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DEVELOPING ALTERNATIVE PRACTICES FOR MANAGEMENT OF FLEA BEETLES ATTACKING EGGPLANT AND LEAFY BRASSICACEOUS GREENS

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DEVELOPING ALTERNATIVE PRACTICES FOR MANAGEMENT OF FLEA BEETLES ATTACKING EGGPLANT AND LEAFY BRASSICACEOUS GREENS

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Agriculture, Food and Environment at the University of Kentucky

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2020

ABSTRACT OF THESIS

DEVELOPING ALTERNATIVE PRACTICES FOR MANAGEMENT OF FLEA BEETLES ATTACKING EGGPLANT AND LEAFY BRASSICACEOUS GREENS

Flea beetles are a challenging pest for many producers of vegetable crops in Kentucky. Chewing numerous small holes in the leaves of their host plants, high flea beetle populations can quickly overwhelm unestablished crops. I tested the efficacy of several alternatives to insecticides within brassicaceous leafy greens and eggplant. Four field trials in 2019 and 2020 compared essential oil sprays, the woven-mesh row cover ProtekNet, the spunbonded row cover Agribon, and reflective silver mulch to an untreated control, a conventional insecticide rotation of dinotefuran and pyrethroids, and an organic insecticide rotation of spinosad and pyrethrins. The silver reflective mulch was used within the eggplant trials and was compared against black plastic mulch. This thesis demonstrates the efficacy of row covers in limiting damage by flea beetles and improving marketable yield in brassicaceous greens and eggplant. On the contrary, other new alternatives, including silver plastic mulches and the essential oils from thyme, rosemary, eucalyptus, neem, peppermint, and geranium showed no better control than the untreated control, and in some cases, reduced yield by harming plants. For this reason, further research and outreach should focus on the life expectancy of row covers and expanding their adoption.

KEYWORDS: Insecticide Alternatives, Row Covers, Essential Oils, Reflective Silver Mulch, Flea Beetles

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November 23rd, 2020

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Alternative pest management strategies for control of flea beetles in vegetable crops

Introduction

The sustainability of our agricultural systems has become a topic of great concern in recent years. Interest in the health of agricultural systems has intensified due to concerns such as a growing world population, climate change, the decline of pollinators, and loss of ecological diversity. Both growers and the public alike have become interested in insect pest management that is sustainable from both ecological and economic standpoints. Integrated pest management (hereafter IPM) is a system of pest control that focuses on the sustainability of the system and preventing insect pests from developing resistance to any one pest management strategy (Abrol, 2009a, b; Aluja et al., 2009; Saenz-de-Cabezon et al., 2010). To prevent resistance, IPM relies on multiple forms of pest management that are combined to reduce selection pressure against any one tactic used alone. This approach prevents pests from adapting to insecticides or any other form of insect management which can lead to outbreaks (Abrol, 2009a, b; Aluja et al., 2009; Saenz-de-Cabezon et al., 2010). IPM was created as a response to the over reliance on the spraying of insecticides (Abrol, 2009a, b; Aluja et al., 2009; Saenz-de-Cabezon et al., 2010). Insecticide sprays, however, are still allowed within IPM and are often reserved for controlling pest populations that exceed a predetermined threshold level. Research into additional pest management strategies is needed to control insect pests that are not adequately controlled by insecticides. These additional strategies must, in addition to controlling pest populations and improving yield, be cost effective for growers to implement.

A few alternatives to insecticides which have received much interest in recent years include essential oils, reflective plastic mulches, and row covers. Researchers are evaluating the use of essential oils derived from plants, oftentimes culinary herbs, for use against pest insects. As plant essential oils are often made from plants already present in our diets (Figure 1, (A)), they are often viewed by the public as safe for direct contact with food crops (Tripathi et al. 2009) and are believed to have minimal negative effects on beneficial insects (Atanasova and Leather 2018; Tripathi et al. 2009). Essential oils are usually obtained through steam distillation (Koul et al. 2008) and have a wide range of activities against pest insects. Essential oils have antifeedant, insecticidal, repellant, oviposition deterrent, growth regulatory, and antivectorial properties (Koul et al. 2008). Laboratory experiments have revealed that essential oils such as peppermint (*Mentha x piperita*), thyme (*Thymus vulgaris*), rosemary (*Salvia rosmarinus*), cloves (*Syzygium aromaticum*), Norwegian angelica (*Angelica archangelica*), and basil (*Ocimum basilicum*) could be used as repellents for pests such as spotted wing drosophila (*Drosophila suzukii*) (Renkema et al. 2016), aphids (*Aphis spp.*) (Pavela et al. 2013; Atanasova and Leather 2018; Atanasova et al. 2017; Atanasova and Nenov 2017), and the Colorado potato beetle (*Leptinotarsa decemlineata*) (Saroukolai et al. 2014; Ayse et al. 2016).

Reflective mulches such as silver plastic (Figure 1 (B)), reflect wavelengths of light thought to disrupt pests, and are another promising potential alternative to insecticides. Plastic mulches are common for the cultivation of crops such as eggplant (*Solanum melongena*), tomatoes (*Solanum lycopersicum*), peppers (*Capsicum annum*), squash (*Cucurbita* spp.), melon (*Cucumis* spp.), and strawberries (*Fragaria x ananassa*). Black is the most common color of plastic mulch, and in addition to preventing weeds from competing with the crop, black plastic increases the soil temperature which can help with crop growth in cooler periods. However, different colors of plastic mulch have been shown to be beneficial as well. The use of colored mulches has been shown to increase production of crops such as potatoes (Lamont et al. 2003; Ruiz-Machuca 2015), peppers (Ogutu 2006) and strawberries (Johnson and Fennimore 2005). These yield increases are believed to come from differences in temperature, light reflected onto leaves, and pest control. Reflective silver plastic mulch reflects light back at pests and can disrupt or prevent them from landing in the crop field (Kring 1972, Summers et al. 2004). Reflective plastic mulches such as silver metalized plastic mulch and white plastic mulch, when compared against black plastic and bare ground, are effective at reducing populations of Mexican Bean Beetle (*Epilachna varivestis*) in green beans (*Phaseolus vulgaris*) and improving yield (Nottingham and Kuhar 2016). Additionally, within a bell pepper cropping system, reflective silver mulch was shown to lowered early season thrips (*Frankliniella occidentalis*) populations when compared to black plastic mulch (Reitz et al. 2003). Silver plastic mulch was shown to reduce aphid and silverleaf whitefly (*Bemisia argentifolii*) populations in zucchini (*Cucurbita pepo*) when compared to white plastic mulch (Frank and Liburd, 2005). One of the potential advantages of using reflective plastic mulch is that producers can easily switch the color of plastic mulch laid down by their machinery. The use of plastic mulch is already common for many fruit and vegetable crops. However, still few studies have investigated the efficacy of reflective mulch for different crops.

Another alternative to insecticides is that of row covers. Row covers are thin fabrics that cover the crop (Figure 1 (C)). Row covers were first used for altering the temperature around the crop during cold periods which allows farmers to extend the growing season (Aziz et al. 2001; Moreno et al. 2002). However, these covers can also form a physical barrier and limit insect's access to the crop. Many of the row covers used for season extension are made of a spun-bonded or perforated polyethylene material. Row covers have been developed more recently to specifically control insects while having minimal increases in temperature. ProtekNet is a knitted row cover that limits most pest species while having a maximum increase in temperature of 0.5 °C (Chouinard et al. 2016). Insect exclusion row covers have successfully limited pests in broccoli (Adams et al. 1990), grape (*Vitis vinifera*) (Strang et al. 1992), apple (*Malus domestica*) (Chouinard et al. 2016), squash (*Cucurbita spp.*) (Skidmore et al. 2019; Adams et al. 1990), muskmelon (*Cucumis melo*) (Skidmore et al. 2019), blackberry (*Rubus fruticosus*) (Kuesel et al. 2019), blueberry (*Vaccinium spp.*) (Cormier et al. 2015; Link et al. 2014), and raspberry (*Rubus spp.*) (Leach et al. 2016; Rogers et al. 2016). These insecticide alternatives are necessary for the sustainable management of pest insects, particularly those poorly controlled by insecticides in fruit and vegetable crops.

Need for alternative flea beetle control practices

An insect pest that has become increasingly difficult to manage through insecticides alone are flea beetles (Order: Coleoptera). Much of the research into flea beetle management has been conducted in agronomic crops such as the brassicaceous crop canola (*Brassica napus*). Canola growers have long relied on neonicotinoid treated seeds with 95% of U.S. canola and 90% of Canadian canola relying on this single class of insecticides (Soroka et al., 2008). Because of the widespread use of this single class of insecticide, insecticide resistance has been observed since 2008 (Tansey et al., 2008). Organic brassica producers have long relied on spinosad as the most effective OMRI approved spray. Spinosad was shown to be more effective at controlling crucifer flea beetle (*Phyllotreta cruciferae*) populations in komatsuna (*Brassica rapa var. perveridis*) and canola than neem essential oil, pyrethrin, kaolin clay and *Beauveria bassiana* (Andersen et al., 2006; Antwi et al., 2007a, b). However, Spinosad's efficacy dropped 65.5% one day after application (McLeod et al. 2002) suggesting that frequent applications are needed. A study involving five OMRI approved insecticides for control of the eggplant flea beetle (*Epitrix fuscula*) found that no insecticide lowered flea beetle populations below that of the control, and only cyantraniliprole lowered damage, doing so in two of the six time periods (Frank and Shamblin 2020). Other researchers, looking at the eggplant flea beetle and tobacco flea beetle (*Epitrix fasciata*) found that the conventional insecticide dinotefuran, a neonicotinoid, was effective at controlling flea beetles and improving yield (Mason and Kuhar 2016). However, as populations of brassicaceous flea beetles have already developed resistance to neonicotinoids, growers need additional management strategies to stretch out the amount of time farmers can use dinotefuran and other insecticides. Additionally, as some producers are growing vegetables organically to attain market premiums, alternative pest management strategies must be developed to work within organic certification requirements.

Flea beetle biology

Flea beetles are small leaf eating members of the Chrysomelidae family of beetles. They are diverse, feeding on many different plant families, and cause damage in several ways. The most common damage caused by flea beetles are the many small holes eaten throughout the leaves of their host plant. These small holes are termed "shot holes". Flea beetles are most damaging to crops shortly after transplanting or seedling emergence. High flea beetle populations lower the photosynthetic capabilities of unestablished plants and can stunt or kill these plants (Turnock and Lamb, 1982; Lamb, 1984; Chalfant et al. 1979). Additionally, in crops such as mustard greens, radish greens, and arugula where the leaf is sold to consumers, shot hole damage can lead to loss of marketability. Lastly, in some cases, flea beetles can act as vectors of diseases such as Stewart's wilt (*Pantoea stewartii*) in corn (*Zea mays*) (Correa et al. 2012).

Flea beetles are often oligophagous, eating only a group of closely related plants. Flea beetles within the genus *Phyllotreta* feed primarily on members of the Brassicaceae family (Knodel, 2017). The Brassicaceae family includes agronomic and horticultural crops such as canola (*Brassica napus*), radish (*Raphanus sativus*), mustards (*Brassica spp.*), arugula (*Eruca vesicaria* ssp. *sativa*), broccoli (*Brassica oleracea* var. *italica*), kale (*Brassica oleracea* var. *sabellica*), cauliflower (*Brassica oleracea* var. *botrytis*), and collards (*Brassica oleracea* var. *viridis*). Members of the Brassicaceae family often present in the field as weeds include wild mustard (*Sinapis arvensis*), wild radish (*Raphanus raphanistrum*), and wild turnip (*Brassica rapa*). Flea beetles within the genus *Epitrix* feed primarily on members of nightshade (Solanaceae) family (Germain et al. 2013). The Solanaceae family includes agronomic and horticultural crops such as potatoes (*Solanum tuberosum*), tomatoes (*Solanum lycopersicum*), eggplant (*Solanum melongena*), and tobacco (*Nicotiana* spp.). Members of the Solanaceae family often present in the field as weeds include horse nettle (*Solanum carolinense*) and eastern black nightshade (*Solanum nigrum*). This tendency towards oligophagy, numerous wild and weedy hosts, and flight, makes flea beetles difficult to control as local populations can quickly be replaced by populations in unmanaged areas.

Flea beetles have saltatorial hind legs which allows them to jump short distances and evade predators. Flea beetles are more likely to use flight over longer distances to seek out new host plants (Oku et al. 2010). Adult flea beetles lay eggs in the soil near the roots of their host plants. Larvae will feed on roots as they develop through three larval stages before pupating in the soil. The larval damage to host plants roots is not considered economically damaging (Cranshaw 2006), except in the case of *Epitrix* flea beetles feeding on potato tubers. The length of the life cycle varies greatly by species and location. Flea beetles overwinter as adults (Sorensen and Baker, 1994). Many crops within the Brassicaceae family are cold tolerant and are grown through the winter. Members of the *Phyllotreta* genus of flea beetles can take advantage of brassica plants during sunny days of the winter. Hard winter snaps can also kill portions of the overwintering adult population.

Organization of thesis

This thesis consists of a General Introduction (Chapter 1), two primary research chapters, and a Summary and Implications (Chapter 4). The main objective of this thesis was to develop alternative pest control strategies for flea beetle control. At the time of writing, the first research chapter has been published. All research focuses on evaluating alternatives to insecticides for the management of flea beetle populations in vegetable crops.

Chapter 2 (published; *Insects* 11(10): 714; 2020) compares two types of row covers and three essential oil sprays against an untreated control, conventional insecticide rotation, and organic insecticide rotation for the control of flea beetles within brassicaceous greens crops. Chapter 3 compares reflective silver mulch, two types of row covers, and four essential oils sprays, against black plastic mulch, an untreated control, conventional insecticide rotation, and organic insecticide rotation for the control of flea beetles within eggplant fields. Chapter 4 will focus on the how effective the insecticide rotation and alternative control practices were in all field trials and will show where further research is necessary.

Throughout the thesis, I occasionally use plural words such as “we” when describing methods, observations, and results. I was often assisted by lab members when planting trials and collecting data, as well as by my Major Professor when planning field trials and analyzing data. Nonetheless, I was the primary investigator of all research described within.

