HABITAT MANAGEMENT FOR BENEFICIAL INSECTS IN MICHIGAN CUCURBIT AGROECOSYSTEMS

By

Nicole F. Quinn

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ABSTRACT

HABITAT MANAGEMENT FOR BENEFICIAL INSECTS IN MICHIGAN CUCURBIT AGROECOSYSTEMS

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Natural enemies and pollinators require additional cover, habitat resources, and minimal disturbance, which are not found in conventional agricultural fields. The purpose of this thesis was to quantify the effects of habitat management for conservation biological control and pollination in Michigan cucurbit fields and their impacts on the arthropod community and yield. In the first study, the effects of mulch and reduced tillage on the arthropod community in acorn squash were examined. Natural enemies of weed seeds and insects were expected to be more abundant in strip-tilled, mulched plots than full-tilled, unmulched plots. Foliar observations did not differ among treatments. Treatment effects on ground-dwelling arthropod activity density and weed seed survival were recorded, though they varied by year. Full-tilled plots tended to have higher granivore activity densities than strip-tilled plots. In the second study, the effects of floral intercropping on beneficial insects and yield in a commercial cucumber field were examined. Beneficial insect abundance was expected to greater in plots containing flowers, with more beneficials found in the rows closest to the floral strips. Some floral treatments successfully attracted more beneficial insects than others, but the beneficials did not disperse out to the cucumber plants. Cucumber yield was generally unaffected. Habitat management for beneficial insects still holds a great deal of potential to improve yield, profitability, and sustainability, but many questions as to their application in cucurbit agroecosystems remain.

This thesis is dedicated to my sister, Leanne, who was diagnosed with cancer during my master's program. Her trials have made graduate study seem easy by comparison. I look forward to enjoying many more years together.

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CHAPTER 1:

Habitat complexity and arthropod management in cucurbits.

Introduction

Squashes, cucumbers, pumpkins, melons, and other gourds are domesticated members of the plant family Cucurbitaceae. There are 95 genera and over 950 species within this diverse group (Schaefer *et al.* 2011). Originally domesticated in pre-Colombian Mesoamerica and India approximately 10,000 years ago, today hundreds of cucurbit varieties are grown worldwide for food, decoration, and other purposes (Ranere *et al*. 2009, Zheng et. al 2013).

Cucurbits are economically important crops in the United States. In 2013, 140,040 acres of pumpkins, squash and cucumber were planted, yielding over 2.5 million pounds of saleable fruit valued at over $602 million (USDA/NASS 2014). In Michigan alone, pumpkins, squash and cucumber were grown on over 45,400 acres and valued at over $43.2 million (USDA/NASS 2014). The state accounts for 37% of all U.S. acreage for these crops.

Insect pests in cucurbits. Insect damage is one of the main causes of reduced yield in cucurbits. Among the most deleterious pests in Midwestern cucurbits are striped cucumber beetles (*Acalymma vittatum*, Coleoptera: Chrysomelidae), spotted cucumber beetles (*Diabrotica undecimpunctata*, Coleoptera: Chrysomelidae), squash bugs (*Anasa tristis*, Hemiptera: Coriedae), squash vine borer (*Melittia cucurbitae*, Lepidoptera: Sesiidae), thrips (*Frankliniella* sp., Thysanoptera: Thripidae), and two-spotted spider mites (*Tetranychus urticae*, Trombidiformes: Tetranychidae). Cucurbits for the fresh market that are damaged by insects receive lower grades and may not be approved for sale (United States Standards for Grades of

Cucumbers 1997, United States Standards for Grades of Fall and Winter Type Squash and Pumpkin 1997). Herbivory in cucurbits can reduce yield by diverting energetic resources away from fruit production and towards defense (Hladun and Adler 2009). In addition to direct damage, insects can also harm cucurbits by vectoring disease through feeding and depositing frass. For example, spotted cucumber beetles have been shown to effectively transmit bacterial wilt (*Erwinia tracheiphila*) in squash (Shapiro *et al.* 2014).

