kentland Research Farm in Whitethorne, VA in 2015 and 2016. Eight week old ‘Classic’ eggplant
transplants were planted on 25 May, 2015 and 26 May, 2016 in rows spaced 0.91m apart, plants were spaced 0.46m within rows. Eggplants were maintained according to commercial recommendations (Arancibia et al. 2017), including preplant fertilizer application (rate of 10:10:10), pre-emergence herbicide, and drip irrigation as needed.

**Flea beetle species complex.** In order to determine which species of flea beetles were attacking eggplant, vacuum samples were taken weekly from late May until mid-August each year. Flea beetle samples were obtained using a leaf blower vacuum (Black and Decker, Baltimore, MD) with the intake tube attached to the vacuum suction fan for beetle collection. A fine-mesh, 3.8-liter paint strainer bag was attached to the end of the tube to catch the flea beetles. Samples consisted of flea beetles obtained by vacuuming ten randomly selected plants for ten seconds in one row, and four samples were collected in a single sampling day each week, one sample per row of untreated eggplant. After vacuuming ten plants, the mesh bag was tied off and secured with a rubber band before turning off the leaf blower and taking off the bag to ensure no beetles escaped while switching bags. Each sample was placed in a freezer to kill all the beetles and preserve the sample for processing at a later date. Each sample was processed by counting and sorting all flea beetles present, and identifying them using Downie (1994) and Capinera (2001).

**Insecticide efficacy.** Using the eggplant field plots described in the previous section, an eight treatment field experiment was set up in a randomized complete block design in 2015. Plots consisted of single 7.62m long rows spaced 0.91m apart with eggplant planted 0.46m within rows. Treatments included: 1) an untreated control, 2) a transplant soil application of 300 g Al per ha of dinotefuran (Venom® 70SG, Valent USA
LLC, Walnut Creek, CA), 3) a soil application of 294 g AI per ha imidacloprid (Admire Pro®, Bayer Crop Science USA, Research Triangle Park, NC), 4) a soil application of 98.6 g AI per ha cyantraniliprole (Verimark™ 1.67SC, Dupont USA, Wilmington, DE), 5) a foliar spray of 0.052 g AI per ha imidacloprid (Admire Pro®, Bayer Crop Science USA, Research Triangle Park, NC), 6) a foliar spray of 0.05 g AI per ha of dinotefuran (Venom® 70SG, Valent USA LLC, Walnut Creek, CA), 7) a foliar spray of 0.10 g AI per ha cyantraniliprole (Exirel™, Dupont USA, Wilmington, DE), 8) a foliar application at 36.8 g AI per ha of bifenthrin (Brigade®2EC, FMC USA, Philadelphia, PA).

In 2016, the same design was used as the previous year, except that the treatments were modified. The untreated control and the same three soil application treatments of dinotefuran, imidacloprid, and cyantraniliprole were included as described above, but an additional soil treatment of clothianidin (Belay™, Valent USA LLC, Walnut Creek, CA) at 56 g AI per ha was included, and only one foliar treatment was included, bifenthrin (Brigade®2EC, FMC USA, Philadelphia, PA) at 36.8 g AI per ha. In both years soil treatments were applied at planting, whereas foliar sprays were applied a week after planting to simulate typical grower practices. The soil drench applications were mixed with 236.6 mL transplant water used to water the insecticide treated plots at time of planting, other treatments received 236.6 mL water as normal.

Each week for four weeks, each plot in the insecticide experiment was evaluated by counting the number of live flea beetles on ten randomly selected plants per plot, and evaluating flea beetle feeding injury by visually assessing ten randomly selected leaves for defoliation. In order to ensure that no further feeding injury occurred from any pests beyond that of the initial flea beetle feeding, all plots were sprayed with a broad
spectrum insecticide Besiege®, (Syngenta® Greensboro, NC) containing lambda-cyhalothrin (36.4 g AI per ha) and chlorantraniliprole (72.8 g AI per ha), after the last flea beetle sample date. To assess yield, the total number of market-sized eggplant fruit was counted per plot in the experiment. Eggplant were harvested on 5 August, and 17 August, 2015 and on 4 August, 15 August, and 29 August, 2016. For the insecticide component, number of live beetles per sample date, mean defoliation, and yield were analyzed for treatment significance at the (P<0.05) using the software JMP Pro 11 (SAS Institute Inc. 2007). Treatment effects were determined using ANOVA, when p < 0.05, and means were separated using Tukey’s HSD.

**Impact of feeding injury.** In order to further assess the effects of flea beetle feeding injury on yield, plants were grouped by defoliation category. Plants were separated into five defoliation categories ranging from 0- >60% defoliation, plants were placed into their overall category based on how defoliated a majority of the leaves on the plant were. The categories included: pristine plants representing 0% overall defoliation, plants with 1-20% overall defoliation, plants with 21-40% overall defoliation, plants with 41-60% overall defoliation, and plants with >60% defoliation. Ten plants fitting each category were selected a month after transplanting, and were selected from treated plots to ensure a variety of damage. Plants were marked in the field to denote their appropriate categories and to ensure the same plant was evaluated during harvest. Eggplants were harvested over the same period as the insecticide trial, and yield was assessed for each plant individually by counting the number of eggplant from each plant. Yield was analyzed among overall defoliation categories to assess the effects of flea beetle feeding injury for treatment significance at the (P<0.05) using the software
JMP Pro 11 (SAS Institute Inc. 2007). Treatment effects were determined using ANOVA, when p < 0.05, and means were separated using Tukey’s HSD.

**Results**

**Flea beetle species complex.** *Epitrix fuscula* (Crotch) was the dominant species found on eggplant comprising 94 and 96% of all flea beetles caught in 2015 and 2016, respectively (Fig. 1). Tobacco flea beetle, *Epitrix hirtipennis* (Melsheimer) was the only other species found in both years (Fig 1). Throughout 2015, 5,499 flea beetles were sampled and identified, whereas 11,460 were examined in 2016.

**Seasonal abundance of flea beetles in eggplant.** Flea beetles appeared on plants immediately following transplanting in late May in both years, with densities slowly increasing over the month of June (Fig. 1). In both years, there was a noticeable increase in densities in mid-July, which peaked in early August.

**Impact of feeding injury.** In 2015, there was a significant positive relationship between the mean number of flea beetles per 10 plants per plot and the mean defoliation per 10 leaves per plot (F= 51.97; P < 0.0001) (Fig. 2). In 2016, there was a similar trend between these factors, but the relationship was not significant (F= 3.43; P < 0.0776) (Fig 2). In regards to yield, in 2015, there was a significant negative relationship between the amount of defoliation per plot and the cumulative number of eggplant produced per plot (F=27.95; P < 0.0001) (Fig. 3). In 2016, there was a similar significant trend between defoliation and yield, but the relationship was not as strong (F= 6.59; P < 0.0176) (Fig. 3).
Looking at individual plants in various defoliation categories there was a significant difference in yield between defoliation categories. In 2015, plants with 0% overall defoliation cumulatively produced significantly more eggplant than those plants with 21-60% overall defoliation (F=6.76; df= 4; P < 0.0040) (Fig. 4). Eggplants with 1-20% overall defoliation produced significantly more eggplant than plants with >60% overall defoliation, and these plants produced statistically similar numbers of eggplant to plants in other categories (F=6.76; df= 4; P < 0.0040) (Fig. 4). In 2016 eggplant with 0% and 1-20% overall defoliation cumulatively produced significantly more eggplant than plants with 41-60% and >60% overall defoliation (F=6.25; df= 4; P < 0.0004) (Fig. 4). Eggplants in the 21-40% overall defoliation category did not produce statistically different numbers of eggplant than any of the other defoliation categories (F=6.25; df= 4; P < 0.0004) (Fig. 4).