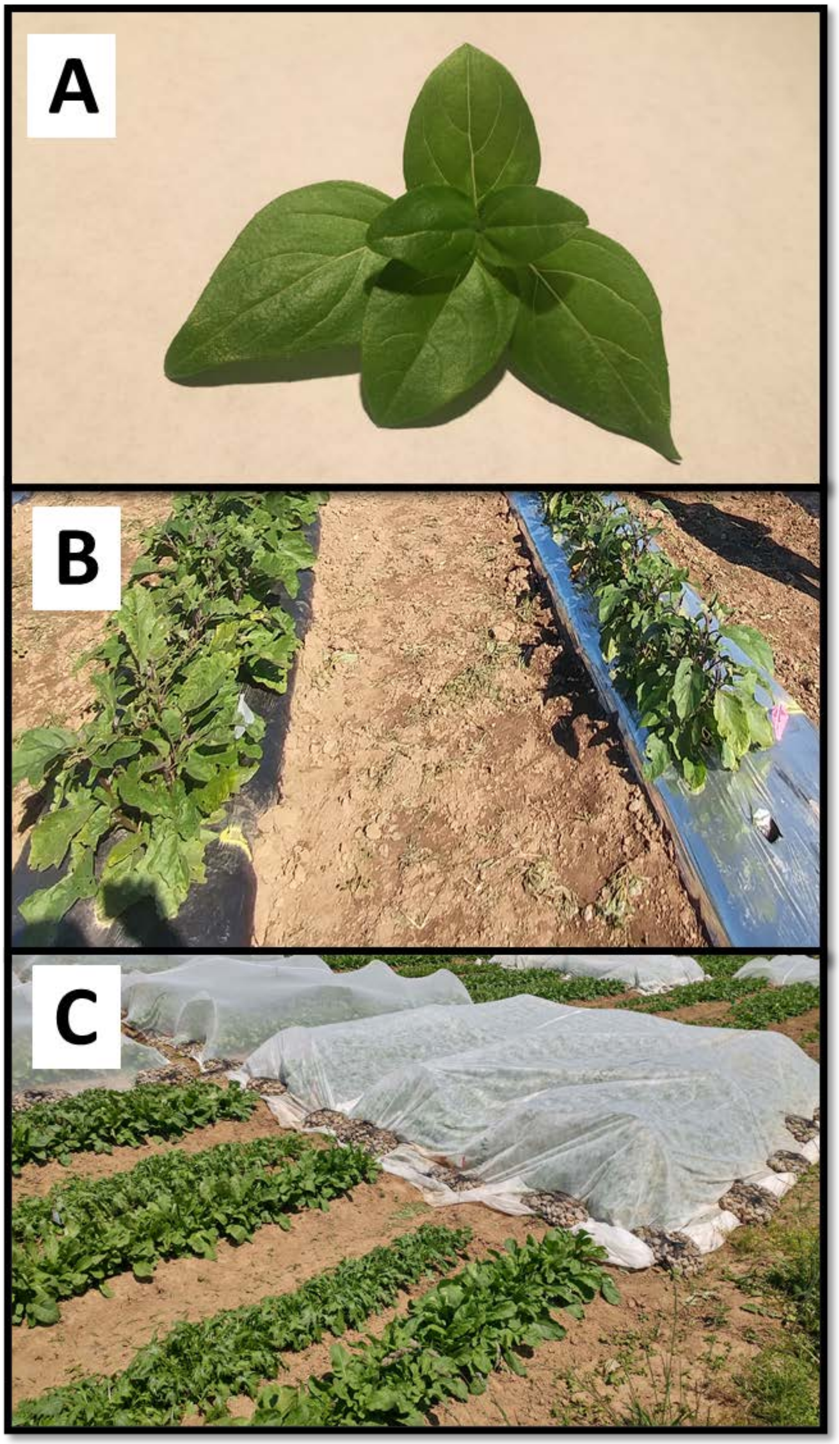

Figure 1. Examples of essential oils, reflective plastic mulch, and row covers. From top to bottom, the aromatic herb basil (A) which is sometimes used as an essential oil, reflective silver plastic mulch and black plastic mulch (B), and the row covers Agribon and ProtekNet (C).

Chapter 2

The Impact of Plant Essential Oils and Fine Mesh Row Covers on Flea Beetle (Chrysomelidae) Management in Brassicaceous Greens Production

Abstract: Brassicaceous leafy greens are an important crop for small growers but are difficult to produce due to damage by flea beetles. Flea beetles are problematic for growers as they chew many small holes through leaves rendering produce unmarketable. I tested the efficacy of several essential oils, the woven-mesh row cover ProtekNet, and the spunbonded row cover Agribon, compared to organic and conventional insecticides and no spray controls in the spring and fall of 2019. I found that the two row cover treatments (Agribon and ProtekNet) provided the best control of flea beetles and associated damage. Thyme oil was highly phytotoxic and killed the crop entirely and rosemary and neem essential oils caused mild phytotoxic burns. Organic insecticides rarely performed better than the no spray control. While conventional insecticides controlled most flea beetles, the crop was often still too highly damaged to sell. The results of my study suggest row covers offer producers an effective method of flea beetle control that reduces their dependence on insecticides for conventional and organic production.

Introduction

Brassicaceous leafy greens (*Brassicaceae*) are an economically important and micro-nutrient rich crop grown in many parts of the world. Brassicaceous leafy greens are termed a specialty crop (2002 U.S. Farm Bill), and within Kentucky, are grown on a small scale and sold directly to consumers. Farmers can grow brassicaceous greens crop in the fall and spring to elongate their offerings at farmer's markets. The demand for local fresh produce has grown dramatically in the last two decades. Much of the interest in local foods has emerged as consumers believe that the food is fresher, of higher quality, and healthier (Penney and Prior 2014). Leafy greens are nutrient dense and rich in antioxidants (Subhasree et al. 2009) making them popular with health-conscious consumers. Eighty five percent of Community Supported Agriculture businesses believe that demand for local food is increasing (Woods 2017) and farmer's markets grew from 1755 in 1994 to 8687 in 2017 ('National Count of Farmer's Market Directory Listings' 2019). Many consumers are willing to pay large price premiums to buy produce that is local (Hu et al. 2012; Meas et al. 2015) and even more for produce that is both locally grown and organic (Connolly and Klaiber 2014). The US organic food industry has grown from 9.6 billion dollars in 2003 to 47.9 billion dollars in 2018 (US Organic Trade Association 2019). Within Kentucky, leafy greens sold for an average of $3.15/pound between 2014 and 2018 (Wolff 2019).

Despite this demand, brassicaceous leafy greens are difficult to produce due to heavy pest pressure from flea beetles (Coleoptera: Chrysomelidae: Alticini) that can render the leaf tissue unmarketable. Adult beetles feed on the foliage which leads to direct damage to produce. The damage associated with flea beetles is very distinctive with many small holes spread throughout the leaves which are termed "shot holes". Flea beetles owe their common name to their saltatorial hind legs which are used for jumping long distances and escaping from predators. Additionally, the small size of the flea beetles allows them to hide within leaves where they are protected from contact with foliar insecticides. Flea beetles spend a portion of their lives underground which can further complicate control as their eggs, larvae, and pupae are protected from insecticide sprays. Flea beetles start their lives as eggs laid on the surface of their host plant's roots (Knodel 2017). These eggs hatch and go through three larval instars before pupating and emerging as adults. This portion of the life cycle takes 44 to 55 days in the Canadian Great Plains for species within the problematic genus *Phyllotreta* (Knodel 2017; Tahvanainen 1983). In the northern portion of the Canadian Great Plains, most species only have one generation per year while in the southern portion of the Canadian Great Plains and the New England area, two generations are common (Knodel 2017). Most of the damage to the crop occurs during the beetle's adult life stage with only minimal damage caused by larval feeding on roots (Knodel 2017). Currently, farmers raising brassicaceous leafy greens rely primarily on conventional insecticide treatments (Hahn 2018).

While conventional insecticides are the most common method of flea beetle control, research suggests that they are relatively ineffective at controlling flea beetles. A study comparing the efficacy of insecticides in Canada found that the effects of thiamethoxam and pyrethrin were not statistically different from the control. However, carbaryl, the most effective synthetic insecticide treatment, was better than the unsprayed control (Andersen et al. 2006). Furthermore, Walgenbach and Schoof (Walgenbach and Schoof 2017), found that five classes of systemic insecticide did not reduce flea beetle damage compared to no spray controls. Only at high concentrations did application of cyantraniliprole result in lower flea beetle damage (Walgenbach and Schoof 2017). For organic growers, organic insecticides show some success at reducing flea beetle abundance and damage (Seaman and Lange 2017). Andersen et al. (Andersen et al. 2006), found that an organic spinosyn mix reduced flea beetle damage compared to the control. The poor effectiveness of many insecticides may be due to the development of resistance in some flea beetle populations. For example, Canadian populations of the crucifer flea beetle, *Phyllotreta cruciferae* (Turnock and Turnbull 1994) and European populations of cabbage stem flea beetle, *Psylliodes chrysocephala L.* (Zimmer et al. 2014) have developed resistance to insecticides. Furthermore, conventional, and organic insecticides have non-target effects on beneficial insects such as pollinators and natural enemies (Batzer and Gleason 2011). Thus, integrated pest management programs (IPM) often promote the use of alternative non-chemical practices in place of insecticides.

A number of alternative practices for controlling flea beetles have been evaluated, including: removing old crop debris during winter, planting trap crops, modifying planting date, plant-derived essential oils, and row covers (Hahn 2018). These alternatives vary in success rates and feasibility of implementation. For example, flea beetles overwinter as winged adults which can move across fields easily (Lamb 1984), making removal of crop residues unlikely to be effective. Trap cropping systems for brassicaceous greens may be difficult to implement given that greens growers often have complex planting schedules and little extra time or space, making incorporation of trap crops difficult (Bohinc and Trdan 2013). Modifying planting dates to avoid flea beetles is problematic as high temperatures prevent leafy greens production during mid-summer for much of the southern U.S. and other regions. While trap cropping and modifying planting dates may be difficult for brassicaceous greens growers to implement, many of these alternatives show promise for the future.

Recently, the use of plant-derived essential oils that act as insect repellents has been promoted as a safer alternative to synthetic insecticides. As plant essential oils are natural products and are often extracted from culinary herbs, they are viewed as safe to eat

(Tripathi et al. 2009) and are believed to have minimal negative effects on beneficial insects (Atanasova and Leather 2018; Tripathi et al. 2009). Essential oils are exempt from EPA registration under FIFRA (Federal Insecticide, Fungicide Rodenticide Act) 25 (b). Laboratory experiments have revealed that essential oils such as peppermint (*Mentha x piperita*), thyme (*Thymus vulgaris*), rosemary (*Salvia rosmarinus*), cloves (*Syzygium aromaticum*), Norwegian angelica (*Angelica archangelica*), and basil (*Ocimum basilicum*) have repellent effects on spotted wing drosophila (*Drosophila suzukii*) (Renkema et al. 2016), aphids (*Aphis spp.*) (Pavela et al. 2013; Atanasova and Leather 2018; Atanasova et al. 2017; Atanasova and Nenov 2017), and Colorado potato beetle (*Leptinotarsa decemlineata*) (Saroukolai et al. 2014; Ayse et al. 2016). Essential oils are volatile and have poor water solubility which make them difficult to use in agricultural settings (Moretti et al. 1998). Some aromatic and culinary herbs have essential oils which are phytotoxic and give them a competitive edge over weeds (Dhima et al. 2010). Studies involving coriander (*Coriandrum sativum*), tobacco (*Nicotiana tobacum*), and fenugreek (*Trigonella foenum-graecum*) oils found no phytotoxic effects to apple, rose, and oleander plants (Atanasova et al. 2017; Atanasova and Nenov 2017). However, relatively little research has examined the phytotoxicity of many essential oils. Regardless, pest control companies have started to market essential oil mixes. Commercial essential oil mixes include Trifecta Crop Control (Trifecta LLC, South Williamsport PA, USA), Essentria (Zoecon, Schaumburg IL, USA), and Ant Out (JH Biotech Inc., Ventura CA, USA). Few studies on essential oils have tested the longevity of repellent effects under field cropping conditions. Furthermore, few field studies on flea beetles have been published in the scientific literature.

Perhaps the most effective alternative flea beetle control tactic is the use of row covers (Andersen et al. 2006; Rekika et al. 2008). Row covers are light fabrics or netting that cover the crop to form a physical barrier to a pest insect. The use of row covers in vegetable production was first introduced for season extension through the use of spun-bonded or perforated polyethylene blankets that raise the temperature 2–7 °C (Aziz et al. 2001; Moreno et al. 2002). However, these same covers can be applied to limit insects' access to vegetable crops. Furthermore, insect exclusion row covers have successfully limited pests in broccoli (Adams et al. 1990), grape (*Vitis vinifera*) (Strang et al. 1992), apple (*Malus domestica*) (Chouinard et al. 2016), squash (*Cucurbita spp.*) (Skidmore et al. 2019; Adams et al. 1990), muskmelon (*Cucumis melo*) (Skidmore et al. 2019), blackberry (*Rubus fruticosus*) (Kuesel et al. 2019), blueberry (*Vaccinium spp.*) (Cormier et al. 2015; Link et al. 2014), and raspberry (*Rubus spp.*) (Leach et al. 2016; Rogers et al. 2016). ProtekNet, made of knitted polyamide, provides a maximum increase in temperature of only 0.5 °C and a maximum decrease of 5% humidity (Chouinard et al. 2016). ProtekNet also protects crops from diseases and extreme weather events such as hail (Chouinard et al. 2016). To our knowledge only one study has looked at the efficacy of row covers for control of flea beetles in brassicaceous greens. Andersen et al., (2006) found that the row cover CovertanPro 30 reduced flea beetle abundance and damage more than any conventional and organic insecticide treatment. While Andersen et al.,(2006) found strong results in Massachusetts, few growers have adopted row covers in the southeastern United States. Questions remain if row covers can be successful in the heat of the south.

Given the challenge of controlling flea beetles in leafy brassicaceous greens, it is imperative to develop best management systems by comparing and combining alternative practices. In this study, we compare the efficacy of the woven-mesh row cover ProtekNet, the poly spunbonded row cover Agribon AG-30 (hereafter known as Agribon), several plant-derived essential oils, and organic and conventional insecticide treatments in both arugula and mizuna mustard greens. I hypothesized that row covers would increase quality by reducing flea beetle damage to leafy greens. I expected the plots treated with row covers and conventional insecticides to have higher yields than all other treatments. Furthermore, I hypothesized that combining plant essential oil sprays and row covers would maximize flea beetle control.