Chemical control. Current insect management practices in cucurbit crops are highly dependent on a relatively narrow range of insecticides, which inadequately control several key pests and are cause for environmental concern. A large-scale conventional commercial cucumber grower's standard insect pest management program in Michigan consists of about 8 broad-spectrum insecticide applications in any given growing season. Expenditures for insect management in these crops can easily exceed $100 per acre for pesticide applications alone (Barnett 2012). Despite this rate of pesticide application, yield losses due to insects remain high. Fungicides are also used extensively in cucurbits, which may have negative implications for beneficial insects. Pollinators can be particularly vulnerable to the synergistic effects of multiple pesticide residue exposure, whether encountered directly on the plants or from spray drift (Sanchez-Bayo and Goka 2014).

Natural enemies. Several parasitoids are known to attack squash bugs (Worthley 1923, Olson *et al.* 1996). However, these parasitoids often only provide significant control after squash bug populations have increased beyond economic thresholds (Decker and Yeargan 2008). The majority of the natural enemies of cucurbit pests in the North Central region are generalist predators. Important generalist natural enemies include ground-dwelling spiders (Linyphiidae, Lycosidae, Salticidae), ground beetles (Carabidae), damsel bugs (Nabidae), big-eyed bugs (Geocoridae), and lacewing larvae (Chrysopidae) (Decker and Yeargan 2008, Snyder and Wise 2001). Many of these generalist natural enemies are more abundant and effective in systems that provide greater habitat complexity and reduced disturbance (Landis *et al.* 2000). In zucchini, increased non-crop vegetation led to improved pest control and natural enemy abundance in cropped areas (HansPetersen *et al.* 2010, Hinds and Hooks 2013). Control of squash bugs by carabids and spiders was improved in cucumber and squash fields with increased structural complexity (Snyder and Wise 2008). Increasing structural complexity through mulch applications while decreasing disturbance through the use of conservation tillage may improve biological control in cucurbit fields.

Generalists such as ground beetles (Carabidae) and crickets (Gryllidae) can be important sources of weed seed and insect mortality in agricultural systems (Rebek *et al.* 2005, Westerman *et al.* 2008, Lundgren *et al.* 2013). Seeds consumed include common weed species such as giant foxtail (*Setaria faberi*), redroot pigweed (*Amaranthus retroflexus*), velvetleaf (*Abutilon theophrasti*), and common lambsquarters (*Chenopodium album*) (Kirk 1972, Kromp 1999, White *et al.* 2007). Seeds on the soil surface are the most readily consumed (White *et al.* 2007). Though there is some evidence that carabid larvae primarily consume seeds, they may also eat microorganisms, plant roots, or small soil-dwelling insects (Kirk 1972, Blubaugh and Kaplan 2015). Peak foraging activity of several granivorous adult carabid species occurs in the fall, synchronized with the release of grass seeds (Tooley and Brust 2002). Fresh, hydrated seeds are preferred (Law and Gallagher 2015). Taken together, the literature suggests that invertebrate granivores can be effective predators of newly dispersed weed seeds in agricultural settings.

Pollinators. In response to decreasing honey bee populations worldwide, attracting and maximizing the efficacy of wild bees and syrphids as pollinators has become of increasing interest (Isaacs and Kirk 2010, Petersen *et al.* 2013, Garibaldi *et al.* 2015). A recent review suggests that the decline in managed and wild pollinators can be attributed to the combined effects of multiple stressors, including repeated long-distance transport, increased disease transmission, increased exposure to a variety of fungicides and insecticides, and limited floral resources, which culminate in reduced pollinator abundance and diversity (Goulson *et al.* 2015). Fewer pollinators could result in decreased crop production, as approximately 35% of food crops are pollination-dependent (Klein *et al*. 2007). Maintaining habitat that supports resilient and effective wild pollinator complexes is crucial to ensure continued, sustainable food production.