**Insecticide efficacy.** Overall the soil-drench dinotefuran provided the most effective control for flea beetles in eggplant. In 2015 it had significantly fewer flea beetles than the control, and by 23 June it also had fewer flea beetles than every other treatment (F= 6.11; df= 7; P < 0.0006) (Table 1). In 2016 it had significantly fewer flea beetles than the control in the first (F= 3.06; df= 7; P < 0.0496) (Table 1), and second (F= 3.15; df= 7; P < 0.0385) (Table 1) week after treatment, and fewer flea beetles in the third week than the control, although there wasn’t a significant treatment difference (F= 2.36; df= 7; P < 0.0903) (Table 1).

Soil-drench dinotefuran had significantly less defoliation than all other treatments with the exception of imidacloprid in 2015 (F= 36.33; df= 7; P < 0.0001) (Fig. 5), and in 2016, all of the soil applied treatments had significantly less defoliation than the control.
Soil applied imidacloprid provided similar results to soil applied dinotefuran in regards to defoliation. Overall the preventative soil-drench treatments had less defoliation among plots than the foliar spray treatments due to longer residual activity.

In 2015 in regards to yield, dinotefuran applied as a soil-drench cumulatively produced more eggplant than all other treatments, and it produced significantly more eggplant than the control plots (F= 27.95; df= 7; P < 0.0001) (Fig. 6). In 2016, it cumulatively produced more eggplant than the control, however it did not produce significantly more than any of the other treatments (F= 1.20; df= 5; P < 0.3505) (Fig. 6). Soil applied imidacloprid also performed well in both 2015 and 2016 with respect to yield. In 2015 it cumulatively produced significantly less eggplant than dinotefuran, but significantly more than the untreated control and performed similar to the other treatments (F= 27.95; df= 7; P < 0.0001) (Fig. 6). In 2016, imidacloprid cumulatively produced a similar number of eggplant to dinotefuran and more eggplant than the control, there was not a significant difference (F= 1.20; df= 5; P < 0.3505) (Fig. 6).

It is worth noting that bifenthrin performed the best of all the foliar spray treatments. In 2015 it had significantly less flea beetles than the control, and statistically similar flea beetle numbers to soil applied dinotefuran until the last sample date (F= 62.25; df= 7; P < 0.0001), (F= 4.78; df= 7; P < 0.0024), (F= 14.24; df= 7; P < 0.0001) (F= 6.11; df= 7; P < 0.0006) (Table 1), while in 2016 it performed statistically similar to soil applied dinotefuran in the second week (F= 3.15; df= 5; P < 0.0386) (Table 1). In regards to defoliation it had the least amount of flea beetle feeding in 2015 when compared to the other foliar sprays, and significantly less than the control (F= 36.33; df= 28
7; P < 0.0001) (Fig. 5). In 2016 it again had significantly less flea beetle feeding than the control, though more than the other treatments (F= 16.02; df= 5; P < 0.0001) (Fig. 5). In 2015 regarding yield bifenthrin treated eggplant cumulatively produced a statistically similar amount of eggplant as the other treatments and significantly more than the control (F= 27.95; df= 7; P < 0.0001) (Fig. 6). In 2016 it produced more eggplant cumulatively than the control, though they were not statistically different (F= 1.20; df= 5; P < 0.3505) (Fig. 6).

**Figure 1.** Densities of flea beetles *Epitrix fuscula* = EFB, *Epitrix hirtipennis* = TFB in vacuum samples collected from eggplant in Whitethorne, VA in (A) 2015 and (B) 2016.
**Figure 2.** Relationship between number of flea beetles and flea beetle defoliation on eggplant in Whitethorne, VA in 2015 (A) and 2016 (B). A defoliation of 1 represented no injury and 5 represented severe > 60% defoliation.

![Graph A](image1.png)

![Graph B](image2.png)

**Figure 3.** Relationship between flea beetle defoliation and number of eggplant produced in Whitethorne, VA in 2015 (A) and 2016 (B). A defoliation of 1 represented no injury and 5 represented severe > 60% defoliation.

![Graph C](image3.png)

![Graph D](image4.png)
Figure 4. Mean number of eggplant produced by plants placed in various overall defoliation categories (located on the x-axis), in Whitethorne, VA in 2015 (A) and 2016 (B). Means followed by the same letter within a column are not significantly different (P>0.05) according to Student’s t-test. Data without letters did not show a significant treatment effect.

Table 1. Mean flea beetle densities for various insecticide treated eggplant plots in Whitethorne, VA in 2015 and 2016.

<table>
<thead>
<tr>
<th>Treatment*</th>
<th>Rate Amt g Al / ha</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5 Jun</td>
<td>9 Jun</td>
</tr>
<tr>
<td>Untreated Control</td>
<td>-</td>
<td>124.0 a</td>
<td>99.3 a</td>
</tr>
<tr>
<td>Imidacloprid (S)</td>
<td>294</td>
<td>9.0 c</td>
<td>3.5 b</td>
</tr>
<tr>
<td>Dinotefuran (S)</td>
<td>300</td>
<td>1.5 c</td>
<td>1.8 b</td>
</tr>
<tr>
<td>Cyantraniliprole (S)</td>
<td>98.6</td>
<td>31.3 b</td>
<td>44.0 b</td>
</tr>
<tr>
<td>Clothianidin (S)</td>
<td>56</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Imidacloprid (F)</td>
<td>36.8</td>
<td>12.3 c</td>
<td>23.5 b</td>
</tr>
<tr>
<td>Dinotefuran (F)</td>
<td>0.05</td>
<td>5.5 c</td>
<td>8.3 b</td>
</tr>
<tr>
<td>Cyantraniliprole (F)</td>
<td>0.05</td>
<td>8.5 c</td>
<td>29.5 b</td>
</tr>
<tr>
<td>Bifenthrin (F)</td>
<td>0.10</td>
<td>1.5 c</td>
<td>5.3 b</td>
</tr>
</tbody>
</table>

* S = soil transplant drench; F = foliar spray application ** Bifenthrin was applied this date and data was not collected for this treatment until the following week.

Means followed by the same letter within a column are not significantly different (P>0.05) according to Student’s t-test. Data without letters did not show a significant treatment effect.
Figure 5. Mean percent defoliation for various insecticide treated eggplant plots in Whitethorne, VA in 2015 (A) and 2016 (B). Means followed by the same letter within a column are not significantly different (P>0.05) according to Student’s t-test. Data without letters did not show a significant treatment effect.

Figure 6. Mean number of eggplant produced for various insecticide treated eggplant plots in Whitethorne, VA in 2015 (A) and 2016 (B). Means followed by the same letter within a column are not significantly different (P>0.05) according to Student’s t-test. Data without letters did not show a significant treatment effect.
Discussion

Several species of flea beetles are reported to be pests of solanaceous vegetables such as eggplant in the U.S., including eggplant flea beetle, palestriped flea beetle *Systena blanda* (Melsheimer), tobacco flea beetle, and potato flea beetle (Bessin et al. 2005, and Capinera 2001). In southwest Virginia, we found only two species attacking eggplant with *E. fuscula* comprising 94% and 96% of beetles sampled in 2015 and 2016, respectively, and *E. hirtipennis* comprising 6% and 4% in 2015 and 2016, respectively. These species have been reported on eggplant throughout the U.S. (Bessin et al. 2005). Due to the low numbers of *E. hirtipennis*, it likely has little impact on eggplant in southwest Virginia when compared to *E. fuscula*.