Materials and Methods

Site: Field studies were conducted during the spring and fall of 2019 at the University of Kentucky's Horticulture Research Farm, located in Lexington, Kentucky (37°58′25.92″ N, 84°32′5.85″ W). This 100-acre farm is within plant hardiness zone six. The farm is split into organic and conventional zones and includes a diverse arrangement of crops. Our field was located next to fields growing clover, tomatoes, and radishes in the conventional section of the farm. To study the impact of row covers, essential oils, and organic and conventional insecticides, we performed two field trials grown on a 0.275-acre field site of arugula (Astro) and mustard greens (Mizuna) in the spring (11 April–20 May) and fall (16 August–20 September) of 2019. In Kentucky, high temperatures in the mid-summer limit the success of mustard greens. For this reason, we focused on spring and fall plantings.

A randomized block design was used for both field trials in 2019. Each plot consisted of three raised beds with two rows being planted in each raised bed. The rows within each bed were 18 inches apart and seed was spaced 0.6 inches apart within row. Within each bed, one row of arugula was grown and one row of mizuna mustard was grown. The outer two raised beds were established and treated identically but were used as guard rows with no data collection. All data were taken from the center four feet of the raised bed to provide a three-foot buffer from the edge of the plot in all directions.

Spring trial field design: there were seven treatments for each field trial that varied between the spring and fall trials (Table 1). These treatments were replicated four times among four blocks for the spring and fall trials. The treatments were as follows: (1) control treatment. (2) The organic insecticide treatment. (3) The conventional insecticide treatment. (4) The Agribon treatment fully covered the plot from the time of cotyledon emergence until harvest. (5) The ProtekNet treatment fully covered the plot from cotyledon emergence until harvest. (6) The ProtekNet + rosemary (Salvia rosmarinus) oil treatment. (7) The ProtekNet + thyme (*Thymus vulgaris*) oil treatment.

Field preparation and treatment implementation: in 19–22 March 2019, the field was disked, and compost was applied at a rate of 10 tons per acre. On 24 March, the field was spaded to incorporate the compost, beds were formed, and two lines of drip tape were buried per bed (Aqua-Traxx 6", Toro Garden Company, Bloomington, MN, USA). The field was then shallowly cultivated on 4 and 11 April to form a stale seed bed. Arugula and mizuna mustard were planted on 11 April at 0.6 inch spacing. All seed was sourced from Johnny's Selected Seed (Winslow, ME, USA). Mizuna was planted in the northern row of each bed while arugula was planted in the southern row of each bed. Nature Safe 10-0-8 (Darling Ingredients Inc., Irving, TX, USA) was applied at a rate of 50 lbs.(pounds) N per acre. All plots were planted on bare ground and we manually weeded as needed to suppress weeds.

Row covers were implemented shortly after germination on 23 April. Essential oils were sprayed twice a week with a spray bottle at a rate of 500 mL per ten feet of row. We selected this rate and frequency to test the maximum realistic rate for our field study. We anticipated that this high rate would not be used for market farming systems, and we anticipated lowering the rate for future studies. Flea beetles were first observed on 29 April which initiated the weekly insecticide spray schedule. Plots were sprayed a total of three times with insecticide treatments. Organic insecticides were rotated between Entrust SC (spinosad, Corteva Agriscience [Dow AgroScience], Indianapolis, IN, USA) and Pyganic 5.0 (pyrethrins, Valent U.S.A. Corporation, MGK, Minneapolis, MN, USA), while the conventional insecticides were rotated between Mustang Maxx (pyrethroid, Zeta-cypermethrin, FMC Corporation, Philadelphia, PA, USA) and Scorpion 35SL (dinotefuran, Gowan Company, Yuma, AZ, USA). Insecticides were applied at the industry recommended concentrations. These rates were 0.0496 kg/acre for Scorpion 35SL, 1.36 kg/acre for Entrust, 0.0104 kg/acre for Mustang Maxx, and 0.0151 kg/acre for Pyganic 5.0. Sprays were made using an electric powered Jacto backpack sprayer (Jacto, Pompeia, São Paulo) and were completed at a spray volume of 182 gallons per acre. At the conclusion of the spring trial, we seeded buckwheat as a cover crop for four weeks. This cover was flail mowed and incorporated into the soil on 8 August.

Fall trial field design: the experimental design of the fall trial differed from the spring trial only in terms of the essential oil treatments. Here, seven treatments were replicated four times among four blocks (Table 1). The treatments were as follows: (1) control treatment; with no spray and no row covers. (2) The organic insecticide treatment. (3) The conventional insecticide treatment. (4) The Agribon treatment. (5) The ProtekNet treatment. (6) The rosemary oil treatment. (7) The neem (*Azadirachta indica*) oil treatment.

Field preparation and treatment implementation: the same field used for the spring trial was used for the fall trial. Field preparation for the field trial was the same as the spring trial. The field was cultivated on 15 August and the beds were formed with the stale seed bedding attachment. Two lines of drip tape were buried in each bed on 16 August and beds were reformed. Arugula and mizuna mustard were planted on August 16th at a 0.6 inch spacing. Mizuna was planted in the northern row of each bed while arugula was planted in the southern row of each bed.

Seedlings started to emerge on 20 August and row covers were implemented on that day. Essential oils were sprayed twice a week. For the first week only, both essential oils were sprayed at a rate of 60 mL per 10 ft (feet) or 180 mL per plot. For the rest of the trial, essential oils were sprayed at a rate of 125 mL per 10 ft or 375 mL per plot. The choice to lower application rates in the second trial was made to match the difference in surface area requiring spray coverage. In the fall trial, spray coverage was only needed to cover the brassicaceous greens' foliage whereas in the spring trial, we sprayed the entire netted canopy. Insecticides were sprayed weekly starting on 27 August. Organic and conventional insecticide treatment plots were sprayed a total of four times following the same rotations outlined in the spring trial.

Data collection:

Insect pest monitoring data: all insect pests were sampled during the season using yellow sticky traps (Arbico Organics, 5" × 7" Yellow Sticky Traps, Tucson, AZ, USA). Yellow sticky traps were placed in the field twice during each growing season. During each of the two time periods, yellow sticky traps were left in the field for one week before being collected. For each time period, a standard 5” × 7” yellow sticky trap was cut in half and these two halves were placed within the plot. As an additional measurement to determine the relative abundance of flea beetle species, we made collections by vacuum sampling with an inverted leaf blower before harvest in the spring and fall (STIHL 5H 56C, STIHL, Inc., Waiblingen, Germany). We modified protocols from Swezey et al. (Swezey et al. 2014). Before harvest at the close of the spring and fall trials, we sampled insect populations using a vacuum within each plot, six sections of row were vacuumed for two seconds blasts each. These samples were bagged and later analyzed under magnification to determine the number of individual pest species. Yellow sticky trap data can be found in table 2 while data from vacuum samples can be found in table 3. Pest species other than those of flea beetles were present in very low quantities and are not presented in this publication.

Leaf damage data: to determine the impact of treatments on flea beetle damage to arugula and mizuna greens, we measured the number of shot holes per unit leaf area. Prior to, but on the same day as harvest, we collected 10 arugula and 10 mizuna leaves sampled randomly from the middle row per plot. We measured leaf area using the application, LeafByte, on an Apple iPhone SE. The application LeafByte estimates total leaf area from photographs of leaves. After the leaf area was estimated, we counted the number of flea beetle damage holes per leaf and calculated the number of damage holes per cm^2 of leaf area. Leaf damage data can be found in table 3.

Harvest data: in the spring trial, we harvested arugula and mizuna on 20 May. Within the middle, experimental row, we cut all foliage within the central four feet of both crop species. Harvest was completed by cutting the entirety of the sampled foliage to the ground level using scissors. This sample was weighed, and all measurements were written down for analysis. In the fall trial, we harvested on 20 September. Two samples, each of which were a two foot length of row, was harvested for each crop species. This harvesting method was maintained consistently to prevent any biases. Harvest data can be found in table 3.

Both arugula and mizuna mustard are harvested when they are young and only have a rosette of leaves near the ground. As both plant species mature, they will produce a shoot with a flowering head above the rosette of leaves, this phenomenon is termed bolting. At this time, the leaves of the plant become very bitter tasting due to a transformation of the sugars within the leaf. This bitterness is unpalatable, rendering the produce unmarketable. To measure the bolting of the greens, we counted the total number of bolting stems within a ten-foot length of row for each crop. We defined bolting for this study as any shoot with a flower head that was above the rosette of leaves. Harvest data can be found in table 3.

Temperature data: to determine potential differences in temperature between treatments, we placed temperature sensors (SpecWare 9, Spectrum Technologies, Inc., Aurora, IL, USA) within the Agribon and ProtekNet row cover treatments as well as in the uncovered control treatment. Using these field sensors, we followed temperature in the control treatment ($n = 4$), the fine mesh ProtekNet treatment ($n = 4$), and the spun-bonded polyethylene Agribon treatment ($n = 4$). We made the assumption that all uncovered treatments would experience the same temperature. Temperature data was only collected for the final five days of the spring trial as there was a delay in the arrival of the temperature sensors from the manufacturer. In the fall trial, we collected temperature data across the entire experiment. These sensors were placed within these three treatments to determine temperature differences between the row covers and bare ground. The sensor was placed in the middle of the row at a height of 10 to 12 inches above the ground. We calculated maximum and average temperatures and compared them across treatments. Temperature data can be found in table 4.

Data analysis: to determine the impact of row covers, essential oils, and organic and conventional insecticides on flea beetle abundance, damage, and crop yield we performed general linear mixed models (GLMM). We conducted analyses for the spring and fall trials independently given that the essential oil treatments differed between trials. For each dependent variable (flea beetle abundance, shot-holes per cm^2, number of bolting stems, yield, maximum temperature, minimum temperature, average temperature), we incorporated treatment as a fixed effect within models. In order to nest the randomized block design into the model structure, we incorporated block as a random effect within models. Following GLMM, we performed Tukey's post hoc tests to determine pairwise comparisons of different treatment levels if the overall treatment effect was significant. We tested all models for normality using a Shapiro–Wilk test on model residuals. If model residuals were not normally distributed, we transformed independent variables with square-root or log transformations until residual distributions met the assumptions of normality. For flea beetle abundance in vacuum samples of spring arugula, transformations did not improve the assumptions of normality. In this case, we analyzed data with a non-parametric Kruskal–Wallis test. All analyses were conducted in the program R (3.3.3) using the packages 'LME4′, 'stats', and 'emmeans' (R Foundation, Vienna, Austria). Test statistics can be found in table 5.

Results spring trial

Yellow sticky trap sampling of flea beetles: in the spring trial, we observed 698 flea beetles on the yellow sticky traps. There was a significant effect of treatment on flea beetle abundance in the spring trial (Tables 2 and 5). The Agribon treatment had fewer flea beetles than the control ($p = 0.0001$) and organic insecticide ($p = 0.001$) treatments. The ProtekNet treatment had fewer flea beetles than the control ($p < 0.001$) and organic insecticide ($p < 0.001$) treatments. The ProtekNet + rosemary oil treatment had fewer flea beetles than control ($p < 0.001$) and organic insecticide ($p = 0.001$) treatments. The conventional insecticide treatment had fewer flea beetles than the control ($p < 0.001$) and organic insecticide ($p = 0.008$) treatments. There were no other significant pairwise comparisons.

ProtekNet + Thyme oil treatment: heavy phytotoxic burns were found 30 April on the ProtekNet + Thyme oil treatment. This was the day after the first essential oils spray was made. 25% of arugula plants were dead and an additional 70% of plants had lost most of their leaves; 73.5% of Mizuna died as a result of this spray with an additional 26.5% plants losing the majority of their leaves. Due to the magnitude of these burns, this treatment was removed from the project (Tables 2 and 3).

Arugula

Vacuum sampling of flea beetles: we collected 65 flea beetles from vacuum samples at the end of the growing season with 74% of these being *Phyllotreta striolata* and 5% being *P. bipustulata*. The remaining 21% were not identified. There were no significant pairwise comparisons within the vacuum samples (Tables 3 and 5).

Flea beetle damage: there was a significant effect of treatment on flea beetle damage to arugula in the spring trial (Tables 3 and 5). A Tukey post hoc test revealed that the control treatment had more damage than the conventional insecticide (p = 0.001), ProtekNet (p < 0.001), Agribon (p < 0.001), and ProtekNet + rosemary oil (p < 0.001) treatments. The organic insecticide treatment had more damage than the conventional insecticide (p = 0.018), ProtekNet (p < 0.001), Agribon (p < 0.001), and ProtekNet + rosemary oil (p < 0.001) treatments. Additionally, the conventional insecticide treatment had more damage than the Agribon (p = 0.044) treatment. There were no other significant pairwise comparisons.

Yield: there was no significant effect of treatment on arugula yield in the spring trial (Tables 3 and 5).

Bolting: there was a significant effect of treatment on arugula bolting in the spring trial (Tables 3 and 5). A Tukey post hoc test revealed that the Agribon treatment had higher rates of bolting than the control (p = 0.050), organic insecticide (p = 0.026), and conventional insecticide (p = 0.026) treatments. There were no other significant pairwise comparisons.

Mizuna Mustard

Vacuum sampling of flea beetles: we collected 104 flea beetles from vacuum samples at the end of the growing season with 67% of these being *Phyllotreta striolata* and 13% being *P. bipustulata*. The remaining 20% were not identified. There was a significant effect of treatment on the abundance of flea beetles on mizuna mustard within the spring trial (Tables 3 and 5). A Tukey post hoc test revealed that the ProtekNet + rosemary oil treatment had fewer flea beetles than the organic insecticide (p = 0.014) and conventional insecticide (p = 0.004) treatments. Additionally, the ProtekNet + rosemary oil treatment had marginally fewer flea beetles than the control (p = 0.071) treatment. There were no other significant pairwise comparisons.

Flea beetle damage: there was a significant effect of treatment on the abundance of flea beetles on mizuna mustard within the spring trial (Tables 3 and 5). A Tukey post hoc test revealed that the control treatment had more damage than the conventional insecticide (p < 0.001), ProtekNet (p < 0.001), Agribon (p < 0.001), and ProtekNet + rosemary oil (p < 0.001) treatments. The organic insecticide treatment had more damage than the conventional insecticide (p = 0.003), ProtekNet (p < 0.001), Agribon (p < 0.001), and ProtekNet + rosemary oil (p = 0.001) treatments. There were no other significant pairwise comparisons.

Yield: there was a significant effect of treatment on mizuna mustard yield in the spring trial (Tables 3 and 5). A Tukey post hoc test revealed that the ProtekNet treatment had higher yields than the control (p < 0.001) and organic insecticide (p = 0.001) treatments. There were no other significant pairwise comparisons.