In cucurbits, pollination is essential for proper fruit set, with inadequate pollination being associated with fruit abortion and low fruit quality (McGregor 1976, Stanghellini *et al.* 1997, Vidal *et al.* 2010). The main pollinators of cucurbits are honey bees (*Apis mellifera*), the common bumble bee (*Bombus impatiens*), and squash bees (*Peponapis pruinosa*), though the role of other pollinators is not well-understood (Smith *et al.* 2012). Squash bees are cucurbit specialists that are among the most effective pollinators of cucurbit crops (Hurd *et al*. 1974, Terpedino 1981, Canto-Aguilar and Parra-Tabla 2000). Information on squash bee biology is generally limited. They are wild, solitary bees that nest gregariously in the soil at depths of 12-30cm below the surface among the cucurbits that they pollinate (Mathewson 1968, Hurd *et al*. 1974). They begin foraging as early as an hour before sunrise in synchrony with the opening of cucurbit flowers (Hurd *et al*. 1974). Though univoltine, females may construct multiple nests each year, with overwintering prepupae emerging as adults the following year (Mathewson

1968). Squash bees appear to be sensitive to field management practices, such as tillage and irrigation (Shuler *et al.* 2005, Julier and Roulston 2009). Other wild pollinators have demonstrated higher pollination rates than managed pollinators in several cases (Garibaldi *et al.* 2013, Holzschuh *et al*. 2014, Blaauw and Isaacs 2014, Phillips and Gardiner 2015). In cucumbers, wild pollinators, such as bumble bees, have been shown to pollinate cucumbers more effectively than honey bees, even when managed honey bee hives are added to the field (Gajc-Wolska *et al.* 2011, Petersen *et al.* 2013). The addition of managed honey bee hives adjacent to or within cucurbit fields does not necessarily increase their abundance or density (Shuler *et al.* 2005). Therefore, developing a method to attract wild bumble bees to cucurbit fields should be a priority.

Habitat management to enhance beneficial insect activity. The drivers behind insect population dynamics in agroecosystems have been a subject of investigation and debate for decades. Perhaps one of the most well-known hypotheses generated to explain these patterns is the *resource concentration hypothesis*, which states that herbivorous insects are most abundant in monocultures as opposed to polycultures, because a monoculture consists of a large, contiguous area of a single plant species that provides all the necessary resources for certain pests (Root 1973). For natural enemies, adding diversity to an agricultural field should increase biological control because it provides alternative prey, shelter, and nesting habitat, thus increasing natural enemy abundance in what is known as the *enemies hypothesis* (Root 1973). A diverse landscape may act to drive away herbivores by presenting them with a mix of attractive crop and unattractive noncrop plant species, of which the noncrop species may be less appropriate oviposition sites. If the herbivore encounters more inappropriate oviposition sites than appropriate ones, it is more likely to leave a given area without reproducing, thus reducing pest pressure. This is known as the *appropriate/inappropriate landings hypothesis* (Finch and Collier 2000). Pollinator movement may also be explained by this hypothesis. Solitary bees have been observed to spend less time in plots that lack appropriate pollen or nectar resources (Collevatti *et al.* 1997). If a bee repeatedly land on plants that are low-quality foraging sources, then it is more likely to leave the plot in search of better pollen and nectar. This could have negative implications for crop pollination and yield.

Beneficial insects require resources that are not typically found in conventional agricultural fields, such as pollen, shelter, and a stable microclimate. The goal of habitat management for conservation biological control and pollination enhancement is to provide additional food and shelter so that beneficial insects will be more abundant and effective within cropped areas (Landis *et al.* 2000). Modifications to the habitat in an agricultural field can be in the form of living plants or their residues, both of which can be important in supporting beneficial insects (Langellotto and Denno 2004, Tsitsilas *et al.* 2001). Insectary plants and windbreaks are living additions to agroecosystems that can provide insects with shelter and nutritional resources that are not provided by the crop itself. Non-crop flowering plant species are rarely found adjacent to or within agricultural fields due to intensive herbicide use and the perception of revenue loss from uncultivated space, but there is increasing support for the use of habitat diversification as a means to increase the number, diversity and efficacy of beneficial insects (Goverde *et al.* 2002, Carvell *et al.* 2006, Blaauw *et al*. 2012). Mulches and nest boxes are manipulations that can provide nesting habitat, shelter, and favorable microclimate to beneficials.