In both years flea beetles were active and found on plants the same day they were transplanted and were present through the last harvest in both 2015 and 2016. Capinera (2001) reports that *E. fuscula* feeding in the early stages of plant development can stunt plant growth, and it is known that serious damage is typically caused by overwintering flea beetle adults attacking seedling plants (Bessin et al. 2005). In southwest Virginia, flea beetles active in May and early June pose a significant threat to eggplant, which is often planted during those times. In both 2015 and 2016, there were two population peaks, one peaked in the middle to end of June and the other in the middle of July. The early population of flea beetles likely emerged as overwintering adults and coincided with the first few weeks after planting eggplant, which is similar to what was reported in the past (Capinera 2001, Bessin et al. 2005). In southwest Virginia, it is important to protect eggplant during this critical period when flea beetles are active and eggplants are young.
As previously stated, flea beetle feeding can cause conspicuous leaf-feeding injury, but how this injury affects yield of surviving eggplants is largely unknown. Insect feeding can cause a variety of effects on plants, it can cause early crop loss, a negative yield effect, have no effect on the crop, or cause a compensatory effect on the crop having a positive yield effect (Briske and Richards 1995). By looking at the relationship between flea beetles and defoliation and then at the relationship between flea beetles and yield, we are now better able to understand how flea beetle feeding affects eggplant. The significant negative relationship between defoliation and yield on a per plot basis, coupled with significantly less eggplant produced as defoliation increases on an individual plant basis, shows that flea beetle feeding can cause a negative yield effect. If flea beetles cause crop loss or a negative yield effect from feeding on eggplant, and most of the damage is caused during the early stages of the plants life then preventative flea beetle control methods could significantly improve the yield of eggplants attacked by flea beetles.

In order to determine the efficacy and yield benefits of various insecticide control methods we wanted to evaluate the insecticides in regards to flea beetle density, defoliation, and plant yield. Insecticides were chosen based on the Mid-Atlantic Vegetable Production Guide using insecticides that were specifically recommended for flea beetle control on eggplant (Arancibia et al 2017). Bifenthrin was used as an industry standard to test its performance and used to compare the other insecticides to it. The pyrethroid has been used to control flea beetles with success in the past, it has been reported to reduce *E. fuscula* numbers and feeding injury in eggplant (McLeod and Diaz 1999 and McLeod and Diaz 2000). The systemic neonicotinoids have also shown
success on flea beetles in the past, thiamethoxam significantly reduced *E. fuscula* numbers in Arkansas (McLeod et al. 2002), and imidacloprid was used to reduce *E. hirtipennis* density and feeding on tobacco (Semtner and Wright 2009). When looking at all three metrics imidacloprid and dinotefuran provided the best flea beetle control, typically reducing flea beetle density, defoliation, and increasing yield. Of the foliar sprays, bifenthrin was the most effective at controlling flea beetles, although the preventative post-transplant soil drench insecticides typically performed better than the foliar sprays. In part the foliar sprays had more defoliation than the soil drench insecticides because the foliar sprays were applied curatively a week after planting to mimic how a grower would treat for flea beetles, while the soil drenches had to be applied at planting to parallel how they would be applied in a commercial setting.

In future experiments, flea beetle populations could be assessed in other parts of the state. By evaluating defoliation and its effect on yield with more seasons of data and perhaps using a different method for evaluating defoliation could help solidify the relationship between defoliation and yield. Testing the efficacy of other labeled insecticides, both soil applied and foliar, could be assessed to determine other, possibly cheaper, effective chemical control methods. By assessing the flea beetle species complex attacking eggplant, evaluating the impact of their feeding injury on yield, and determining the efficacy of various insecticides for flea beetle control, we were able to characterize the threat a large population of flea beetles pose to eggplant grown in Virginia. In the southwestern part of the state, *E. fuscula* is the most dominant flea beetle found on eggplant, their feeding injury can significantly reduce yield, and a
preventative soil applied dinotefuran treatment is one of the most promising ways to control them.

References


SAS Institute Inc. 2007. JMP user's guide. SAS Institute Cary, NC.
Chapter Three

Flea beetle (Coleoptera: Chrysomelidae) populations, effects of feeding injury, and efficacy of insecticide treatments on cabbage in Virginia

Introduction

Cabbage, *Brassica oleracea* L. Brassicaceae, is widely grown throughout the United States and is attacked by a variety of arthropod pests, including flea beetles (Coleoptera: Chrysomelidae), which can pose a serious threat to cabbage seedlings (Eastman et al. 2005). In North America, several species are known to attack cabbage including striped flea beetle, *Phyllotreta striolata* Fabr., crucifer flea beetle, *Phyllotreta cruciferae* (Goeze), Zimmermann’s flea beetle, *Phyllotreta zimmermanni* (Crotch), and palestriped flea beetle, *Systena blanda* (Melsheimer) (Capinera 2001, Eastman et al. 2005). All flea beetles chew small “shot-holes” in the leaves of their host plants, reducing the plants ability to photosynthesize (Feeny et al. 1970). Major feeding damage can leave plants with a burned appearance as leaf tissue around the feeding holes dries out and dies (Capinera 2001). In canola, a moderate amount of flea beetle feeding injury can slow development and reduce yield (Lamb 1984). Less is known about the effect of flea beetle feeding on cabbage yield. Herein, we investigated the species complex of flea beetles attacking cabbage in Virginia, assessed the impact of their feeding injury on crop yield, and evaluated the efficacy of recommended insecticide treatments at controlling these pests.
Materials and Methods

Field Plots. Field experiments were conducted at Virginia Tech’s Kentland Farm in Whitethorne, VA (37.2013° N, −80.5656° W), where soil type is a Shottower Loam, and where mixed vegetables had been grown on the land for decades. Six week old ‘Bravo’ cabbage transplants were planted on 25 May, 2015, and 26 May, 2016, in rows spaced 0.91m apart, plants were spaced ~38.1cm within rows. Fields were prepared for planting by broadcasting 10-10-10 fertilizer at a rate of 112-kg per ha, followed by an application of pre-emergence herbicide, S-metolachlor (Dual Magnum, Syngenta, Greensboro, NC), at 0.59-liter a.i./ha. Drip irrigation was applied as needed. Plants were also sprayed the week of transplanting with Bacillus thuringiensis (Dipel® DF, Valent USA LLC, Walnut Creek, CA) at 1.12 kg/ha, to protect them from early-season lepidopteran pests and ensure feeding injury from these insects did not influence defoliation or yield.

Flea beetle species complex. To learn which flea beetle species were attacking cabbage at our location, vacuum samples were taken weekly from late May until mid-August both years. Samples were collected using a leaf blower with a vacuum setting (Black and Decker, Baltimore, MD) with the intake tube attached to the vacuum suction fan to collect flea beetles from the cabbage. A fine-mesh, 3.8-liter paint strainer bag was attached to the end of the tube with rubber bands to collect the flea beetles. Each week, flea beetle samples were obtained by vacuuming ten randomly-selected plants for ten seconds per cabbage row. This was repeated four times on the same day, sampling different rows each time. To avoid beetles escaping while switching bags, after
vacuuming ten plants, the mesh bag was tied off and wrapped with a rubber band before turning off the leaf blower and removing the bag from the vacuum tube. Each bag sample was then placed in a freezer to kill beetles and preserve the sample for counting and identification at a later date. Flea beetles in each sample were counted, sorted, and then identified using Downie and Arnett Jr (1995) and Capinera (2001).