Bolting: there was no bolting of mizuna mustard within the spring (Tables 3 and 5).

Results fall trial

Yellow sticky trap sampling of flea beetles: in the fall trial, we observed 3578 flea beetles on yellow sticky traps. There was a significant effect of treatment on the abundance of flea beetles within the fall trial (Tables 2 and 5). The Agribon treatment had fewer flea beetles than the control (p < 0.001), organic insecticide (p < 0.001), neem (p < 0.001), rosemary (p = 0.025), and conventional insecticide (p = 0.018) treatments. The ProtekNet treatment had fewer flea beetles than the control (p = 0.004), organic insecticide (p <

0.001), and neem (p = 0.001) treatments. There were no other significant pairwise comparisons.

Temperature data: there was a significant effect of treatment on temperature in the fall trial (Tables 4 and 5). The Agribon treatment had a higher average temperature over the course of the trial than the control treatment (p = 0.008). The control treatment also had a lower max temperature than the Agribon (p = 0.049) and ProtekNet (p = 0.037) treatments. There were no other significant pairwise comparisons.

Arugula

Vacuum sampling of flea beetles: the vacuum sampling caught 726 flea beetles with 73% of these *P. striolata*, 10% *P. cruciferae*, 6% *P. bipustulata*, 8% *Chaetocnema concinna*, and the remaining 3% were not identified. The eggplant flea beetle, *Epitrix fuscula*, the tobacco flea beetle, *Epitrix fasciata*, and the pigweed flea beetle, *Disonycha glabrata*, were all found at low levels. There was a significant effect of treatment on the abundance of flea beetles within the vacuum samples (Tables 3 and 5). The control treatment had significantly higher levels of flea beetles than the conventional (p = 0.001), ProtekNet ($p < 0.001$), and Agribon ($p < 0.001$) treatments. The neem oil treatment had more flea beetles than the conventional (p = 0.009), ProtekNet (p = 0.001) and Agribon ($p < 0.001$) treatments. The organic insecticide treatment had more flea beetles than the ProtekNet (p = 0.05) and Agribon (p = 0.04) treatments. The organic insecticide treatment had marginally more flea beetles than the conventional treatment (p = 0.07). There were no other significant pairwise comparisons.

Flea beetle damage: there was a significant effect of treatment on flea beetle damage to arugula in the fall trial (Tables 3 and 5). A post hoc test revealed that the control treatment had more damage than the conventional insecticide (p = 0.025), Agribon ($p < 0.001$), and ProtekNet ($p < 0.001$) treatments. The Agribon treatment had less damage than the organic insecticide ($p < 0.001$), conventional insecticide (p = 0.001), rosemary oil ($p < 0.001$), and neem oil ($p < 0.001$) treatments. The ProtekNet treatment had less damage than the organic insecticide ($p < 0.001$), conventional insecticide ($p < 0.001$), rosemary oil ($p < 0.001$), and neem oil ($p < 0.001$) treatments. There were no other significant pairwise comparisons.

Yield: there was a significant effect of treatment on arugula yield in the fall trial (Tables 3 and 5). A Tukey post hoc test revealed that the rosemary oil treatment had lower yield than the organic insecticide (p = 0.038), Agribon (p = 0.005), and ProtekNet (p = 0.003) treatments. There were no other significant pairwise comparisons. Yield within the rosemary oil and neem oil treatments are believed to be impacted by light phytotoxicity burns first observed on 7 September. These burns were seen through the death of apical leaf tissue.

Bolting: There was no bolting of arugula within the fall trial.

Mizuna Mustard

Vacuum sampling of flea beetles: the vacuum sampling caught 1012 flea beetles with 70% of these *P. striolata*, 13% *P. bipustulata*, 9% Chaetocnema concinna, 7% *P. cruciferae*, and the remaining 1% were not identified. There was a significant effect of treatment on the abundance of flea beetles within vacuum samples (Tables 3 and 5). A Tukey post hoc test found that the control treatment had significantly more flea beetles than the organic ($p = 0.007$), conventional ($p < 0.001$), ProtekNet ($p < 0.001$), Agribon ($p < 0.001$), and rosemary oil ($p < 0.001$) treatments. The neem oil treatment had more flea beetles than the organic insecticide ($p = 0.015$), conventional insecticide ($p < 0.001$), ProtekNet ($p < 0.001$), Agribon ($p < 0.001$), and rosemary oil ($p < 0.001$) treatments. The organic insecticide treatment had more flea beetles than the conventional insecticide ($p < 0.001$), ProtekNet ($p < 0.001$) and Agribon ($p < 0.001$) treatments. The rosemary oil treatment had more flea beetles than the conventional insecticide ($p = 0.007$), ProtekNet ($p = 0.007$) and the Agribon ($p = 0.007$) treatments. There were no other significant pairwise comparisons.

Flea beetle damage: there was a significant effect of treatment on flea beetle damage to mizuna mustard in the fall trial (Tables 3 and 5). A Tukey post hoc test revealed that the control treatment had more damage than the rosemary oil ($p = 0.006$), organic insecticide ($p < 0.001$), conventional insecticide ($p < 0.001$), Agribon ($p < 0.001$), and ProtekNet ($p < 0.001$) treatments. The neem oil treatment was the same as the rosemary oil ($p = 0.90$) and the organic insecticide ($p = 0.15$) treatments. The conventional insecticide treatment had less damage than the neem oil ($p < 0.001$), rosemary oil ($p < 0.001$), and organic insecticide ($p < 0.001$) treatments. The Agribon treatment had less damage than neem oil ($p < 0.001$), rosemary oil ($p < 0.001$), organic insecticide ($p < 0.001$), and conventional insecticide ($p < 0.001$) treatments. The ProtekNet treatment had less damage than neem oil ($p < 0.001$), rosemary oil ($p < 0.001$), organic insecticide ($p < 0.001$), and conventional insecticide ($p < 0.001$) treatments. There were no other significant pairwise comparisons.

Yield: there was a significant effect of treatment on mizuna mustard yield in the fall trial (Tables 3 and 5). A post hoc test revealed that the ProtekNet treatment had higher yields than the control ($p = 0.017$), neem oil ($p = 0.003$), and rosemary oil ($p = 0.004$) treatments. There were no other significant pairwise comparisons. Yield within the rosemary oil and neem oil treatments are believed to be impacted by light phytotoxicity burns first observed on 7 September. These burns were seen through the death of apical leaf tissue.

Bolting: there was no bolting of mizuna mustard within the fall trial.

Discussion

This study found that row covers are an effective method for controlling flea beetles within brassicaceous leafy greens. Both the fine-mesh row cover ProtekNet and the spun-bonded row cover Agribon had similar or gave better control of flea beetles than all other treatments. Both row cover treatments, without essential oil sprays, always reduced flea beetle damage significantly below the control and organic insecticide treatments (Table 3). One trend that was observed over the course of the two trials was that we had higher numbers of flea beetles within the fall trial and fewer beetles in the spring trial. This was likely due to cold snaps in the previous winter that killed off portions of the population. This information could be useful for growers when choosing when to grow brassicaceous greens and what management strategy to use for that season. Flea beetles were the only pest that was seen in damaging levels within these trials. In the fall trial, when flea beetle pressure was high, row cover treatments provided stronger flea beetle suppression than the conventional insecticide treatment. Furthermore, in the fall trial, ProtekNet was the only treatment to have significantly higher yields relative to the control treatment. To my knowledge, the only other study to compare the effectiveness of row covers with insecticide treatments corroborates our findings, with a few exceptions (Andersen et al. 2006). Andersen et al., (Andersen et al. 2006) found that the row covers CovertanPro30 and Agril 17 gave the best control of flea beetles and the corresponding damage. They also found that carbaryl and Spinosad lowered flea beetle numbers below that of the control. In their experiment, treatment with Kaolin and pyrethrin showed no difference from the control. Interestingly within their experiment, the conventional insecticide thiamethoxam had higher levels of flea beetles and damage than the control. Similarly, within my study, row covers served as the best control for flea beetles. Additionally, the conventional insecticide rotation of pyrethroids and neonicotinoids behaved similar to carbaryl in Andersen et al. (Andersen et al. 2006).

The two insecticide rotations behaved very differently in the field. The rotation of group 3A and 4A conventional insecticides provided intermediate control of flea beetles within both the spring and fall trials. Flea beetle damage within the conventional insecticide plots was statistically similar to the row cover treatments for both trials and crops. However, damage to leaves was higher in conventional insecticide plots and leaves may not be marketable due to the higher damage. High levels of flea beetles were found through vacuuming the conventional insecticide plots at the conclusion of the spring trial. One possible reason for the high numbers of flea beetles, which I observed in vacuum samples, is that there was a time delay between the last insecticide spray and the vacuuming (6 days).

As opposed to conventional insecticides, organic insecticides provided very poor management of flea beetles. Over the course of the two trials and within both crops, the number of flea beetles and the corresponding crop damage rarely differed between organic insecticide treatments and the untreated control. Andersen et al. (Andersen et al. 2006) found that their control treatment averaged 120 and 137 damage holes per leaf in the two Komatsuna (*Brassica rapa* var. *perviridis*) trials planted mid-June. If I convert my data to damage holes per leaf instead of holes per cm^2, my study had lower damage levels than Andersen et al. (Andersen et al. 2006). Within the arugula control treatment, I found an average of 29 holes per leaf in the spring and 98 holes per leaf in the fall. Within the mizuna mustard control, I found an average of 28 holes per leaf in the spring and 79 holes per leaf in the fall. If I analyze just the arugula organic treatment, there was 21 holes per leaf in the spring and 57 holes per leaf in the fall. The high levels of damage to the leafy greens would lead to unmarketability. Additionally, these organic insecticides often must be purchased in impractical quantities for small farmers such as those in this region, who primarily sell their produce at local farmer’s markets. For these reasons, organic farmers need new management strategies that can be used within organic certification requirements.

Although plant essential oils have shown promising effects on pests in laboratory experiments, my studies failed to observe benefits in the field. The results of the essential oil treatments within these two field trials were not promising due to phytotoxicity responses from the crop. Within the spring field season, the thyme oil passed through the row cover and completely killed both crops within a day of the first spray. This led to the removal of the thyme oil treatment for the remaining duration of the study. Essential oils were sprayed directly on the crop in the fall due to concerns of the cost effectiveness of spraying essential oils over row covers. In the fall field season, both the neem and the rosemary oils caused moderate drops in yield (Table 3) due to stunting associated with early season phytotoxicity. I believe that the phytotoxicity effects among the neem and rosemary oils were due to spikes in temperature which heated the oil and scalded leaves.

Only one spray in the fall trial resulted in phytotoxicity, all other sprays in the fall trial did not cause plant damage. While researchers have evaluated thyme for insect repellency, it has also been studied, among other essential oils, for functionality as a herbicide (Tworkoski 2002). Rosemary oil sprayed on ProtekNet within the spring field season did not have stunting due to phytotoxicity but did not provide better protection than the ProtekNet alone. We used a five percent concentration of essential oils and sprayed twice a week. This concentration and frequency were estimated as the maximum practical level of control that producers would use. When sprayed at lower concentrations or less frequently, these essential oils may behave differently. Further research is needed to determine the proper concentration and frequency to balance insect repellency and the negative effects to plant leaves.

I observed small numbers of flea beetles under the row cover and their corresponding damage. I suspect that most flea beetles entered the plots through small gaps where the row covers met the ground rather than entering through the material. The fine-mesh row covers did not have any rips over the course of the two trials and I do not believe that flea beetles entered through the mesh. However, I did find several small rips in the Agribon material. These rips were mended when found but flea beetles could have taken advantage of these holes before mending. To improve efficacy, care should be taken to minimize damage to the row cover, and the row cover should be held firmly to the ground with a weight such as a polyvinyl chloride pipe filled with water. Further studies that span several years are needed to understand the life expectancy of ProtekNet. Within my trials, the ProtekNet treatment had a positive effect on crop yield, particularly in the fall trial. This boost in yield could be due to a lack of stress from herbivores or abiotic conditions. Bolting was found within the spring trial arugula and was statistically higher in the Agribon treatment. I believe the higher levels of bolting were due to increased temperatures underneath the row cover. Increased bolting may occur when using row covers, particularly during warmer times of the year and in warmer climates than that of central Kentucky.

Despite the strong effects of row covers on flea beetle damage in our study, there are a number of considerations that growers may want to make before adopting this practice. First, not all Brassicaceous crops may perform as well as arugula and mizuna under row covers. Furthermore, while I was able to compare the efficacy in the spring and fall in Kentucky, I was not able to compare multiple years or across regions. The efficacy of row covers may vary across time and across growing regions. Andersen et al. (Andersen et al. 2006) found similarly positive results for Komatsuna grown under row covers in a multi-year study in Massachusetts, but both my study and Andersen et al. (2006) should consider the challenges of scaling plot size up to commercial scale. For instance, all plots in our study were grown on bare ground and weeding was done manually while the row cover remained on. Future research must include a viable weed management system for commercial growers to adopt row covers on a large scale. Additionally, treatments may become more, or less, effective when implemented on a field scale rather than a plot scale. For instance, Growers should also consider the cost of implementation. Many growers are already using Agribon within the field, and while ProtekNet is more expensive to cover the same area, ProtekNet should last many more seasons than Agribon. Future studies should include an analysis of longevity, cost analysis, and profitability of different row cover systems.

While row covers were first introduced for season extension, mounting research is showing their effectiveness for insect exclusion. Row covers are most popular with organic and conventional growers in cropping systems that have a very low tolerance of insect damage. There is very low tolerance for insect damage where insects are causing direct damage to the produce such as in brassicaceous leafy greens (Andersen et al. 2006), lettuce (Rekika et al. 2008), and apples (Chouinard et al. 2017). Additionally, there is very low tolerance for insect pests in crops where insects are vectors of plant pathogens such as whiteflies in tomatoes (Hilje et al. 2001), cucumber beetles in cucurbits (Skidmore et al. 2019), and aphids (*Aphis gossypi* Glover, *Myzus persicae* Sulzer), whiteflies, and thrips species in hot peppers (Karungi et al. 2013). There are many types of row cover for various purposes. The ProtekNet row cover used within our experiment is a fine mesh, high-density, polyethylene netting manufactured for insect exclusion. The Agribon row cover we used is most often used as a frost blanket which allows producers to plant earlier in the spring and later in the fall. Our study shows that producers can use row covers, especially Agribon, for multiple reasons to maximize cost effectiveness. Row covers offer producers in the southeastern United States an effective method of flea beetle control that reduces their dependence on insecticides for conventional and organic production.