Habitat can be managed at two different spatial scales: at the landscape or local level. Landscape level habitat management can involve increasing the amount of natural area within farms and can be effective (Tscharntke *et al* 2008). The management of expansive landscapes is hindered by the fact that landowners with large contiguous areas are relatively rare, so land management decisions are often made by multiple landowners who have competing interests. Local level habitat management on the other hand is more possible for vegetable growers who typically grow annual crops that are frequently rotated; therefore these growers need habitat management methods that can be implemented over a short period of time in a well-defined agricultural field. Kremen *et al.* (2011) conclude in a meta-analysis that landscape scale habitat manipulation benefit generalist natural enemy abundance and efficacy. Generalist predators are desirable components of a biological control program because of their flexibility in prey selection, which allows them to reduce the abundance of a variety of pests. Crops can be attacked by multiple pests at once, making the attraction of generalist natural enemies to fields via habitat management an appealing option.

Intercropping, cover cropping, polycultures, and strip tillage are forms of within-field habitat manipulation that can affect the arthropod community on a local scale. Specialist, rather than generalist, natural enemies tend to benefit the most from local scale habitat manipulation (Kremen *et al.* 2012). Attracting specialist natural enemies can be useful in addressing specialist pest pressure. The parasitoid *Cotesia rubecula* for example has higher abundances in more complex local habitats, aiding in the control of the *Brassica* specialist herbivore *Pieris rapae* (Bryant *et al.* 2014). Many insects, such as cucumber beetles and squash bugs, specialize in using cucurbits as hosts. The identification of local scale habitat management techniques that benefit their natural enemies is thus of great importance.

The addition of flowering plants and fallow fields adjacent to cultivation can increase the abundance of bees and natural enemies found within the field itself (Long *et. al* 1998, Rebek *et al.* 2005, Wanner *et al.* 2006, Fiedler et al. 2008). Even plants traditionally considered to be weeds can contribute to beneficial insect enhancement. In cucurbits, natural enemy abundance was greater in fields adjacent to weeds or pigeon peas (*Cajanus cajan*) compared to bare ground (HansPetersen *et al.* 2010). Since growers eliminate weeds in and around their crops, the addition of insectary crops into undisturbed areas around a field may be a more viable option for biological control improvement in this system.

Habitat management for pollination. The vast majority of the literature on habitat manipulation concerns natural enemies and pest control rather than pollination. A meta-analysis of the effects of habitat diversification on beneficial insects could not definitively determine the effects of local versus landscape scale habitat manipulation on bees due to the relative lack of published literature on the topic (Kremen and Miles 2012). What is known is that bees tend to be sensitive to environmental changes or human activity and require additional food and resources (Tuell *et al.* 2008, Williams *et al.* 2010, Winfree *et al.* 2011). Providing additional nesting and foraging areas could protect against temporal fluctuations in pollinator resources (Williams *et al.* 2010). Preliminary evidence suggests that wild pollinators, such as the common Eastern bumble bee (*Bombus impatiens*), can pollinate cucumber more effectively than honey bees, even when managed honey bee hives are added to the field (Gajc-Wolska *et al.* 2011). Cucurbits require thorough pollination to produce viable, symmetrical fruit (Stanghellini *et al.* 1997). Therefore, attracting wild pollinators to agricultural fields should be a priority for growers.

Pollinator abundance and diversity can be affected by landscape-scale habitat resources. Landscape level factors include proximity to natural areas or other habitat resources, patch size of the resources, and quality of those resources within the landscape (Kennedy *et al*. 2013). When grown adjacent to wooded or natural areas, the abundance of wild bees in cucumber fields tends to increase (Lowenstein *et al.* 2012, Smith *et al.* 2013). This may be due to the fact that native bees are often sensitive to environmental disturbances and require additional food and nesting resources that are more easily obtained from natural areas (Tuell *et al.* 2008, Williams *et al.* 2010, Winfree *et al.* 2011). Proximity to natural areas can increase the amount and diversity of wild bees in agricultural fields by providing nesting and nutritional resources, increasing the landscape's carrying capacity. The size and quality of the landscape-level resources available are also factors in pollinator diversity and abundance. In Michigan and other temperate areas, larger patches of undisturbed, diverse floral resources enhance pollinator and natural enemy activity more than small patches of less diverse floral resources or unmanaged areas (Meyer *et* al. 2007, Blaauw and Isaacs 2012, 2014). However, the effects of landscape fragmentation and vegetative diversity on wild pollinators are generally considered weaker than those of local disturbance or diversification (Kennedy *et al.* 2013).