**Insecticide efficacy.** Using the cabbage field plots described in the previous section, an eight treatment field experiment was set up in a randomized complete block design in 2015. Plots consisted of single 7.62m long rows spaced 0.91m apart with cabbage planted ~38cm within rows. Treatments included: 1) an untreated control, 2) a transplant soil application of 300 g AI per ha of dinotefuran (Venom® 70SG, Valent USA LLC, Walnut Creek, CA), 3) a soil application of 294 g AI per ha imidacloprid (Admire Pro®, Bayer Crop Science USA, Research Triangle Park, NC), 4) a soil application of 98.6 g AI per ha cyantraniliprole (Verimark™ 1.67SC, Dupont USA, Wilmington, DE), 5) a foliar spray of 0.052 g AI per ha imidacloprid (Admire Pro®, Bayer Crop Science USA, Research Triangle Park, NC), 6) a foliar spray of 0.05 g AI per ha of dinotefuran (Venom® 70SG, Valent USA LLC, Walnut Creek, CA), 7) a foliar spray of 0.10 g AI per ha cyantraniliprole (Exirel™, Dupont USA, Wilmington, DE), 8) a foliar application at 36.8 g AI per ha of bifenthrin (Brigade®2EC, FMC USA, Philadelphia, PA). The soil drench applications were mixed with 236.6 mL transplant water used to water the insecticide treated plots at time of planting, other treatments received 236.6 mL water as normal.

In 2016, the same design was used as the previous year, except that the treatments were modified. The untreated control and the same three soil application
treatments of dinotefur, imidacloprid, and cyantraniliprole were included as described above, but an additional soil treatment of clothianidin (Belay™, Valent USA LLC, Walnut Creek, CA) at 56 g AI per ha was included, and only one foliar treatment was included, bifenthrin (Brigade®2EC, FMC USA, Philadelphia, PA) at 36.8 g AI per ha. In both years soil treatments were applied at planting, whereas foliar sprays were applied a week after planting to simulate typical grower practices.

In both 2015 and 2016, each week for four weeks, every plot in the insecticide experiment was evaluated by counting the number of live flea beetles on ten randomly selected plants per plot, and evaluating flea beetle feeding injury by visually assessing ten randomly selected leaves. To prevent damage caused by pests other than flea beetles, all plots were sprayed with the broad spectrum insecticide Besiege®, Syngenta® Greensboro, NC) containing lambda-cyhalothrin (36.4 g AI per ha) and chlorantraniliprole (72.8 g AI per ha), after the last flea beetle sample date. Cabbage was harvested and yield was assessed on 27 July, 2015, and 1 August, 2016, by hand-harvesting and weighing each cabbage head produced per plot. To determine the efficacy of each insecticide, number of live beetles per 10 plants per sample date, mean defoliation, and yield were analyzed for treatment significance at the (P<0.05) using ANOVA in JMP Pro 11 (SAS Institute Inc. 2007). Means were separated using Student’s t test at a significance level of P < 0.05.

**Impact of feeding injury.** To better understand the effects of flea beetle feeding injury on cabbage yield, individual plants were selected and grouped by defoliation category. Each plant was assigned one of five overall defoliation categories ranging from 0- >60% defoliation, plants were placed into their category based on how
defoliated a majority of their leaves were. The defoliation categories included; uninjured plants with 0% overall defoliation, plants with 1-20% overall defoliation, plants with 21-40% overall defoliation, plants with 41-60% overall defoliation, and plants with >60% defoliation. Ten plants were selected for each category a month after transplanting, and were selected from treated plots to ensure a variety of damage. Plants were marked in the field using a flag to denote which category they belonged to and to ensure the same plant was assessed during harvest. Yield was assessed for each individual plant by weighing the cabbage head produced by the plant, these plants were harvested at the same time as the plots in the insecticide trial. Yield was analyzed among overall defoliation categories to assess the effects of flea beetle feeding injury for treatment significance at the (P<0.05) using the software JMP Pro 11 (SAS Institute Inc. 2007). Treatment effects were determined using ANOVA, when p < 0.05, and means were separated using Student’s t test.

Results

Flea beetle species complex. P. striolata was the dominant species found on cabbage, comprising 58% of all flea beetles captured in 2015 and 72% in 2016 (Fig. 1). The only other species found on cabbage, P. cruciferae, comprised the other 42 and 28% of flea beetles captured in 2015 and 2016, respectively (Fig. 1). Throughout 2015, 6,432 flea beetles were sampled and identified, whereas 22,299 were examined in 2016.

Seasonal abundance of flea beetles in eggplant. Both flea beetle species were present in low numbers on plants a week after transplanting in early June in both 2015 and 2016, with densities increasing beginning in early to mid-June (Fig. 1). In
2015 the peak beetle population occurred in June whereas in 2016 there were many more beetles throughout all of July peaking toward the end of the month and early August (Fig 1).

Impact of feeding injury. In 2015, there was a significant positive relationship between the mean number of flea beetles per 10 plants per plot and the mean percent defoliation per 10 leaves per plot (F= 20.7; P < .0001) (Fig. 2), as the number of beetles increased the amount of defoliation also increased. In 2016, there was also a significant positive relationship between these factors (F= 27.3; P < 0.0001) (Fig. 2). With respect to yield, in 2015, there was a significant negative relationship between the amount of defoliation per plot and the total weight (Kg) of cabbage heads per plot (F= 22.3; P < 0.0001) (Fig. 3). In 2016, there was no significant relationship between these factors (F= 0.034; P < 0.855) (Fig. 3).

When assessing individual plants, defoliation ranking had a significant effect on cabbage head weight (Fig. 4). In 2015, plants with 0% overall defoliation produced significantly larger cabbage heads than plants in any other defoliation category (F= 16.3; df= 4; P < 0.0001) (Fig.4). The plants with 1-20% overall defoliation were statistically similar to those with 21-40% overall defoliation (F= 16.3; df= 4; P < 0.0001) (Fig.4). The highest categories with 41-60% overall defoliation and >60% overall defoliation produced significantly smaller cabbage heads than the other categories (F= 16.3; df= 4; P < 0.0001) (Fig.4). In 2016, plants with 0% defoliation produced significantly larger cabbage heads than plants in other categories, while plants in defoliation categories 1-20%, 21-40%, and 41-60%, had statistically similar yields (F= 7.3; df= 4; P < 0.0001) (Fig.4). Cabbage plants with the highest overall defoliation had
significantly smaller cabbage heads on average than every other category except plants with 41-60% defoliation (F= 7.3; df= 4; P < 0.0001) (Fig.4).