Conclusions

In conclusion, I found that row covers performed better than organic insecticide treatments and often conventional insecticide treatments. Organic insecticides rarely controlled flea beetles better than the control. While previous studies have shown that essential oils have potential to repel pest insects, I found high levels of phytotoxicity in plots sprayed with an essential oil mixture. This phytotoxicity lowered yields and the quality of the greens. Conventional insecticide plots often had lower numbers of flea beetles than the control, but levels were high enough to cause damage that would seldom be acceptable to consumers. Variability in populations of flea beetles over the course of the season should affect producer’s decisions on when to grow brassicaceous greens and the pest management decisions they make. I found that row covers provide optimal control of flea beetles for the brassicaceous greens arugula and mizuna mustard.

Table 1. Spring and fall treatment descriptions with the brassicaceous greens trials.

Spring Trial 2019	
Control	No spray, no row cover
Organic insecticide	Rotation of spinosad and pyrethrins sprayed once per week [1]
Conventional insecticide	Rotation of pyrethroid and dinotefuran sprayed once per week [2]
Agribon row cover	Spun-bonded polyethylene row cover [3]
ProtekNet row cover	25-gram fine mesh row cover [4]
ProtkeNet and rosemary oil	ProtekNet row cover sprayed with rosemary oil twice a week [5]
ProtkeNet and thyme oil	ProtekNet row cover sprayed with thyme oil twice a week [5]
Fall Trial 2019	
Control	No spray, no row cover
Organic insecticide	Rotation of spinosad and pyrethrins sprayed once per week [1]
Conventional insecticide	Rotation of pyrethroid and dinotefuran sprayed once per week [2]
Agribon row cover	Spun-bonded polyethylene row cover [3]
ProtekNet row cover	25-gram fine mesh row cover [4]
Rosemary oil	Rosemary oil applied directly onto greens twice a week [6]
Neem oil	70% clarified neem extract diluted and applied onto greens twice a week [6]

[1] Pyganic Crop Protection 5.0_{II} (pyrethrins, Valent U.S.A. Corporation, MGK, Minneapolis, MN, USA) and Entrust SC (spinosad, Corteva Agriscience [Dow AgroScience], Indianapolis, IN, USA). [2] Mustang Maxx (pyrethroid, Zeta-cypermethrin, FMC Corporation, Philadelphia, PA, USA) and Scorpion 35SL (dinotefuran, Gowan Company, Yuma, AZ, USA). [3] (Agribon grade-20, Berry Plastics, Indiana, USA). [4] (ProtekNet 25 gram, Dubois, Montreal, state abbr., USA). [5] treated twice a week with rosemary essential oil or thyme essential oil (Aura Cacia, Frontier Natural Products Co-op, Norway, IA, country) mixed at a 5% solution with 2.5% adjuvant (Nu Film P, Miller Chemical and Fertilizer, Hanover, PA, USA) and 92.5% water. [6] treated twice a week with rosemary essential oil (applied at same rate and mix as in 5) or neem oil was treated directly onto greens twice a week with neem oil (70% clarified hydrophobic neem extract) prepared from a concentrate (Safer Brand, Woodstream Corporation, Lititz, PA, USA) 1 fluid ounce per gallon of water with 2.5% spreader sticker adjuvant (Nu Film P).

Table 2. Effects of treatments on the number of flea beetles caught by yellow sticky traps in brassicaceous greens (mean and standard error).

Spring Trial 2019	
Treatment	No. flea beetles (sticky traps)
Control	16.6±1.2 A
Organic insecticide	13.6±1.7 A
Conventional insecticide	5.6±1.0 B
Agribon row cover	3.1±0.2 B
ProtekNet row cover	3.1±0.6 B
ProtkeNet and rosemary oil	1.5±0.3 B
ProtkeNet and thyme oil*	N/A (not applicable)
Fall Trial 2019	
Control	47.8±12.0 A
Organic insecticide	61.5±15.4 A
Conventional insecticide	26.5±6.6 AB
Agribon row cover	8.6±2.1 BC
ProtekNet row cover	3.9±1.0 C
Rosemary oil	24.6±6.2 AB
Neem oil	52.8±14.1 A

Common letters denote means are not significantly different from one another within season, as determined by Tukey's honestly significant difference (HSD) at a 0.05 alpha. * ProtekNet + thyme oil treatment removed due to death of plants after first essential oil spray.

Table 3. Effects of treatment on number of flea beetles caught by vacuum (mean and standard error), flea beetle damage per unit leaf area (mean and standard error), yield in pounds per acre (mean and standard error), and the number of stems bolting (mean and standard error) in brassicaceous greens.

Spring 2019					
Species	Treatment	Number of flea beetles (vacuum)	Damage (holes/cm^2)	Total yield (pounds /acre)	Bolting (stems)
Arugula	Control	3.5±1.9 A	0.9±0.1 C	12,279±1261 A	2.5±1.6 A
	Organic insect.	3.5±0.6 A	0.7±0.1 C	14,006±1447 A	2.3±1.3 A
	Conventional insect.	6±3.1 A	0.3±0 B	12,046±794 A	1.8±0.9 A
	Agribon row cover	1.3±1.0 A	0.1±0 A	15,874±1634 A	7.5±2.4 B
	ProtekNet row cover	1.3±0.8 A	0.1±0 AB	16,948±1027 A	3.8±2.1 AB
	ProtekNet + rosemary	0.8±0.3 A	0.1±0 AB	13,540±1447 A	3.3±1.1 A
	ProtekNet + thyme *	N/A	N/A	N/A	N/A
Mizuna	Control	5.3±2.3 ab	1.5±0.1 b	10,178±2288 a	0
	Organic insect.	7.5±3.1 b	1.1±0.1 b	10,878±2334 a	0
	Conventional insect.	7.5±2.5 b	0.3±0.1 a	14,847±2941 ab	0
	Agribon row cover	2.3±0.8 ab	0.1±0 a	17,415±1074 ab	0
	ProtekNet row cover	2.3±1.0 ab	0.1±0 a	21,617±1587 b	0
	ProtekNet + rosemary	1.3±1.0 a	0.2±0 a	16,247±2101 ab	0
	ProtekNet + thyme *	N/A	N/A	N/A	N/A
Fall 2019					
Species	Treatment	Number flea beetles (vacuum)	Damage (holes/cm^2)	Total yield (pounds/acre)	Bolting (stems)
Arugula	Control	57.3±12.9 B	3.2±0.2 C	9011±560 AB	0
	Organic ins.	37.3±11.2 B	2.0±0.2 BC	9571±840 A	0
	Conventional ins.	5.5±2.3 A	1.2±0.2 B	8544±794 AB	0
	Agribon row cover	1.5±0.3 A	0.3±0.1 A	11,672±1213 A	0
	ProtekNet row cover	3.3±0.9 A	0.2±0 A	12,372±1121 A	0
	Rosemary oil	29.5±2.8 AB	1.4±0.2 BC	3968±327 B	0
	Neem oil	47.3±8.2 B	2.2±0.2 BC	7143±1307 AB	0
Mizuna	Control	77.0±12.3 c	5.1±0.4 d	7844±420 b	0
	Organic ins.	50.3±6.3 b	2.9±0.4 c	9104±607 ab	0

	Conventional ins.	7.8±1.7 a	1.3±0.2 b	9711±420 ab	0
	Agribon row cover	6.8± 1.3 a	0.3±0 a	11,905±514 ab	0
	ProtekNet row cover	6.3±0.6 a	0.2±0 a	15,407±2101 a	0
	Rosemary oil	32.8±3.4 b	3.0±0.3 c	6443±1214 b	0
	Neem oil	74.3±0.2 c	3.58±0.3 cd	6303±980 b	0
Common letters denote means are not significantly different from one another within season, as determined by Tukey's HSD at a 0.05 alpha. Capitalization used for arugula and lowercase letters used for mizuna mustard. * ProtekNet + thyme oil treatment in spring trial removed due to death of plants.					

Table 4. Effect of treatment on overall maximum and overall minimum temperature (Fahrenheit) in the fall brassicaceous greens trial.

Fall Temperature 2019		
Treatment	**Maximum**	**Minimum**
Agribon	109.6±1.0 B	76.3±0.1 B
ProtekNet	110.1±0.8 B	75.8±0.2 AB
Control	103.6±0.8 A	75.3±0.3 A

Common letters denote means are not statistically significant. Numbers in parenthesis are standard errors. Temperature within plot was taken once every hour over the course of the season. These were taken within three different blocks for each of these three treatments. The maximum and minimum temperatures from each sensor was determined and was averaged within treatment.

Table 5. Statistical analysis of effect of treatment on number of flea beetles found, flea beetles damage per unit leaf area, crop yield, and the number of stems bolting in the brassicaceous greens trials.

Spring 2019					
Species	**Treatment Effect**	**Numerator degrees of freedom**	**Denominator degrees of freedom**	**F**	***p***
Both	No. flea beetles (sticky traps)	5	42	22.2	<0.01
Arugula	No. flea beetles (vacuum)	5*	*	9.9 (H statistic*)	0.08
Arugula	Damage (holes/cm^2)	5	15	27.8	<0.01
Arugula	Yield (lbs)	5	15	2.6	0.07
Arugula	Bolting	5	15	3.8	0.02
Mizuna	No. flea beetles (vacuum)	5	15	4.2	0.01
Mizuna	Damage (holes/cm^2)	5	15	21.9	<0.01
Mizuna	Yield (lbs)	5	15	4.8	<0.01
Mizuna	Bolting	-	-	-	-
Fall 2019					
Species	**Treatment Effect**	**Numerator degrees of freedom**	**Denominator degrees of freedom**	**F**	***p***
Both	No. flea beetles (sticky traps)	1	104	2.1	0.15
Both	Temperature maximum	2	9	6.8	0.02
Both	Temperature minimum	2	6	11.1	0.01
Arugula	No. flea beetles (vacuum)	6	21	9.7	<0.01
Arugula	Damage (holes/cm^2)	6	18	26.1	<0.01
Arugula	Yield (lbs)	6	21	5.2	<0.01
Arugula	Bolting	-	-	-	-
Mizuna	No. flea beetles (vacuum)	6	18	31.8	<0.01
Mizuna	Damage (holes/cm^2)	6	270	124.9	<0.01
Mizuna	Yield (lbs)	6	18	5.4	<0.01
Mizuna	Bolting	-	-	-	-
* Kruskal–Wallis test was used for this statistic.					

Chapter 3

The Impact of Plastic Mulches, Plant Essential Oils, and Row Covers on Flea Beetle (Chrysomelidae) Management in Eggplant Production

Abstract: Flea beetles are problematic for growers as they quickly find eggplant transplants and stunt or kill them through herbivory. I tested the efficacy of reflective silver plastic mulch, essential oils and commercial essential oil concentrates, a fine mesh row cover, and a spunbonded row cover, compared to organic and conventional insecticides and no spray controls in the summers of 2019 and 2020. In 2019, we found that the reflective silver mulch did not affect flea beetle abundance or damage, nor eggplant growth or yield. I also found that essential oils did not control pests or improve yield, indeed commercial essential oil concentrates led to lower yields compared to the conventional insecticide and row cover treatments. Organic insecticides did not perform better than the no spray control. The row covers and conventional insecticide provided marginally better flea beetle control and higher yields in a low pest pressure environment. The results of our study suggest row covers should offer producers with large flea beetle populations an effective method of flea beetle control that reduces their dependence on insecticides.

Introduction

One of the founding concepts of integrated pest management (IPM) is the use of multiple management strategies to control pest insects. A diverse set of pest management strategies can reduce the possibility of resistance to any one strategy (Abrol, 2009a, b; Aluja et al., 2009; Saenz-de-Cabezon et al., 2010). Most recommendations within IPM are to assess the population size of the pest as well as develop systems to lower that population size. IPM was created as a response to the over spraying of insecticides (Abrol, 2009a, b; Aluja et al., 2009; Saenz-de-Cabezon et al., 2010), oftentimes insecticides with similar chemistries. Insecticides are often part of an IPM program with the goal of strategically using insecticides to reduce future sprays. Within IPM, insecticides can be used as a preventative measure when sprayed early season, used as seed coats to decrease foliar sprays, or used when pest populations have continued to increase after other pest management techniques are used. While IPM programs are in place for many crops, further research into alternative management strategies is needed for less widely grown specialty crops such as eggplant within the United States.

Eggplant (*Solanum melongena*) is native to India (Doijode 2001) but has spread worldwide, it has been cultivated in North America since at least the eighteenth century. The edible portion of the eggplant is the berry which is used in dishes of varying origin. It is most used in dishes from the Indian subcontinent. Eggplant got its name in the West from the most common shape of its fruit which often resembles a purple egg. However, eggplant fruit can also take on several other shapes such as elongated or round as well as several colors such as white, red, green, or yellow. Eggplant is a member of the nightshade family (Solanaceae) along with other common crops such as tomatoes, peppers, potatoes, and tobacco. While not as popular in the United States as some of its close relatives, eggplant is very popular with some ethnic groups and approximately 142 million pounds of eggplant were grown in 2015 alone (USDA ERS). Still, the United States imports much of the eggplant that is consumed here. In 2019, the United States imported 71.2 million dollars' worth of eggplant (USDA FAS).

Given that eggplant is closely related to other solanaceous crops, it shares many of the same pests. Oftentimes the most damaging of eggplant pests are flea beetles within the genus *Epitrix* (Coleoptera: Chrysomelidae) (Diaz et al. 2004). Adult flea beetles feed on the leaves of eggplant and leave many small holes, giving the appearance that the leaf was hit by small pieces of hail or the spray from a shotgun. This damage is referred to as "shot" holes. While the plant can usually overcome the damage if it occurs later in the season, it can be fatal to seedlings (Sorensen and Baker, 1994). The flea beetle larvae feed on the roots of these same solanaceous plants but are generally not considered economically damaging at this stage. Flea beetles are often mobile over short distances by using their enlarged femur which allows them to jump (Oku et al. 2010). They are also mobile over longer distances by flight which they employ to find new host plants after experiencing hunger (Oku et al. 2010). Flea beetles can overwinter as adults and cause great damage to transplants set out in the spring (Sorensen and Baker, 1994). Large flea beetle populations can lower yields or kill transplants (Chalfant et al. 1979). Eggplant is most susceptible to flea beetle damage shortly after transplanting (Diaz et al. 2004). If populations are low, dispersed across a large field, or managed, eggplant transplants can initiate growth and are much more resistant to subsequent damage (Diaz et al. 2004). A second damaging but more sporadic pest is the Colorado potato beetle. Colorado potato beetles are another *Chrysomelid* which can easily cross over from other solanaceous crops and cause great damage to eggplant.