Few studies have examined the effects of local-scale field management on pollinators. Types of local level management include floral and nesting resources located within or adjacent to cropped areas (Kennedy *et al.* 2013). Bees are central place foragers, meaning that the location of nesting habitat relative to the crop itself is important to their relative abundance within an agricultural field (Lonsdorf *et al*. 2009). In one study, ground nesting squash bees (*Peponapis pruinosa*) were three times more abundant in no-till squash fields than in intensively tilled squash fields (Shuler *et al.* 2005). This may be due to the squash bee's preference to nest among the squash plants at depths of 12-20cm below the soil surface (Hurd *et al.* 1974, Julier and Roulston 2009). Conventionally plowed fields, which disturb soil as deep as 50cm, may disturb overwintering and nesting squash bees (Hurd *et al*. 1974, Julier and Roulston 2009). Ground nesting bees typically prefer sloped, bare, uncompacted soil for nesting, which can be difficult to find in conventionally prepared fields (Sardiñas and Kremen 2014). Many wild bees, including squash bees, prefer to nest adjacent to or among their preferred host plants (Julier and Roulston 2009). The effect of mulching on wild bees is unclear, but it is believed to attract wild bees unless there is an excess of mulch within the field that could impede the bees' access to soil nesting sites (Shuler *et al.* 2005, Julier and Roulston 2009). Squash bees are among the most effective pollinators of squash and pumpkin, so their conservation within areas where these crops are grown is of great importance (Winfree *et al.* 2011). Many other native bee species contribute to cucurbit pollination, but their roles are even less well-studied. While the evidence is promising, whether these habitat manipulations increase crop quality or yield remains an open question. The effect of bee activity on agricultural settings has proven difficult to quantify. Shackelford *et al.* (2013) conclude in a meta-analysis that pollinators and natural enemies may have compatible resource and thus similar habitat management requirements. Taken together, the literature suggests that habitat management may enhance pollination and pest control in cucurbits, but that further investigation is needed.

Thesis objectives. This project aimed to quantify the effects of habitat management for conservation biological control and pollination in cucurbit fields and its impact on the cucurbit arthropod community. The first objective examined the effect of mulch and reduced tillage on the arthropod community in acorn squash (*Cucurbita pepo* var. turbinata). The second objective examined the effect of the inclusion of within-field flower strips on the arthropod community in slicing cucumbers (*Cucumis sativus*) with a particular focus on pollinators.

CHAPTER 2:

The effect of conservation tillage and cover crop residue on beneficial insects and weed seed predation in acorn squash (*Cucurbita pepo* var. turbinata).

Introduction

Herbivory in cucurbits can reduce yield by diverting energetic resources away from fruit production and towards defense (Hladun and Adler 2009). In addition to direct damage, insects can also harm cucurbits by vectoring diseases such as bacterial wilt (*Erwinia tracheiphila*) in squash (Shapiro *et al.* 2014). Expenditures for pest insect, weed, and disease management in these crops can exceed $100 per acre per growing season for pesticide applications alone (Barnett 2012). Despite these costs, yield losses due to insects remain high (Adams and Riley 1997, Schmidt *et al*. 2014, NASS 2014).