**Insecticide efficacy.** Throughout the experiment, soil applied dinotefuran provided the best control for flea beetles in cabbage. In 2015, soil-applied dinotefuran had significantly fewer flea beetles than the control over the entire sampling period (Table 1). Particularly of note, this treatment had significantly fewer flea beetles than the control on 13 June (F= 6.6; df= 7; P < 0.0004) (Table 1), and 23 June (F= 5.8; df= 7; P < 0.0007) (Table 1), when most other treatments did not have significantly fewer flea beetles than the control. In 2016, soil applied dinotefuran had significantly fewer flea beetles than the control on 14 June, which was the only date there was a significant treatment effect (F= 6.1; df= 5; P < 0.0028) (Table 1). In regards to defoliation, soil applied dinotefuran had significantly less defoliation on average than the control and all other treatments with the exception of bifenthrin in 2015 (F= 48.2; df= 7; P < 0.0001) (Fig. 5), and in 2016 it had significantly less defoliation than the control, soil-applied imidaclorpid, and soil-applied clothianidin (F= 5.8; df= 5; P < 0.0086) (Fig. 5). When evaluating yield, in 2015 soil applied dinotefuran produced significantly larger cabbage heads by weight, than the control and every other treatment except bifenthrin (F= 5.7; df= 7; P < 0.0009) (Fig. 6). In 2016, there was not a significant treatment effect with respect to yield (F= 2.3; df= 5; P < 0.0925) (Fig. 6).

As previously mentioned, bifenthrin had similar efficacy to the soil applied dinotefuran, often having fewer flea beetles, less defoliation, and higher yield than the control and many of the other treatments. Although not significantly different from soil applied dinotefuran, bifenthrin on average fell slightly behind it when looking at these
metrics. The other treatments did not perform as well overall as soil applied dinotefuran and bifenthrin.

Figure 1. Densities of flea beetles (*Phyllotreta striolata* = SFB; *Phyllotreta cruciferae* = CFB) from vacuum samples collected from cabbage throughout the season in Whitethorne, VA in (A) 2015 and (B) 2016.

Figure 2. Relationship between number of flea beetles and percent defoliation on cabbage in Whitethorne, VA in 2015 (A) and 2016 (B). A defoliation of 1 represented no injury and 5 represented severe > 60% defoliation.
**Figure 3.** Relationship between flea beetle defoliation and weight of cabbage heads produced in Whithorne, VA in 2015 (A) and 2016 (B). A defoliation of 1 represented no injury and 5 represented severe > 60% defoliation.

\[ y = -12.031x + 38.501 \]
\[ R^2 = 0.4861 \]

**Figure 4.** Mean weight of cabbage heads produced by plants placed in various overall defoliation categories (located on the x-axis), in Whitethorne, VA in 2015 (A) and 2016 (B). All data were analyzed using analysis of variance procedures. Means were separated using Student’s t test at the 0.05 level of significance. Means followed by the same letter within a column are not significantly different (P>0.05). Data without letters did not show a significant treatment effect.

\[ y = -0.4292x + 12.868 \]
\[ R^2 = 0.0015 \]
Table 1. Mean flea beetle densities for various insecticide treated cabbage plots in Whitethorne, VA in 2015 and 2016. All data were analyzed using analysis of variance procedures.

<table>
<thead>
<tr>
<th>Treatment*</th>
<th>Rate Amt g Al / ha</th>
<th>2015</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 Jun</td>
<td>9 Jun</td>
<td>13 Jun</td>
</tr>
<tr>
<td>Untreated Control</td>
<td>-</td>
<td>16.3 a</td>
<td>35.0 a</td>
</tr>
<tr>
<td>Imidacloprid (S)</td>
<td>294</td>
<td>0.5 b</td>
<td>33.8 a</td>
</tr>
<tr>
<td>Dinotefuran (S)</td>
<td>300</td>
<td>1.5 b</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Cyantraniliprole (S)</td>
<td>98.6</td>
<td>2.0 b</td>
<td>13.0 bcd</td>
</tr>
<tr>
<td>Clothianidin (S)</td>
<td>56</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bifenthrin (F)</td>
<td>36.8</td>
<td>2.0 b</td>
<td>1.0 cd</td>
</tr>
<tr>
<td>Imidacloprid (F)</td>
<td>0.05</td>
<td>0.8 b</td>
<td>19.3 ab</td>
</tr>
<tr>
<td>Dinotefuran (S)</td>
<td>0.05</td>
<td>1.0 b</td>
<td>9.8 bcd</td>
</tr>
<tr>
<td>Cyantraniliprole (F)</td>
<td>0.10</td>
<td>0 b</td>
<td>17.8 abc</td>
</tr>
</tbody>
</table>

* S = soil transplant drench; F = foliar spray application

Means followed by the same letter within a column are not significantly different according to Student’s T-test (P>0.05). Data without letters did not show a significant treatment effect.

Figure 5. Mean percent defoliation for various insecticide treated cabbage plots in Whitethorne, VA in 2015 (A) and 2016 (B). Means were separated using Student’s t test at the 0.05 level of significance. Means followed by the same letter within a column are
not significantly different (P>0.05). Data without letters did not show a significant treatment effect.

**Figure 6.** Mean weight of cabbage heads per plant produced for various insecticide treated cabbage plots in Whitethorne, VA in 2015 (A) and 2016 (B). Means followed by the same letter within a column are not significantly different (P>0.05) according to Student’s t-test. Data without letters did not show a significant treatment effect.
Discussion

There are many species of flea beetles reported to be pests of brassica vegetables such as cabbage in North America, including striped flea beetle, crucifer flea beetle, Zimmerman’s flea beetle, and palestriped flea beetle (Capinera 2001, Eastman et al. 2005). In our experiment in southwest Virginia, only two species of flea beetles were found on cabbage, *P. striolata* comprising 58% and 72% of beetles captured in 2015 and 2016 respectively, and *P. cruciferae* comprising 42% and 28% in 2015 and 2016, respectively. Both of these beetles have similar biologies (Feeny et al. 1970, Capinera 2001, Eastman et al. 2005), and therefore methods used to control one species will probably also work for the other.

In both years, these flea beetles were first found on cabbage plants in early to mid-June and were present throughout the season until harvest in August. Eastman et al. (2005) reported that *P. striolata* and *P. cruciferae* feeding on cabbage cotyledons, stems, and foliage causes most crop injury, and that significant feeding injury is a major cause of crop loss and uneven stand development. In southwest Virginia large flea beetle populations can be particularly troubling as cabbage is often transplanted around this time (Arancibia et al. 2017). Furthermore, in 2015 flea beetle populations peaked in mid-June and early August, while in 2016 they peaked in the beginning and end of July; if cabbage seedlings are in a crucial development period from June to July these beetle populations can be crippling. Overwintering adults emerged and threatened cabbage during the beginning of June, and likely are responsible for the first population peak in both 2015 and 2016. These beetles probably died off in mid-summer (Burgess 1977). The second, larger peak in both years is likely an F1 generation of flea beetles emerging
after pupation in the soil. These findings are consistent with Andersen et al. (2005) found in Massachusetts, who reported that *P. cruciferae* populations peaked in June and August and determined that the first peak was the first generation of overwintering flea beetles, and the second peak were second generation flea beetles that emerged from pupation that year. Using our findings and adjusting planting date when possible may allow plants to outgrow this critical development period by the time large flea beetle populations can build up on the plants. Regardless, in southwest Virginia it is imperative to protect cabbage during this crucial developmental period when flea beetles are active and cabbage plants are young.