Currently, the primary method of controlling flea beetle populations is the use of conventional insecticides which have proven to be effective at managing most populations (Diaz et al. 2004). Organic growers are limited to the insecticides compliant with organic regulations and these insecticides have varying degrees of efficacy. Past research has shown that spinosad insecticides are effective at controlling flea beetle populations (McLeod et al. 2002). However, a recent study from New York found that a mixture of pyrethrin and azadirachtin was not effective for controlling the crucifer flea beetle (*Phyllotreta cruciferae*) over a two-week period while spinosad and two microbial based insecticides were effective (Seaman and Lange 2017). Further research has also found that spinosad efficacy dropped 65.5% one day after application (McLeod et al. 2002). This quick drop of efficacy is problematic as insect pests can quickly recolonize, forcing the producer to respray often, or damaging the crop. An important and undesirable side effect of relying on one method of insect management is that other insect species can become more problematic. This is particularly the case with insecticides which can kill beneficial insect species. The Colorado potato beetle is an example of a pest species released from its natural enemies. The Colorado potato beetle is resistant to more than fifty-two insecticides (Whalon et al. 2013; Alyokhin et al. 2008) including all major classes of insecticides.

Because of the potential to release Colorado potato beetle populations from their natural enemies, and the potential to develop insecticide resistance within flea beetles, we must look at additional management techniques to control flea beetle populations.

There are several alternative management techniques that show potential to control flea beetles within eggplant fields. Research into using aromatic essential oils or essential oil mixtures as sprays to repel insect pests has greatly increased in recent years. These essential oils face lower public scrutiny than insecticides as they are made from natural products that are often found within culinary herbs. Extracts of rosemary, lavender, and rue have all been shown to have repellant effects against Colorado potato beetle and bean weevil (*Acanthoscelides obtectus*) adults (Rojht et al. 2012). Essential oils have become particularly popular with controlling stored grain insects such as the rice weevil (*Sitophilus oryzae)* (Vendan et al. 2017) as well as indoor insects (Neupane et al. 2019). While most research has focused on using essential oil sprays to control insect pests, research has shown that intercropping eggplant with marigold (*Tagetes erecta*), coriander (*Coriandrum sativum*), and mint (*Mentha spp*.) can be effective for the management of the eggplant fruit and shoot borer, *Leucinodes orbonalis* Guenée in India (Sujayanand et al. 2015). Furthermore, research in a tomato system has shown that a combination of row covers, and intercropped basil (*Ocimum basilicum* L.) was more effective than either method on their own and lowered whitefly (*Bemisia tabaci*) populations by 68.7% (Mutisya et al. 2016).

Row covers, used as the sole management technique, have grown in popularity among many specialty crops as they have often been found to effectively exclude pest insects. These row covers are often made of fine mesh or blanketlike materials and can be draped directly over the plant or over hoops. Growers use these row covers to form a physical method of excluding insects from the growing space. Row covers have been used for tomatoes where they effectively exclude such pests as whiteflies, aphids (Aphidoidea), mites (Arachnida: subclass Acari), and thrips (Thysanoptera) (Gogo et al. 2014). The row covers that are most effective for pest suppression without increasing temperatures are those with a very fine pore size of 0.4mm (Gogo et al. 2014). Row covers have been used within brassicaceous greens (Andersen et al. 2006), cucurbit crops (Skidmore et al. 2019) and bramble crops (Strang et al. 1992; Kuesel et al. 2019) to control pests including flea beetles (*Phyllotreta* spp.), cucumber beetles (*Diabrotica undecimpunctata* and *Acalymma vittatum*), squash bugs (*Anasa tristis*), squash vine borer (*Melittia cucurbitae*) spotted wing drosophila (*Drosophila suzukii*), and Japanese beetles (*Popillia japonica*). Within pepper production, row covers control populations of thrips, broad mites, and whiteflies (Saioa et al. 2010) and research demonstrates that the plastic color and amount of reflected light can further affect pest suppression as well as plant growth (Legarrea et al. 2010). To our knowledge, no study has assessed the impact of row covers alone on eggplant yield and pest suppression.

The use of plastic mulches for weed suppression is common in the cultivation of many crops such as eggplant, tomatoes, peppers, squash, melon, and strawberries. Plastic mulch is popular in vegetable production as herbicides can be challenging to use, plastic mulch is less labor intensive than natural mulches, and plastic mulches can be used to alter soil temperature. While the most common color of plastic mulch is black, other colors have been used to modify temperature, plant growth, and insect pressure. The use of different colors of mulches has been shown to increase production of crops such as potatoes (Lamont et al. 2003; Ruiz-Machuca 2015), peppers (Ogutu 2006) and strawberries (Johnson and Fennimore 2005). However, studies have shown different results regarding what color of plastic mulch was most effective. These results have differed both by crop and by study within the same crop. The use of reflective silver mulch has been shown to reflect UV light and repel pests (Kring 1972, Summers et al. 2004). Reflective plastic mulches such as silver metalized plastic mulch and white plastic mulch, when compared against black plastic and bare ground, are effective at controlling populations of Mexican Bean Beetle (*Epilachna varivestis*) in green beans (*Phaseolus vulgaris*) and improving yield (Nottingham and Kuhar 2016). Additionally, within a bell pepper cropping system, reflective silver mulch was shown to lowered early season thrips (*Frankliniella occidentalis*) populations when compared to black plastic mulch (Reitz et al. 2003). Silver plastic mulch was shown to reduce aphid and silverleaf whitefly (*Bemisia argentifolii*) populations in zucchini (*Cucurbita pepo*) when compared to white plastic mulch (Frank and Liburd, 2005). Because of these positive effects on a diversity of pests, reflective silver plastic mulch could be a good option for controlling flea beetles in crops such as eggplant that are often grown on plastic mulch.

The purpose of this study is to evaluate alternative management techniques for controlling flea beetles within eggplant fields to reduce reliance on insecticides. Here, I evaluae reflective silver plastic mulch, botanical essential oils, row covers, and botanical essential oils sprayed on row covers. To my knowledge, no study has evaluated the combination of essential oils, row covers, and silver mulch for control of flea beetle populations. I compare these alternative techniques to conventional insecticides, organic insecticides, and an untreated control. The ultimate goal of this research is to find an alternative control method that is comparable with that of the insecticides and is both feasible and compliant with organic certification.

Materials and Methods

Site: Field studies were conducted during the summers of 2019 and 2020 at the University of Kentucky’s Horticulture Research Farm, located in Lexington, Kentucky (37°58’25.92”N, 84°32’5.85”W). This 100-acre farm is within plant hardiness zone six. The farm is split into organic and conventional halves and includes a diverse arrangement of crops. The field was located next to fields growing clover, tomatoes, radishes, apples, and buckwheat in the conventional section of the farm. To study the impact of row covers, essential oils, plastic mulch, and organic and conventional insecticides, I performed two field trials grown on a 0.275-acre field site. I grew the variety Galine during both field seasons. To avoid cold spring and fall weather, eggplant was started in the greenhouse and grown outdoors May 7th through July 16th 2019, and June 19th through August 25th 2020.

The experiment in 2019 was set up as a complete randomized block design (N = 4 blocks). Each block consisted of two paired beds one with silver plastic mulch and one with black plastic mulch. Within each plastic bed, I randomized 7 different insecticide, essential oil, and row cover treatments (here after IER treatments; Table 6, Figure 2). The experimental unit within this study was a plot consisting of a raised bed covered in plastic mulch ten feet long and with eight eggplant transplants planted fifteen inches apart. All data were taken from three of the four center plants and at least two plants were left as a buffer on each edge of the plot. No border rows were implemented as there was not enough space in the field.

Field trial design 2019:

The seven alternative IER management treatments were:

1) The control treatment; with no spray and no row covers.

2) The organic insecticide treatment was treated with a rotation of Pyganic Crop Protection 5.0 (Pyrethrin, Valent U.S.A. Corporation, MGK, Minneapolis, MN) and Entrust SC (Spinosad, Corteva Agriscience [Dow AgroScience], Indianapolis, IN) once weekly.

3) The conventional insecticide treatment was treated with a rotation of Mustang Maxx (Pyrethroid, Zeta-cypermethrin, FMC Corporation, Philadelphia, PA) and Scorpion 35SL (Dinotefuran, Gowan Company, Yuma, AZ), once weekly.

4) The Agribon treatment was implemented by affixing a spun-bonded polyethylene row cover to fully cover the plot from the time of transplanting 50% of plants were flowering (Agribon grade-20, Berry Plastics, Indiana, USA).

5) The ProtekNet treatment was implemented with a fine mesh row cover (ProtekNet 25 gram, Dubois, Montreal) fully covering the plot from transplanting until 50% of plants were flowering.

6) The ProtekNet + rosemary oil treatment was implemented with a ProtekNet row cover as described above, however the row cover was also treated twice a week with eucalyptus (*Eucalyptus globulus*) essential oil (Aura Cacia, Frontier Natural Products Co-op, Norway, IA) mixed at a 5% solution with 2.5% spreader sticker adjuvant (Nu Film P, Miller Chemical & Fertilizer, Hanover, PA) and 92.5% water.

7) The ProtekNet + thyme (*Thymus vulgaris*) oil treatment was implemented with a ProtekNet row cover and the row cover was treated twice a week with thyme essential oil (Aura Cacia, Frontier Natural Products Co-op, Norway, IA; same rate as above).

Field preparation and treatment implementation: On March 25th, eggplant was seeded in the greenhouse and was transplanted six weeks later on May 7th. On March 19th, 2019, the field was disked, and compost was applied at a rate of ten tons per acre. On April 4th and April 18th, and May 1st, the field was cultivated. Beds were formed, and a line of drip tape were buried per bed (Aqua Traxx 6" emitter spacing), and plastic mulch was laid on May 1st. Nature Safe 10-0-8 (Darling Ingredients Inc, Irving, TX) was also incorporated into the soil at 50 lbs. N per acre on May 1st. On July 1st, 1.4 pounds of calcium nitrate was incorporated by fertigation. On May 7th, the field was planted at a fifteen-inch spacing between plants, and treatments were implemented. Row covers were implemented at this time on May 7th. These row covers were removed June 11th as 50% of plants were flowering. Insecticides were sprayed on May 14th, May 23rd, June 4th, June 21st, and July 9th. Organic insecticides were rotated between Entrust SC and Pyganic, while the conventional insecticides were rotated between Mustang Maxx and Scorpion 35SL. Insecticides were applied at the industry recommended concentrations. These rates were 0.0496 kg/acre for Scorpion 35SL, 1.36 kg/acre for Entrust, 0.0104 kg/acre for Mustang Maxx, and 0.0227 kg/acre for Pyganic 5.0. Sprays were made using an electric powered Jacto backpack sprayer (Jacto, Pompeia, São Paulo) and were completed at a spray volume of 182 gallons per acre. I manually weeded with hoes between rows after planting as needed to suppress weeds. Essential oils were sprayed twice a week using a spray bottle until row cover removal at a rate of 12.5 fluid ounces per ten feet of row. We selected this rate and frequency to test the maximum realistic rate for our field study.

Field trial design 2020: The 2020 trial mirrored the 2019 trial with two exceptions: 1) Only black plastic mulch was used; 2) the essential oil treatments were replaced by a clarified 70% neem extract (Safer Brand, Woodstream Corporation, Lititz, PA) and a commercial mix of rosemary oil, geraniol, and peppermint oil (Essentria IC^3, Envincio LLC, Cary, NC) and were applied directly onto the plants without row covers. The reason for the removal of the silver plastic mulch was due to poor flea beetle management in addition to reduced plant height. Because of the removal of silver plastic mulch during the 2020 season, plastic mulch was removed as a treatment variable for all statistical tests. The statistical design in 2020 was a complete randomized block with only the IER treatments randomized on black plastic mulch (Table 1). I also decided to spray essential oil concentrates directly on plants due to concerns about the feasibility of farmers using row covers in addition to spraying essential oils. The Essentria IC^3 oil treatment was treated twice a week with an essential oil mixture made from concentrate and mixed at a rate of three fluid ounces Essentria IC^3 per gallon water with 2.5% spreader sticker adjuvant (Nu Film P). The neem (*Azadirachta indica*) oil treatment was treated directly onto greens twice a week with neem oil prepared from a concentrate and mixed at a rate of one fluid ounce per gallon of water with 2.5% spreader sticker adjuvant (Nu Film P).

Field preparation and treatment implementation: Eggplant was seeded May 7th in the greenhouse and transplanted six weeks later on June 18th. On May 27th, the field was disked. On June 2nd, compost was applied at a rate of ten tons per acre and was cultivated into the soil. On June 8th, the field was cultivated, beds were formed, a line of drip tape was buried in each bed (Aqua-Traxx 6" emitter spacing), and plastic mulch was laid. Nature Safe 10-0-8 (Darling Ingredients Inc, Irving, TX) was also incorporated into the soil at 50 lbs. N per acre on June 8th. On July 24th, 0.7 pounds of calcium nitrate was incorporated by fertigation. On June 18th, the field was planted at a fifteen-inch spacing between plants, and treatments were implemented. Row covers were implemented at this time on June 18th. These row covers were removed July 22nd as 50% of plants were flowering. Insecticides were sprayed on July 7th, July 15th, July 21st, and July 30th. Organic insecticides were rotated between Entrust SC and Pyganic, while the conventional insecticides were rotated between Mustang Maxx and Scorpion 35SL. Insecticides were applied at the industry recommended concentrations. These rates were 0.0496 kg/acre for Scorpion 35SL, 1.36 kg/acre for Entrust, 0.0104 kg/acre for Mustang Maxx, and 0.0227 kg/acre for Pyganic 5.0. Sprays were made using an electric powered Jacto backpack sprayer (Jacto, Pompeia, São Paulo) and were completed at a spray volume of 182 gallons per acre. We manually weeded with hoes between rows after planting as needed to suppress weeds. Essential oils were sprayed twice a week until row cover removal at a rate of 5 fluid ounces of diluted spray per ten feet of row. This rate was lower than in previous trials as the essential oil mixtures were sprayed directly onto the plant rather than on the larger surface area of a row cover. Additionally, all essential oil sprays were made before 9:00 a.m. when temperatures were low as previous trials in brassicaceous greens had phytotoxic burns (Brockman et al. 2020).