Beneficial insects, including predators, parasitoids, and pollinators, require resources that are not typically found in conventional agricultural fields, such as food, shelter, and a stable microclimate. The goal of habitat management is to provide additional food and shelter so that beneficial insect will have greater stability (Landis *et al.* 2000). Modifications to the habitat in an agricultural crop field can be in the form of living or nonliving elements, both of which can be important in supporting beneficial insects (Langellotto and Denno 2004). For example, insectary plants are living additions to agroecosystems that can provide insects with energetic and nutritional resources not provided by the crop itself. The addition of plant materials, such as mulches between crop rows, is a form of habitat manipulation that can provide nesting habitat, shelter, and favorable microclimate to beneficials. Growers often use conservation tillage techniques, such as strip tillage, and mulches to protect soil quality by reducing runoff, erosion, and soil compaction (Gebhardt *et al.* 1985, Luna *et al.* 2012). The presence of cover crop residues can improve natural enemy abundance (Hooks *et al.* 2011, Bryant *et al.* 2013) and performance (Lundgren and Fergen 2010, Bryant *et al.* 2014) in other cropping systems. Conservation tillage and mulching may enhance natural enemy activity by reducing disturbance and improving habitat complexity, protecting natural enemies from intraguild predation and environmental extremes (Landis *et al.* 2000, Finke and Denno 2002, Langellotto and Denno 2004). Insect pests, such as *Diabrotica undecimpunctata* (Mannerheim, 1843) (Coleoptera: Chrysomelidae) (spotted cucumber beetles), squash vine borer (*Melittia cucurbitae*, Lepidoptera: Sesiidae)and *Diabrotica virgifera virgifera* (LeConte, 1868) (Coleoptera: Chrysomelidae) (striped cucumber beetles) and *Anasa tristis* (De Geer, 1773) (Hemiptera: Coreidae) (squash bugs), are important pests of cucurbits. The identification of local scale habitat management techniques that benefit their natural enemies is thus of great importance.

Insects such as ground beetles (Carabidae) and crickets (Gryllidae) can be important sources of weed seed and insect mortality in agricultural systems (Rebek *et al.* 2005, O'Rourke *et al.* 2006, Westermann *et al.* 2008, Baraibar *et al.* 2012, Bagavathiannan and Northsworthy 2013, Lundgren *et al.* 2013). Seeds consumed include common weed species, such as giant foxtail (*Setaria faberi*), redroot pigweed (*Amaranthus retroflexus*), velvetleaf (*Abutilon theophrasti*), and common lambsquarters (*Chenopodium album*) (Kirk 1972, Kromp 1999, White *et al.* 2007). Seeds on the soil surface are the most readily consumed (Westerman *et al.* 2003, White *et al.* 2007). Though there is some evidence that carabid larvae primarily consume seeds, they may also eat microorganisms, plant roots, or small soil-dwelling insects (Kirk 1972, Blubaugh and Kaplan 2015). Peak foraging activity of several granivorous adult carabid species occurs in the fall, synchronized with the release of grass seeds (Tooley and Brust 2002). Fresh, hydrated seeds are preferred (Law and Gallagher 2015). Taken together, the literature suggests that invertebrate granivores can be effective predators of newly dispersed weed seeds in agricultural settings.

Tillage and mulch treatments can affect seed predation. Under strip-tillage, seeds tend to remain at the soil surface, where they would likely face greater levels of predation than if they were buried during conventional tillage (Brainard *et al.* 2013). Strip tillage reduces disturbance for both weeds and seed predators, potentially increasing their populations relative to conventionally tilled plots (Brainard *et al.* 2013, Eyre *et al*. 2013). However, conventionally tilled fields have been shown to have greater granivore activity density than no-till fields and lower weed pressure (Westerman *et al.* 2003, Liebman and Davis 2000, van der Laat *et al.* 2015). These results however have not been consistent, varying greatly by crop, year, and study (Brainard *et al.* 2013).

The aim of this study was to quantify the effects of conservation tillage and mulching on the arthropod community and weed seed predation in acorn squash (*Cucurbita pepo* var. turbinata) to identify habitat management techniques that enhance natural enemy activity. I hypothesized that mulching and reduced tillage would increase natural enemy abundance and activity and increase predation of seeds of important weed species.