As previously stated, flea beetle feeding can affect stand development and cause early crop loss, but how this feeding affects yield of surviving cabbage is not well known. Briske and Richards (1995) detail the possible effects of insect feeding injury on plants including early crop loss, a negative yield effect, no yield effect, or a compensatory effect where feeding injury increases plant yield. Gavloski and Lamb (2000) simulated *P. cruciferae* feeding in white mustard *Sinapis alba* L., which produced an immediate increase in relative growth, and in rapeseed *Brassica napus* L., which harmed plant development. By analyzing the relationship between flea beetles and defoliation, as well as defoliation and yield, we are better able to understand how flea beetle feeding affects cabbage yields. In 2015, we found a significant negative relationship between defoliation and yield on a per plot basis, and in both 2015 and 2016 plants with any amount of flea beetle defoliation produced significantly smaller cabbage heads than undamaged plants showing flea beetle feeding injury causes a negative yield effect. In 2016 there was no significant relationship between defoliation
and yield, which could be caused by several factors including lack of flea beetle pressure in the first 2 weeks or environmental factors that affect yield variability. Due to the ability of flea beetles to cause crop loss and a negative effect on yield during crucial cabbage development periods, a preventative insecticidal control could dramatically improve the yield of cabbage attacked by flea beetles.

To evaluate efficacy and yield benefits of recommended insecticidal control methods we assessed their performance in regards to flea beetle density, defoliation, and plant yield. The selected insecticides were chosen based on the Mid-Atlantic Vegetable Production Guide using insecticides recommended for flea beetle control on cabbage (Arancibia et al. 2017). Bifenthrin was used as a comparison for other insecticides having shown effectiveness at controlling flea beetles on cabbage in previous studies (Shelton and Wilsey 1996, Walgenbach and Schoof 2011). Systemic neonicotinoids have also shown success with controlling flea beetles in brassica crops, where thiamethoxam and clothianidin as seed treatments for canola caused mortality of \textit{P. cruciferae} and \textit{P. striolata} and reduced their feeding injury when compared to a control (Tansey et al. 2008). In our field insecticide efficacy evaluations, soil-applied dinotefuran and foliar-applied bifenthrin were the most effective insecticides for controlling flea beetles. Dinotefuran is a soil applied systemic insecticide and would be recommended as a preventative treatment; whereas, bifenthrin is a curative, quick knock-down inexpensive insecticide that would be recommended as a rescue treatment to combat insect infestations that are attacking plants after planting.

This study was conducted in Whitethorne, VA in the Appalachian Mountains, and flea beetle populations may vary in other parts of Virginia, particularly in regions with
different climates and sandier soil types. Regardless of location, the highly significant negative relationship between flea beetle defoliation and cabbage yield illustrates the potential impact of this pest group if not controlled. Understanding the efficacy of the insecticides would benefit from more testing, as there was little treatment significance for these insecticides in 2016. It is also possible that there are other insecticides that are equally as efficacious as dinotefuran and bifenthrin, and could be tested to evaluate the ideal treatment for controlling flea beetles in cabbage. There are many other cruciferous crops similar to cabbage that are attacked by flea beetles (Eastman et al. 2005), and our results regarding the impact of feeding injury and the efficacy of insecticides would likely be similar for those crops.

References


**SAS Institute Inc. 2007.** JMP user’s guide. SAS Institute Cary, NC.


Chapter Four

Deltamethrin-incorporated Screen Row Covers for Flea Beetle Control in Vegetables

Several species of *Eptrix* and *Phyllotreta* flea beetles (Coleoptera: Chrysomelidae) can be serious pests of Cruciferous and Solanaceous vegetables (Capinera 2001). Densities of adults on seedling plants can be quite high in some regions of the U.S., and the combined effects of numerous small chewing holes in leaves can seriously impact yield or even kill plants if control measures are not employed (Chalfant et al. 1979, Mason and Kuhar 2016a,b). A number of insecticides, particularly neonicotinoids, pyrethroids, and spinosyns, are efficacious on flea beetles (Mcleod et al. 2002, Walgenbach and Schoof 2011, 2016, Mason and Kuhar 2016a,b). However, because flea beetle adults are highly mobile and can continuously re-invade crops, and because plants are often small, but rapidly growing during the period of vulnerability, control using foliar insecticide applications can sometimes be a challenge.

As an alternative, floating row covers have been shown to serve as physical barriers to exclude flea beetles on plants (Hough-Goldstein 1987). Problems can occur with this control tactic when row covers are installed over the crop with flea beetles on the plants already, flea beetles emerging from overwintering sites below the cover, or if openings occur in the row cover allowing flea beetles under the row cover. Under these conditions, flea beetles can feed without interruption from natural enemies or adverse environmental factors (Parker and Snyder 2017).

Long-lasting insecticidal nets (LLINs) were developed using netting material (usually polyethylene, or polyester) with insecticide incorporated within or bound around
the fibers (Martin et al. 2007). With LLINs, insecticide from within the fibers continues to move to the surface over time, replacing the residue that may have been removed by washing; this enables long (multi-year) residual efficacy of the nets (Martin et al. 2007). Although primarily used for control of human disease vectors such as biting diptera (Hill and Rowland 2006, Martin et al. 2007), their uses for management of agricultural pests have recently begun. For instance, pyrethroid-incorporated nets applied as floating row covers, or 2-m high fences, have been shown to control various lepidopteran and aphid pests of vegetables in Europe (Martin et al. 2006, Licciardi et al. 2008, Dáder et al. 2015), and are considered to be cost-effective because they control multiple key pests, last multiple years, and the larger mesh sizes in comparison to untreated polyester spun-bonded row covers can reduce disease and other plant growth inhibiting factors from covering plants (Dáder et al. 2015). To our knowledge, the efficacy of LLINs for control of flea beetles has not been investigated. Herein, we report on the efficacy of a deltamethrin-incorporated LLIN, D-Terrence® screen (Vestergaard –Frandsen, Washington DC) used as a hoop row cover for control of flea beetles on eggplant and cabbage.

**Materials and Methods**

**Deltamethrin-incorporated netting.** The insecticide netting deployed in this study was the same used by Kuhar et al. (2017) and was provided by Vestergaard-Fransden (Lausanne, Switzerland). The black or yellow polyethylene netting is known by different commercial names such as Zero-fly™ and D-Terrence™, and comes packaged in rolls 1.8 m wide with a mesh size of 32-33 holes per cm², and contains ~3.85 mg deltamethrin/g mesh fiber (Kuhar et al. 2017).
A quick bioassay to determine the activity of the treated netting on flea beetles was conducted in spring 2016 by collecting *Epitrix* spp. flea beetles from eggplant and *Phyllotreta* spp. flea beetles from cabbage plants at Kentland Farm in Whitethorne, VA. The beetles were placed in 9-cm diam. Petri dishes with one of three treatments: untreated screen, D-Terrence® black screen, and D-Terrence® yellow screen, each cut into form fitting 9-cm diam. discs, each replicated four times for each flea beetle genus. All D-Terrence netting treatments resulted in 100% mortality of the beetles within 10 sec of exposure; whereas, no mortality occurred in the untreated screen. The bioassay was repeated in 2017 with one-year and two-year old field-used netting and the same results were obtained, 100% mortality of beetles after 10 sec of exposure.

**Field Study.** To evaluate the efficacy of deltamethrin screen, field experiments were conducted on both eggplant and cabbage in 2016 and 2017. Field experiments were conducted at Virginia Tech’s Kentland Farm in Whitethorne, VA (37.2013° N, −80.5656° W), where soil type is a Shottower Loam, and where the land had been used to grow various vegetables for decades. On May 26, 2016 and June 6, 2017, both six week old ‘Bravo’ cabbage and eight week old ‘Classic’ eggplant transplants were planted. Fields were prepared for planting by broadcasting 10-10-10 fertilizer at a rate of 112-kg per ha, and cabbage fields also included an application of pre-emergence herbicide, S-metolachlor (Dual Magnum, Syngenta, Greensboro, NC), at 0.59-liter a.i./ha. Drip irrigation was applied as needed.