Data collection

Flea beetle monitoring: I made collections by vacuum sampling with an inverted leaf blower after the final harvest (STIHL 5H 56C, STIHL, Inc. USA). I modified protocols from Swezey et al., (2014). Within each plot, six plants were vacuumed for two seconds each. These samples were bagged and later analyzed under magnification to determine the number of individual pest species.

Leaf damage data: To determine the impact of IER treatments on flea beetle damage, I measured the number of shot holes per leaf area. During the 2019 season, I took six leaves per treatment and took a standard 3*5-inch section where I counted shot holes. During the 2020 season, I took five leaves per plot and counted both shot hole number and overall leaf area. I measured leaf area using the application, LeafByte, on an Apple iPhone SE (Zoe Getman-Pickering, Cornell University, Ithaca, New York). The application LeafByte, estimates total leaf area from photographs of leaves. After the leaf area was estimated, I calculated the number of damage holes per cm^2 of leaf area.

Harvest data: I harvested eggplant two to three times a week during both growing seasons. I harvested eight times during the 2019 season and five times during the 2020 season. During these harvests, I followed three plants per plot and harvested fruits that were 0.7 pounds and heavier. I would then grade fruits using USDA guidelines and make note of why the fruit was graded as it was.

Data analysis: These experiments are designed as split-plots with a randomized complete block in the main plot. The main plot factor is plastic mulch type while the split plot factor is IER levels. To determine the impact of the IER treatments and plastic mulch treatments on flea beetle abundance, damage, and crop yield we analyzed the data using general linear mixed models (GLMM). We conducted analyses for the 2019 and 2020 trials independently given that the essential oil treatments and plastic mulch treatments differed between trials. In 2019, for each dependent variable (flea beetle abundance, shot-holes per 45 cm^2, plant height at flowering, marketable yield), we incorporated IER treatment and plastic mulch treatment as a fixed effects within models. Given that the plastic mulch treatment was represented by main plots (N=8; 2 per block) and the IER treatment was represented by subplots (N=56; 14 per block), I incorporated a different random effect structure for each fixed effect. The error structure for the plastic mulch treatment was constructed as a whole plot error term (plastic treatment × block). The error structure for the IER treatment was structured as a subplot error term (block).

In 2020, for each dependent variable (flea beetle abundance, shot-holes per 45 cm^2, plant height at flowering, marketable yield), we incorporated IER treatment as a fixed effect within models. In order to nest the randomized block design into the model structure, we incorporated block as a random effect within models. Following GLMM, we performed Tukey's Post hoc tests to determine pairwise comparisons of different treatment levels if the overall treatment effect was significant. We tested all models for normality using a Shapiro-Wilk test on model residuals. If model residuals were not normally distributed, we transformed independent variables with square-root or log transformations until residual distributions met the assumptions of normality. For flea beetle abundance at flowering, plant height at flowering, and shot-holes per 45 cm^2 in 2019, transformations did not improve the assumptions of normality. In this case, we analyzed data with a non-parametric Kruskal Wallis test. All analyses were conducted in the program R (3.3.3) using the packages ‘LME4’, ‘stats’, and ‘emmeans’.

Results summer 2019

Vacuum sampling at flowering: There was a significant effect of IER treatment on the number of flea beetles found by vacuuming when row covers were taken off at flowering in 2019 (Table 7, Table 8). Flea beetles species present included the eggplant flea beetle (*Epitrix fuscula*) and the tobacco flea beetles (*Epitrix fasciata*). The control treatment had a higher number of flea beetles than the ProtekNet row cover ($p = 0.03$), and ProtekNet + rosemary row cover ($p = 0.03$). The control also had a marginally higher number of flea beetles than the Agribon row cover ($p = 0.06$) and the ProtekNet + eucalyptus row cover ($p = 0.06$). There were no other significant pairwise comparisons of the IER treatment and there was no effect of plastic mulch color.

Vacuum sampling after last harvest: There was no significant effect of IER treatment or mulch treatment on flea beetle number after the last harvest in 2019 (Table 7, Table 8).

Shot holes: There was a significant effect of IER treatment on the number of shot holes caused by flea beetles at the flowering stage in 2019 (Table 7, Table 8). A Tukey post hoc test revealed that the organic insecticide treatment had more shot holes than the conventional insecticide treatment ($p = 0.02$), Agribon row cover ($p < 0.01$), ProtekNet row cover ($p < 0.01$), ProtekNet + eucalyptus ($p < 0.01$), and ProtekNet + rosemary ($p < 0.01$) treatments. The control had more shot holes than the Agribon row cover ($p < 0.01$), ProtekNet row cover ($p < 0.01$), ProtekNet + eucalyptus ($p < 0.01$), and ProtekNet +

rosemary ($p < 0.01$) treatments. There were no other significant pairwise comparisons of IER treatment and there was no effect of plastic mulch treatment.

Plant height in centimeters at flowering: I took data on plant height in the 2019 season as plants grown on silver plastic appeared stunted and were chlorotic. There was a significant effect of IER treatment on the height in 2019 (Table 7, Table 8). The control treatment had less growth than the Agribon row cover ($p < 0.01$), ProtekNet row cover ($p < 0.01$), ProtekNet + eucalyptus ($p < 0.01$), and ProtekNet + rosemary ($p < 0.01$). The organic insecticide treatment had less height than the Agribon row cover ($p < 0.01$), ProtekNet row cover ($p < 0.01$), ProtekNet + eucalyptus ($p = 0.02$), and ProtekNet + rosemary ($p < 0.01$). The conventional insecticide treatment had less growth than the Agribon row cover ($p = 0.03$), ProtekNet row cover ($p = 0.04$), and ProtekNet + rosemary ($p = 0.03$). There were no other significant pairwise comparisons of IER treatment and there was no effect of the plastic mulch treatment.

Marketable yield: There was no significant effect of IER treatment or plastic mulch treatment on marketable yield in 2019 (Table 7, Table 8).

Results summer 2020

Vacuum sampling at flowering: There was a significant effect of the IER treatment on flea beetles found by vacuuming when row covers were taken off at flowering in 2020 (Table 7, Table 8). Flea beetles species present included the eggplant flea beetle (*Epitrix fuscula*) and the tobacco flea beetles (*Epitrix fasciata*). The control treatment had more flea beetles than the neem essential oil ($p = 0.002$), conventional insecticide treatment ($p < 0.001$, organic insecticide ($p = 0.009$), ProtekNet row cover ($p = 0.005$), and Agribon ($p = 0.009$). The essentria essential oil mixture had more flea beetles than the conventional insecticide treatment ($p = 0.009$). There were no other significant pairwise comparisons.

Vacuum sampling after last harvest: There was no significant effect of IER treatment on flea beetle number after the last harvest in 2020 (Table 7, Table 8).

Marketable yield: There was a significant effect of IER treatment on marketable yield in 2020 (Table 7, Table 8). A Tukey post hoc test revealed that the conventional insecticide treatment had higher yields than the neem essential oil ($p = 0.006$) and the essentria essential oil mixture ($p < 0.001$). The ProtekNet treatment had higher yields than the neem essential oil ($p = 0.006$) and the essentria essential oil mixture ($p < 0.001$). The Agribon treatment had marginally higher yields than the essentria essential oil mixture ($p = 0.08$). There were no other significant pairwise comparisons.

Discussion: Within both the 2019 and 2020 growing seasons, flea beetle pressure was low and therefore treatment results reflect the efficacy of these treatments in a low pest pressure environment. This study found that row covers are an effective control for flea beetles within eggplant cropping systems. Both the fine-mesh row cover (ProtekNet) and the spun-bonded row cover (Agribon) had similar or better control of flea beetles than all other treatments. At the time of row cover removal, the row cover treatments always reduced flea beetles and their associated damage significantly below the control treatments (Table 7). Flea beetle populations greatly increased over the growing season but there were no significant differences between treatments later in the season. The trend of increasing flea beetle numbers is consistent with other studies looking at the eggplant flea beetle (Diaz et al. 2004). I also saw during the 2019 season that all plants within row cover treatments were significantly taller at flower onset than the control and organic insecticide treatments (Table 7). During the 2019 season, I used reflective silver plastic mulch as a comparison against black plastic mulch and found that there was no statistical difference between the plants grown on the two plastic mulches. Additionally, plants grown on silver plastic mulch appeared chlorotic compared to those grown on black plastic mulch. Due to these results, I decided to grow all treatments on black plastic in 2020.

Despite evidence from laboratory studies of essential oils (Rojht et al. 2012; Mostafiz et al. 2018; Vendan et al. 2017; Neupane et al. 2019) and studies involving the intercropping of eggplant and culinary herbs (Sujayanand et al. 2015; Mutisya et al. 2016), my study did not find positive effects from the spraying of plant essential oils or commercial essential oil concentrates. I did not see any benefit from spraying essential oil mixtures on the ProtekNet in 2019. The commercial essential oil mixtures did not perform well in 2020 as they had significantly lower yields than both the ProtekNet row cover and the conventional insecticide regime (Table 7). Furthermore, though there was no statistically significant difference, the Agribon row cover yielded twice the weight of marketable fruits than either of the commercial essential oil treatments. I believe this drop in yield was due lingering effects of essential oils which may have continued to repel pollinators. However, the decrease in yield may have been due to minor phytotoxic burns that the essential oils caused when sprayed directly on the crop. I found phytotoxicity burns when rosemary essential oil and the commercial neem concentrate was sprayed directly on brassicaceous leafy greens (Brockman et al. 2020, Chapter 2). While researchers have determined that the essential oils from coriander (*Coriandrum sativum*), tobacco (*Nicotiana tobacum*), and fenugreek (*Trigonella foenum-graecum*) are non-phytotoxic for insect repellant sprays (Atanasova et al., 2017a; Atanasova et al., 2017b), further research is needed to look into the mechanisms of the phytotoxicity experienced in these trials and determine which essential oils are non-phytotoxic when sprayed directly on plants.

The two insecticide spray rotations had very different efficacies. I did not see any benefit from using the organic insecticide treatment within our trials. The organic insecticide treatment rarely differed from that of the control and both had reduced height and increased insect damage during the 2019 growing season. These results are consistent with those of my 2019 study of organic insecticides on brassicaceous leafy greens (Brockman et al. 2020, Chapter 2). However, the results of my study are in contrast with studies from Arkansas and New York where spinosad was found to be highly effective at controlling *Epitrix fuscula* populations (McLeod et al. 2002; Seaman and Lange 2017).

Due to the cost of organic insecticides, my study provides evidence that organic eggplant growers need better options to control flea beetles that are compliant with Organic Certification requirements. The conventional insecticide rotation performed intermediately within my trials. In 2019, the conventional insecticide treatment had intermediate levels of shot-hole damage and in 2020, the conventional insecticide treatment had few flea beetles and was one of the highest yielding treatments.

I believe that the lack of differences in yield during the 2019 season and the relatively low differences in yield within the 2020 season were due to minimal pressure from flea beetles during the early season. Research shows that eggplants become increasingly tolerant of flea beetle damage across the season. If transplants develop a root system and start growing with minimal damage, flea beetles rarely cause economic harm (Diaz et al. 2004). The vacuum samples that we took at the start of flowering and at the end of harvest included the vacuuming of five plants within each treatment replicate. At the onset of flowering, all treatments averaged fewer than one flea beetle per plant. While we did see higher numbers of flea beetles later in the season, these flea beetles were still relatively low and arrived too late to noticeably harm yields. Thresholds for the treatment of flea beetle infestations vary by size of the plant and are 4 beetles/plant when the plant is three to six inches tall and 8 beetles/plant when plants are taller than six inches tall (Delahaut 1999). I attempted to increase the impact of flea beetles in 2020 by planting later in the season to coincide with higher flea beetle populations (Diaz et al. 2004). While I observed higher flea beetle abundance, these densities still only had minimal impact on yield. Because of these low numbers of beetles, I saw a decrease in flea beetle abundance for some treatments without a corresponding increase in yield.

The low abundance of flea beetles and low flea beetle damage on eggplant resulted in no pest control treatment outweighing the untreated control treatment. This suggests that in years of low flea beetle pressure, best management would be to do nothing at all to avoid the costs of pest control implantation. However, many growers experience high flea beetle pressure and therefore my studies do not provide results that are highly relevant to these scenarios. This limitation might be overcome through additional years of research or through the addition of new research sites. Additionally, the collection of leaf damage data in 2020 could not be compared to the data I took in 2019. When I originally went to collect data on this measurement in 2020, there was minimal damage, and it was decided to push this data collection back until damage was observed. This data was not collected until harvest was complete and could not be compared to the leaf damage data in 2019 as this was taken at flower onset. Leaf damage data in 2020 should have been taken at flower onset, even with low damage levels, so that a proper comparison could be made. Furthermore, these trials were done with small plot sizes of ten feet and pest control results may differ when production of eggplant is scaled to a commercial level.

My study provides support for further research into row cover use in eggplant systems. While my study did not provide strong support for yield benefits from row covers in this system, the sporadic nature of flea beetle population sizes suggests that a study is needed to capture treatment differences when high pressure from flea beetles occurs early in the season. Growers must consider the pest pressure their crop will experience when developing a flea beetle management system. As row covers should be placed over plants at transplant, this information will need to be determined by looking at past pest pressure as well as planting size. Small plantings of eggplant can easily be overwhelmed by flea beetles while larger plantings often have less damage per plant (Diaz et al. 2004). My research demonstrates that less expensive row covers such as the spun-bonded Agribon cover, are competitive with more expensive covers such as that of the fine-mesh ProtekNet cover. My study did not find support for the use of organic insecticides, silver reflective mulch, or essential oil sprays when flea beetle pressure is low.

Conclusions: In conclusion, I found that row covers performed better than both the organic insecticide treatment and the untreated control within an eggplant cropping system. Organic insecticides rarely controlled flea beetles better than the untreated control. I found that plant essential oils did not improve flea beetle management when sprayed on row covers and that these essential oils decreased yields when sprayed directly on eggplant. I also found that silver reflective mulch did not have statistical effects on pest pressure or yield. Conventional insecticides provided flea beetle management superior to that of organic insecticides and the untreated control. The population of flea beetles can vary greatly from location to location and knowledge of this should inform management decisions. In areas and times where flea beetle pressure is high, row covers can provide organic producers with an effective management tactic that will work with organic certification requirements.

Table 6. Description of the insecticide, essential oil, and row cover (IER) treatments used within the eggplant field trials.