Materials and Methods

Field plots. The field trial on reduced tillage and mulching took place at the Southwest Michigan Research and Extension Center in Benton Harbor, Michigan (42° 4'57.01"N, 86°21'16.13"W) in 2014 and 2015 in two separate fields approximately 265m apart. Major field plot operations are summarized in Table S.1. The experiments in both years had four treatments, a combination of tillage and ground cover factors, each with two levels: strip-tillage or full tillage, and cover crop mulch or no cover crop mulch (bare). Treatments were organized in a split plot design with six replications. Tillage was the main plot factor, and cover crop mulch the subplot factor. In October 2013 and 2014, the entire 31x97.5m field was disked and planted with winter rye (*Secale cereal*) at a rate of 67.25/ha using a Great Plains Compact Drill 3P606NT (Land Pride, Salina, KS, USA). At the end of May, Roundup (Monsanto Company, St. Louis, MO)(glyphosphate) and ammonium sulfate were applied to plots containing the bare treatments. Due to insufficient rye emergence in both years, additional rye mulch was added to the cover crop treatment plots before tilling at a rate of 0.41kg/m^2. In all plots, 19-19-19 (N-P-K) fertilizer at a rate of 86.25kg/ha was applied. Tillage treatments were applied in the first week of June in 2014 and 2015. In strip-tilled plots, a single row Unverferth Zone Builder 120 (Unverferth Manufacturing Co, Inc., Kalida, OH, USA) with strip building attachment, burming disks, and rolling basket was used to apply the strip tillage treatment. Full tillage treatment was applied using a John Deere model JD F835 moldboard plow (Deere & Company, Moline, IL). The entire field was then planted with acorn squash (*Cucurbita pepo* var. turbinata, “Autumn Delight”, 2014: Seigers Seed Company, Holland, MI, USA; 2015: SeedWay, Hall, NY) using a Matermacc Magicsem series 8000 precision vacuum planter (Via Gemona, 18, 33078 San Vito al Tagliamento PN, Italy). Seeds were planted 40.64cm apart within the rows with 1.5m separating the rows. Individual plots were 5.5x15m and contained three rows of acorn squash.

Foliar arthropod sampling. To determine the effect of tillage and mulching treatments on the arthropod community, insects were sampled on the squash leaves and on the ground in each plot. Insects on foliage were visually sampled in the center row of each plot on 10 randomly selected whole plants during the first two weeks following squash emergence. Once the plants had approximately five leaves each, the numbers of insects on 10 randomly selected squash leaves in the central row were recorded. Insects were identified to major taxonomic groups in the field.

Weekly activity density sampling. Two covered pitfall traps per plot were deployed 3m apart in the center of the plot slightly offset from the central squash row. The traps were constructed from 946.4mL cups (Dart Container Corporation, Mason MI, USA) containing approximately 200mL of a 50% propylene glycol, 50% water solution. Traps were covered with metal lids, to protect them from rain, that were raised approximately 4cm above the trap. Pitfall traps were deployed for a week (+/- 1 day), then the contents were strained in the field through gauze. Samples from individual traps were preserved in 75% ethanol, then stored at -20°C in lab. Insects from pitfall traps were identified under a microscope to major taxonomic groups in the laboratory (Marshall 2006, Bousquet 2010, Albert J. Cook Arthropod Research Collection).

Arthropod abundance was analyzed by taxonomic group and sampling method with Generalized Linear Mixed Models using Laplace approximation and Poisson distribution with tillage and mulch as independent variables and tillage as the main effect. The interaction of tillage, mulch, and sampling date were nested within block as random effects. Due to a highly significant date effect, but low sample size for each individual date, the data were combined into three temporal bins: early (July 3-16), mid (July 25-August 14) and late (August 20-September 4) season. Where main effects were significant (α=0.05), pairwise Tukey-Kramer adjusted least-square means tests were performed to determine differences among treatments (PROC GLIMMIX, SAS 9.4, SAS Institute, Cary, NC, USA). Voucher specimens of arthropods that were collected as part of this project are kept at Michigan State University's A.J. Cook Arthropod Collection.

Weed seed predation. To determine the activity density of weed seed predators, the disappearance of sentinel weed seeds from the field plots on three dates at the end of the growing season was evaluated. Three species of commonly occurring weed seeds were used: Powell amaranth (*Amaranthus powellii)*, common lambsquarters (*Chenopodium album*), and giant foxtail (*Setaria faberi)*. In each plot, seeds of each species were deployed in separate 15cm diameter Petri dish arenas (VWR International, Radnor, PA, USA). Seeds were placed on the surface of 100mL of general-purpose sand (KolorScape, Oldcastle Materials, Atlanta GA, USA). Each arena contained 100 seeds of a single weed species as counted by a Seedboro Model 801 COUNT-A-PAK Seed Counter (Seedburo Equipment Co., Des Plaines, IL). Three, 15cm diameter Petri dishes were placed at the center of each plot. Two pitfall traps per plot were deployed concurrently as described previously to measure weed seed predator activity density. Weed arenas and pitfall traps were collected from the field after 48 hours. No rainfall occurred during the period of deployment. Sampling took place on September 6-8 and 23-25 in 2014. In 2015, sampling occurred on: August 26-28, August 31-September 2, September 5-7, and September 13-15. Remaining weed seeds were frozen at 20°C to prevent germination and kill any other organisms inside the arenas. The arenas were allowed to dry at room temperature for 48 hours before sifting. Powell amaranth and common lambsquarters seeds were separated from the sand using a standard #35, 500 micron sieve. A #30, 600 micron sieve was used to isolate the giant foxtail seeds. The number of remaining fully-intact weed seeds were counted under a microscope and recorded. Pitfall traps were collected and processed as described previously.