Plots consisted of single 3.048m long rows spaced 0.91m apart, with cabbage planted ~38 cm apart and eggplant planted 0.46m apart within rows. A five treatment test with six replicates per treatment per crop was applied to five transplants per crop,
set up in a completely randomized design. Treatments included: 1) an untreated control consisting of five transplants by themselves, 2) a 300 g Al/ha soil applied neonicotinoid dinotefuran, (Venom® 70SG, Valent USA LLC, Walnut Creek, CA), 3) an open ended screen row cover made from ordinary black window screen, 4) a screen row cover made from black deltamethrin incorporated screen, and 5) a screen row cover made from yellow deltamethrin incorporated screen. Each screen row cover was fashioned using three 0.64cm x 1.22m dowel rods bent into a hoop, a 1.0m x 2.44m section of black or yellow D-Terrence®, deltamethrin incorporated netting, from Vestergaard-Frandsen (V-F), or untreated window screen, and zip ties used to attach the screen to the rods. The screen row covers then went over five transplants in each appropriate plot, and the dowel rods were pushed into the soil to secure the screens, row covers were placed over rows the week of transplanting. The two colors of treated screen, black and yellow, were used to see if screen efficacy was affected by color. It was also used to assess any possible not target insect effects, particularly natural enemies. The dinotefuran was mixed with 236.6 mL transplant water, used to water the insecticide treated plots at time of planting, other treatments received 236.6 mL water as normal.

Throughout the experiment plants were monitored to ensure other insect pests did not damage the plants. *Bacillus thuringiensis*, (Dipel® DF, Valent USA LLC, Walnut Creek, CA) at 1.12 kg/ha, was applied to cabbage plots to protect the plants from early-season lepidopteran pests, there were not many other pests of cabbage and eggplant present, any that were encountered such as an occasional Colorado potato beetle, *Leptinotarsa decemlineata* Say, were physically removed. The *Bacillus thuringiensis*
treatment was applied the week of planting before row covers were placed over the transplants.

Once a week over a five week period each treatment was evaluated by counting the number of live flea beetles on three randomly selected plants per plot. In screen row cover treatments plants were only selected if they were wholly under the row cover adjusting them to access the plants for counting before readjusting the cover. Dead natural enemies were also counted if they were found on any of the plants, on the row cover, or on the ground at the base of the row covers. At the same time, plants in each treatment were also evaluated by assessing the defoliation of five randomly selected leaves per plot, using leaves also wholly under the screen. Each leaf was placed in one of five defoliation categories: 0%, 1-20%, 21-40%, 41-60%, and >60%, adapted from Soroka et al. (2011). Lastly, yield was taken at harvest to determine if there was a treatment effect on yield. After the five week assessment period, all screen row cover treatments were removed to keep from stifling plant growth, and a long lasting broad spectrum insecticide Besiege®, (Syngenta® Greensboro, NC) containing lambda-cyhalothrin (36.4 g Al per ha) and chlorantraniliprole (72.8 g Al per ha) was applied to all plants to ensure further insect injury did not affect yield. At the time of harvest, plants were selected only if wholly under the screen when harvesting from a relevant treatment, and yield was assessed by weighing three cabbage heads, or by counting the total number of marketable eggplant produced by three plants per plot. Eggplant was harvested on 4, 15, and 29 August, 2016 and 22 August, and 7 September, 2017, as needed selecting the same three plants each time. Cabbage in 2017 was unable to be harvested. To determine the efficacy of each treatment, number of live beetles per
sample date, mean percent defoliation, and yield were analyzed for treatment significance at the (P<0.05) using the software JMP Pro 11 (SAS Institute Inc. 2007). Treatment effects were determined using ANOVA, when p < 0.05, and means were separated using Student’s t test.

Results

**Flea beetle bioassay.** The bioassay showed without a doubt that deltamethrin incorporated LLIN has strong insecticidal activity for flea beetles. In each treatment, regardless of screen age or weather exposure, there was 100% flea beetle mortality in every treatment except the control which had 0% beetle mortality.

**Field Study.** Flea beetles on cabbage consisted of *Phyllotreta striolata* Fabr., and *Phyllotreta cruciferae* (Goeze), beetles found on eggplant consisted of *Epitrix fuscula* (Crotch), and *Epitrix hirtipennis* (Melsheimer). In both 2016 and 2017, the deltamethrin-incorporated LLINs (either black or yellow) provided the most effective flea beetle control, having the fewest numbers of beetles (virtually none) compared with the untreated control plants and, in some instances, the untreated netting and dinotefuran treatments as well (Tables 1-2). In 2016 by the last sample date, both treated screens still had virtually no flea beetles and had significantly fewer flea beetles than any other treatment in cabbage (F= 14.33; df= 4; P < 0.0001) (Table 1) and eggplant (F= 9.88; df= 4; P < 0.0001) (Table 2). In 2017, the treated screens had a similar performance with little to no live flea beetles present, and by the last sample date they had significantly fewer flea beetles than the control in cabbage (F= 11.93; df= 4; P < 0.0001) (Table 1), and had significantly fewer than the control and insecticide treatment in eggplant (F= 9.56; df=4; P < 0.0001) (Table 2).
In regards to defoliation (Fig. 1), both treated screens in cabbage had significantly less defoliation than any other treatment in 2016 ($F= 28.97; df= 4; P < 0.0001$), and had significantly less defoliation than any other treatment except the insecticide treatment in 2017 ($F= 30.5; df=4; P < 0.0001$). For eggplant plots in both years (Fig. 2), there was significantly more defoliation in the control and untreated screen plots than in any of the others (in 2016, $F= 64.24; df= 4; P < 0.0001$) (in 2017, $F= 11.63, df= 4; P < 0.0001$).

In 2016, yield of cabbage (Fig. 3) and eggplant (Fig. 4) was highest in the yellow LLIN row cover and dinotefuran drench treatments, however in eggplant only the dinotefuran treatment yield was significantly higher than the control and untreated screen ($F=3.88; df= 4; P < 0.0138$), whereas in cabbage yield in the dinotefuran and yellow LLIN treatments were only significantly higher than the untreated screen ($F= 3.92; df= 4; P < 0.0132$). In 2017 eggplant, the untreated control had significantly more eggplant produced than every other treatment ($F= 5.40; df= 4; P < 0.0028$).

Dead natural enemy numbers were generally low in cabbage and eggplant in both 2016 and 2017. In cabbage during 2016, there were 9 natural enemies found, and all on yellow LLIN plots (3 Coccinellidae, 4 Syrphidae, and 2 Araneae), in eggplant there were 23 natural enemies found on yellow LLIN plots (7 Coccinellidae, 6 Syrphidae, 9 Cantharidae, and a spider), and 4 natural enemies found on black LLIN plots (1 Coccinellidae, 2 Syrphidae, and 1 Araneae). In 2017, cabbage had 28 dead natural enemies found on yellow LLIN plots (14 Coccinellidae, 5 Syrphidae, 4 Cantharidae, and 5 Araneae), and 4 natural enemies found on black LLIN plots (2 Coccinellidae and 2 Araneae). Eggplant during 2017 had 30 dead natural enemies found on yellow LLIN
plots (11 Coccinellidae, 6 Syrphidae, 10 Cantharidae, and 3 Araneae), and on black LLIN plots there were 16 dead natural enemies found (11 Coccinellidae and 4 Syrphidae). No dead natural enemies were found on untreated screen plots.
Table 1. Mean flea beetle densities per three plants per plot for various treatments (Insecticide = dinotefuran drench, UT = untreated screen, YT = yellow D-Terrence netting, BT = black D-Terrence netting) in cabbage plots in Whitethorne, VA in 2016 and 2017. All data were analyzed using analysis of variance procedures.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.00</td>
<td>12.2a</td>
</tr>
<tr>
<td>Insecticide</td>
<td>0.00</td>
<td>1.0b</td>
</tr>
<tr>
<td>UT Screen</td>
<td>0.00</td>
<td>5.7b</td>
</tr>
<tr>
<td>YT Screen</td>
<td>0.00</td>
<td>0.3b</td>
</tr>
<tr>
<td>BT Screen</td>
<td>0.00</td>
<td>0.0b</td>
</tr>
</tbody>
</table>

Means followed by the same letter within a column are not significantly different according to Student’s T-test (P>0.05). Data without letters did not show a significant treatment effect.