Summer Trial 2019†	
Control	No spray, no row cover
Organic insecticide	Rotation of spinosad and pyrethrins sprayed once per week[1]
Conventional insecticide	Rotation of pyrethroid and dinotefuran sprayed once per week[2]
Agribon row cover	Spun-bonded polyethylene row cover[3]
ProtekNet row cover	25-gram fine mesh row cover[4]
ProtkeNet & rosemary oil	ProtekNet row cover sprayed with rosemary essential oil[5]
ProtkeNet & eucalyptus oil	ProtekNet row cover sprayed with eucalyptus essential oil[5]
Summer Trial 2020	
Control	No spray, no row cover
Organic insecticide	Rotation of spinosad and pyrethrins sprayed once per week[1]
Conventional insecticide	Rotation of pyrethroid and dinotefuran sprayed once per week[2]
Agribon row cover	Spun-bonded polyethylene row cover[3]
ProtekNet row cover	25-gram fine mesh row cover[4]
Essentria essential oil	Essentria applied directly onto eggplant (no row cover)[6]
Neem essential oil	Neem essential oil applied directly onto eggplant (no row cover)[6]

†In 2019, all treatments were grown on both silver and black plastic mulch. In 2020, all treatments were grown on black plastic mulch. [1] Pyganic Crop Protection 5.0$_{II}$ (pyrethrins, Valent U.S.A. Corporation, MGK, Minneapolis, MN, USA) and Entrust SC (spinosad, Corteva Agriscience [Dow AgroScience], Indianapolis, IN, USA). [2] Mustang Maxx (pyrethroid, Zeta-cypermethrin, FMC Corporation, Philadelphia, PA, USA) and Scorpion 35SL (dinotefuran, Gowan Company, Yuma, AZ, USA). [3] (Agribon grade-20, Berry Plastics, Indiana, USA). [4] (ProtekNet 25 gram, Dubois, Montreal, state abbr., USA). [5] treated twice a week with rosemary essential oil or eucalyptus essential oil (Aura Cacia, Frontier Natural Products Co-op, Norway, IA, country) mixed at a 5% solution with 2.5% adjuvant (Nu Film P, Miller Chemical and Fertilizer, Hanover, PA, USA) and 92.5% water. [6] treated twice a week with a rosemary oil, geraniol, and peppermint oil mix (Essentria IC^3, Envincio LLC, Cary, NC) or neem oil was treated directly onto greens twice a week with neem oil (70% clarified hydrophobic neem extract) prepared from a concentrate (Safer Brand, Woodstream Corporation, Lititz, PA, USA) 1 fluid ounce per gallon of water with 2.5% spreader sticker adjuvant (Nu Film P).

Table 7. Mean and standard error for number of flea beetles caught by vacuum, leaf damage (shot holes per 45 cm2), plant height, and marketable yield for the insecticide, essential oil, and row cover treatments during the eggplant trials.

Summer 2019					
Treatment	Flea beetles (flowering)	Flea beetles (post-harvest)	Shot holes per 45 cm^2	Height (cm)	Marketable yield per plant
Control	1.3±0.4B	7.0±1.0A	5.2±1.2BC	43.8±0.6C	2.4±0.2A
Organic insect.	0.9±0.4AB	8.1±0.9A	6.7±1.8C	45.9±0.6C	2.4±0.3A
Conventional insect.	0.6±0.4AB	5.4±1.4A	2.4±0.8AB	49.8±0.4BC	2.7±0.3A
Agribon	0.1±0.1AB	5.6±1.3A	0.4±0.2A	62.9±0.7A	2.2±0.3A
ProtekNet	0.00±0.0A	4.8±0.9A	0.1±0.1A	59.8±0.6A	3.0±0.3A
ProtekNet + eucalyptus	0.1±0.1AB	8.8±1.6A	0.4±0.4A	56.8±0.5AB	2.2±0.3A
ProtekNet + rosemary	0.00±0.0A	8.7±1.2A	0.4±0.2A	59.9±0.4A	2.9±0.2A
Summer 2020					
Treatment	Flea beetles (flowering)	Flea beetles (post-harvest)	Shot holes per 45 cm^2	Height (cm)	Marketable yield per plant
Control	4.3±0.5c	30.5±7.3a			1.0±0.2ab
Organic insect.	0.8±0.3ab	29±8.8a			1.3±0.3ab
Conventional insect.	0.00±0.0a	45.3±19.4a			2.1±0.2a
Agribon	1.0±0.7ab	50.8±30.8a	N/A	N/A	1.6±0.4ab
ProtekNet	0.8±0.5ab	40.8±8.6a			2.1±0.4a
Neem essential oil	0.5±0.3ab	40.3±17.9a			0.7±0.2b
Essentria essential oil	2.3±0.6bc	11.8±1.6a			0.5±0.1b
Common letters denote means are not significantly different from one another within season, as determined by Tukey's HSD at a 0.05 alpha. Capitalization used for 2019 and lowercase letters used for 2020.					

Table 8. Statistical analysis of effect of IER treatment, plastic mulch color, and interaction between IER treatment and plastic mulch color on number of flea beetles found, flea beetle damage per unit leaf area, plant height, and eggplant marketable yield.

Data	F-statistic	P-value	Numerator degrees of freedom	Denominator degrees of freedom
Summer 2019				
Flea beetles (flowering)	-	-	-	-
Treatment (IER)	3.5	<0.01	6	36
Plastic mulch	0.51	0.53	1	3
Flea beetles (post-harvest)	-	-	-	-
Treatment (IER)	1.83	0.12	6	36
Plastic mulch	0.71	0.41	1	3
Shot holes per 45 cm^2	-	-	-	-
Treatment (IER)	9.31	<0.01	6	36
Plastic mulch	0.18	0.70	1	3
Height in centimeters	-	-		
Treatment (IER)	11.93	<0.01	6	36
Plastic mulch	5.35	0.10	1	3
Marketable yield per plant	-	-	-	-
Treatment (IER)	0.90	0.51	6	36
Plastic mulch	5.67	0.10	1	3
Summer 2020				
Flea beetles (flowering)	-	-	-	-
Treatment (IER)	8.21	<0.01	6	18
Flea beetles (post-harvest)	-	-	-	-
Treatment (IER)	1.31	0.3	6	18
Marketable yield per plant	-	-	-	-
Treatment (IER)	5.35	<0.01	6	74
* Kruskal-Wallis test was used for this statistic				

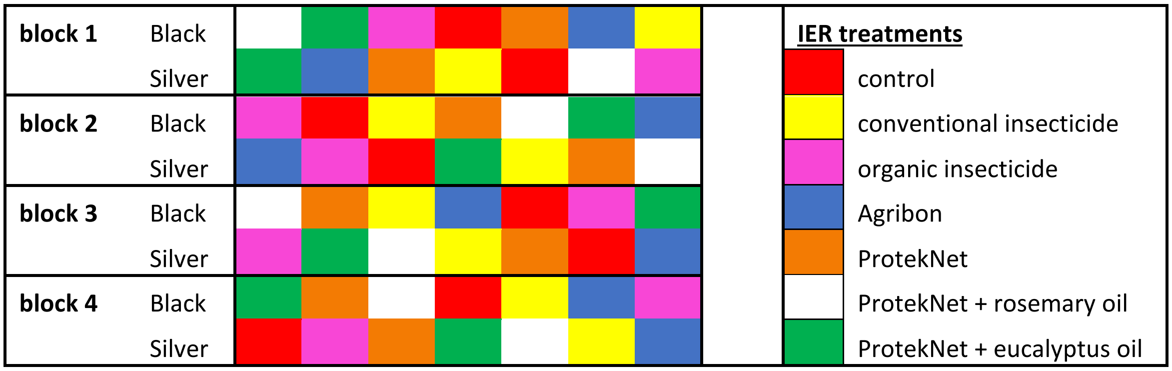

Figure 2. Eggplant 2019 field design. In the 2019 field season, we had seven IER treatments that were replicated on both black and silver plastic mulch. IER stands for insecticides, essential oils, and row covers. A control was also included with the other IER treatments. All plots were ten feet long and included eight plants.

CHAPTER 4

Summary and implications

Summary and implications

Controlling flea beetles through the spraying of insecticides has long been the standard within agronomic crops such as canola (*Brassica napus*) (Knodel, 2017) and corn (Nutter et al. 2003). This simple method of pest management has been mirrored by growers of vegetable crops on small acreage. Relying solely on insecticides runs the risk of flea beetle's developing resistance which has been documented on several occasions (Andersen et al. 2006; Walgenbach and Schoof 2016; Zimmer et al. 2014). The goal of my thesis was to examine pest management strategies for their ability to control flea beetle damage, increase crop quality, and reduce insecticide usage. These pest management strategies could then be incorporated into an IPM system.

Insecticides had mixed results within the eggplant and brassicaceous leafy green trials. Within the brassicaceous greens chapter (Chapter 2), organic insecticides were not statistically different than the untreated control for flea beetle presence and damage in both arugula trials and one of the two mizuna mustard trials. Within the eggplant chapter (Chapter 3), organic insecticides were not statistically different to the untreated control for flea beetle presence and damage during both seasons. This is important information for growers of organic vegetable crops impacted by flea beetles. This information also suggests that other insect pests may not be properly controlled by the OMRI insecticides in these studies. Conventional insecticides were observed to have intermediate effects on flea beetle populations and damage. In the fall greens trial, conventional insecticides lowered both flea beetle numbers as well as damage. They also lowered flea beetle numbers in the 2020 eggplant trial and lowered damage in the spring greens trial. For conventional growers, conventional insecticides still provide control for most of the flea beetle population and the correlated damage. However, the damage seen within our greens trial indicates that greens that are only sprayed with the conventional insecticide rotation may not meet the quality thresholds for some markets.

The essential oils from thyme, rosemary, eucalyptus, neem and the mixture of rosemary, peppermint, and geraniol were not a viable form of pest control within the field trials. These essential oils did not affect flea beetle presence or flea beetle damage when the essential oils were sprayed on row covers in the spring greens trial and the 2019 eggplant trial. When sprayed directly on the plants, neem essential oil lowered flea beetle presence in the 2020 eggplant trial and rosemary essential oil lowered flea beetle presence and damage in the fall mizuna mustard crop. Phytotoxicity was a reoccurring problem within the essential oil plots. The thyme essential oil used in the spring greens trial was highly phytotoxic while the neem and rosemary essential oils used in the fall greens trial caused minor phytotoxic burns. While no phytotoxicity was observed when spraying the essential oils on the eggplant, no flea beetle control was observed in 2019 when rosemary and eucalyptus sprays were made on the row cover and a yield loss was observed in 2020 when neem and the rosemary, peppermint, and geraniol was sprayed directly on the plant. In the 2020 season, the plots sprayed with essential oils did not produce fruit for the first three harvests which occurred over a week and a half time period. A possible reason for this is that residue from essential oils may have deterred pollinators from visiting flowers. A second possible reason for this delay in yield is that the essential oils may have caused minor phytotoxicity burns and either damaged the flowers or delayed flowering. Further research is needed to understand the nature of phytotoxicity and to develop means of controlling this phytotoxicity. We believe that much of the phytotoxicity was due to essential oils heating up on the thin leaf surface of the brassica crops. Further, I believe that the yield loss seen in the 2020 eggplant season was due to lingering essential oils discouraging pollination. If research can correct issues with phytotoxicity and industries can make cost effective essential oil products, essential oils may become a viable form of pest control.

The silver plastic mulch used within the 2019 eggplant trial did not affect the flea beetle presence or the damage due to flea beetles when compared to black plastic mulch. Additionally, plants grown on silver plastic mulch appeared chlorotic when compared to those grown on black plastic mulch. While these studies found no beneficial effects of silver plastic mulch, other studies haves seen pest damage reduced with the use of silver plastic mulch. Throughout the eggplant trials, flea beetle populations were very low. Flea beetle populations never reached a threshold that would have warranted insecticide use in an IPM system. This information is important for growers as some fields may not require control of flea beetle populations.

Row covers were consistently observed to control flea beetle populations in both the brassicaceous greens and eggplant trials. Shot hole damage was lower in the row cover treatments than in the untreated control during all measurements in both crops. Higher temperatures were observed underneath the Agribon row cover. These higher temperatures led to a loss in arugula crop quality within the spring trial but not the fall trial. While both types of the row covers have potential for further use, growers using Agribon should pay attention to temperature in crops that are temperature sensitive. A possible challenge with the use of row covers is the initial cost of buying the row cover itself and the labor needed to place the row cover over the crop. The Agribon row cover is considered cost effective and is already being used by many growers as a form of season extension. Agribon is typically used for one season. This Agribon row cover is relatively inexpensive and could be even more cost efficient by both extending the season and controlling insect pests. The ProtekNet row cover is much more expensive, costing approximately four times that of Agribon. However, my research shows that ProtekNet is a better row cover during periods of the year when hot weather is common. With the difference in price between ProtekNet and Agribon, it would be necessary for ProtekNet to last several years to be cost effective. My research lasted for two growing seasons, during that period of time, the ultraviolet light resistant ProtekNet did not deteriorate or form holes. Sellers of ProtekNet are marketing the lighter weight forms of ProtekNet as lasting two to three years while the medium and heavy weight forms as five to ten years.

A longer term study using ProtekNet is necessary to determine a reasonable life expectancy for this row cover.

My research found that row covers were the most effective and most consistent form of pest protection. Within the eggplant study, however, the low pest pressure environment did not always equate row covers with an increase in marketable yield. The eggplant trials experienced very low pest pressure and additional studies must look at these alternative pest control strategies within systems that have high levels of pest pressure. A multi-site eggplant field study of flea beetle populations is needed to determine indicators for when pest pressure will be s. Additionally, while my studies did not provide support for the use of essential oil sprays, many laboratory studies have shown that essential oils hold insect repellant and insecticidal properties. Further research is needed to determine the reasons for the phytotoxicity seen in my trials and to determine the quantity of sprays needed to control pests. Lastly, I believe that long term studies of row covers are needed to ascertain the product life expectancies of these row covers. With information on product life expectancy, recommendation can be made for growers as to whether this pest control strategy is economically viable.

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Brockman, R., Kuesel, R., Archer, K., O'Hearn, K., Wilson, N., Scott, D., Williams, M., Bessin, R. and Gonthier, D. The impact of plant essential oils and fine mesh row covers on flea beetle (Chrysomelidae) management in brassicaceous greens production. *Insects*. **2020**, *11*(10), 714.