Table 2. Mean flea beetle densities for various treatments (Insecticide = dinotefuran drench, UT = untreated screen, YT = yellow D-Terrence netting, BT = black D-Terrence netting) in eggplant plots in Whitethorne, VA in 2016 and 2017. All data were analyzed using analysis of variance procedures.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>12.0a</td>
<td>5.8a</td>
</tr>
<tr>
<td>Insecticide</td>
<td>0.0b</td>
<td>0.5b</td>
</tr>
<tr>
<td>UT Screen</td>
<td>14.0a</td>
<td>9.5a</td>
</tr>
<tr>
<td>YT Screen</td>
<td>0.0b</td>
<td>0.0b</td>
</tr>
<tr>
<td>BT Screen</td>
<td>0.3b</td>
<td>0.2b</td>
</tr>
</tbody>
</table>

Means followed by the same letter within a column are not significantly different according to Student’s T-test (P>0.05). Data without letters did not show a significant treatment effect.
**Figure 1.** Mean defoliation rating for various treatments (Insecticide = dinotefuran drench, UT = untreated screen, YT = yellow D-Terrence netting, BT = black D-Terrence netting) in cabbage plots in Whitethorne, VA in 2016 and 2017. All data were analyzed using analysis of variance procedures. Means followed by the same letter within a column are not significantly different according to Student’s T-test (P>0.05). Data without letters did not show a significant treatment effect.

**Figure 2.** Mean defoliation rating for various treatments (Insecticide = dinotefuran drench, UT = untreated screen, YT = yellow D-Terrence netting, BT = black D-Terrence netting) in eggplant plots in Whitethorne, VA in 2016 (A) and 2017 (B). All data were analyzed using analysis of variance procedures. Means followed by the same letter within a column are not significantly different according to Student’s T-test (P>0.05). Data without letters did not show a significant treatment effect.
Figure 3. Mean weight of cabbage heads per 3 plants per plot, produced for various treatments (Insecticide = dinotefuran drench, UT = untreated screen, YT = yellow D-Terrence netting, BT = black D-Terrence netting) in cabbage plots in Whitethorne, VA in 2016. Means followed by the same letter within a column are not significantly different according to Student’s t-test (P>0.05). Data without letters did not show a significant treatment effect.

Figure 4. Mean number of eggplant per 3 plants per plot, produced for various treatments (Insecticide = dinotefuran drench, UT = untreated screen, YT = yellow D-Terrence netting, BT = black D-Terrence netting) in cabbage plots in Whitethorne, VA in 2016 (A) and 2017 (B). Means followed by the same letter within a column are not significantly different according to Student’s t-test (P>0.05). Data without letters did not show a significant treatment effect.

Discussion

Insecticide-incorporated row covers may offer a new and highly-eficacious tool for controlling flea beetles on vegetable crops. It is not surprising that deltamethrin-
incorporated netting shows a high level of insecticidal activity on flea beetles, as pyrethroid insecticides have been highly effective for control of flea beetles in both cabbage and eggplant (Shelton and Wilsey 1996, Mcleod and Diaz 1999, Walgenbach and Schoof 2011, 2016, Mason and Kuhar 2016 a,b), and because the treated netting has been quite effective on much larger insects such as stink bugs (Kuhar et al. 2017).

Using deltamethrin treated LLIN as a screen row cover has potential as a pest management tool in agriculture. Although insecticide applications or standard polyester row covers each can effectively control flea beetles, the deltamethrin LLIN performed as well as the other two control methods, and in some ways outperformed these more traditional flea beetle control methods. In our study, throughout 2016 and 2017, in both crops, the two LLIN treatments had fewer flea beetles than the untreated screen row cover and provided optimal control longer than the dinotefuran treatment. The LLIN treatments showed little to no defoliation, similar to the dinotefuran treatment and far less than the untreated screen row cover. Using these metrics, deltamethrin treated screen row covers combine the long lasting control and reusability of an untreated row cover, with the efficacy of a soil drench neonicotinoid insecticide for flea beetle control, without insecticides coming directly in contact with the plants.

When yield is used as a metric the benefits of using a deltamethrin LLIN in cabbage and eggplant become less clear. In 2016, yellow deltamethrin LLIN both in cabbage and eggplant had produced similar yield numbers to the dinotefuran and higher yield than the control and untreated screen, black deltamethrin LLIN performed similar to the yellow LLIN though it did not have as high yield. Eggplant yield in 2017 showed the untreated control unexpectedly had the highest yield. Many factors play into
yield for eggplant, from air temperature to moisture in the soil (Abney and Russo 1997). Flea beetle densities and defoliation were also light for eggplant in 2017 and the controls may have been able to withstand the small amount of feeding they received throughout the season. Hough-Goldstein (1987) showed the potential yield benefits of using row covers over cabbage, however the screens we used could have inhibited plant growth in some way and impacted yield of the plants. Any number of factors could have played a role in the yield data, but flea beetle defoliation was not a cause of the variable yield in the deltamethrin LLIN row covers. More research is needed to determine if there is a yield benefit to using these row covers for control of flea beetles in cabbage and eggplant.

There appeared to be some differences between the yellow and black treated screen row covers. Although yield was never significantly different between the two treatments, yield in the black LLIN row covers was lower in 2016 for both cabbage and eggplant. This could be due to light transparency or some other factor related to screen row cover color. Natural enemy data was the other major difference between the two colors of treated screen, where yellow screen had more dead natural enemies than the black. This is consistent with color preference in lady beetles (Blackmer and Byers 2009), however, there were not enough natural enemies found on the screen treatment plots in either year to determine the impact these screen row covers could have on natural enemy numbers. It is also possible that there were so few natural enemies found on or around the treated screen plots, because the plots had little impact on the natural enemy populations in cabbage or eggplant. Regardless, more research is needed to
determine the effects deltamethrin treated screen row covers have on natural enemy complexes.

LLIN’s use in agriculture is an understudied topic that could have potential to replace or enhance many traditional insect control tactics. LLIN’s used as floating row covers offer a powerful reusable tool for growers to reduce flea beetle densities and defoliation. For insects able to evade the barrier provided by a traditional row cover, LLIN may be one of the only ways to mitigate insect damage to crops without using conventional insecticides.

References


Kuhar, T. P., B. D. Short, G. Krawczyk, and T. C. Leskey. 2017. Deltamethrin-incorporated nets as an integrated pest management tool for the invasive


SAS Institute Inc. 2007. JMP user’s guide. SAS Institute Cary, NC.