Voucher specimens of arthropods that were collected as part of this project are kept at Michigan State University's A.J. Cook Arthropod Collection.

Differences in seed survival and seed predator abundance were analyzed by taxonomic group and sampling method and treatment with Generalized Linear Mixed Models using Laplace approximation and Poisson distribution with tillage and mulch as the main effects. Treatment was nested within block as a random effect. Where main effects were significant ($\alpha=0.05$), pairwise Tukey-Kramer adjusted least-square means tests were performed to determine differences among treatments (PROC GLIMMIX, SAS 9.4, SAS Institute, Cary, NC, USA). The activity density of Gryllidae and *Harpalus* spp. and seed removal by treatment and year during seed predation trials were correlated using Pearson correlation coefficients for responses that exhibited significant differences according to generalized linear mixed models (PROC CORR, SAS 9.4, SAS Institute, Cary, NC, USA).

Results

Foliar arthropod sampling. In 2014, a total of 2,656 insects of varying life stages were observed on the squash leaves over all of the treatments. Of these, 73 were natural enemies and 2,557 were herbivores. The most frequently observed natural enemies were green lacewings (Chrysopidae) (n=19) and ants (Formicidae) (n=14); 91% of all insects recorded during foliar sampling were aphids (Aphididae), the majority of which were recorded in August 2014 during an aphid outbreak. Tillage treatment did not affect the abundance of the foliar herbivores ($F_{1,28}<0.17$, $P>0.05$) or natural enemies ($F_{1,28}<0.19$, $P>0.05$). Mulch did not affect the abundance of the foliar herbivores ($F_{1,28}<0.17$, $P>0.05$) or natural enemies ($F_{1,28}<0.19$, $P>0.05$). The interaction of tillage and mulch was not significant for herbivores ($F_{1,28}$<1.57, P>0.05) or natural enemies ($F_{1,28}$<0.19, P>0.05).

Fewer arthropods were observed on squash leaves in in 2015. Of the 746 arthropods observed, the most frequently encountered were thrips (n=453), aphids (n=111), and squash bugs (*Anasa tristis*) (n=44). Natural enemies were especially rare, accounting for only 54 (7.2%) of the total arthropods encountered. Tillage and mulch treatments did not significantly affect the abundance of herbivores or natural enemies observed on squash leaves at any point in the season ($F_{1,459}$<1.92, P>0.05).

Weekly activity density sampling. Pitfall trap catch composition for both years is summarized in Figure 2.1. A total of 14,761 arthropods were captured in pitfall traps in the 2014 season. Out of these, 26% were springtails (Collembola) (n=7,570), 13% were ants (Formicidae) (n=3,357), 11% were rove beetles (Staphylinidae) (n=2,957), 7% were spiders (Araneae) (n=1,763), and 5% were ground beetles (Carabidae) (n=1,242) (Table S.2). Adult carabids had significantly higher activity densities in full-tilled plots compared to strip-tilled plots in July, early in the season ($F_{1,77}$ =4.67, P<0.04) (Fig. 2.2). Mulch treatment did not affect early season carabid activity density ($F_{1,77}$ =0.01, P>0.05) (Fig. 2.2). Mulch, tillage, and the interaction of mulch and tillage did not affect mid-season carabid activity density ($F_{1,55}$ <1.98, P>0.05) (Fig. 2.2). The activity density of carabids found late in the season was not affected by tillage ($F_{1,77}$ =0.2, P>0.05) (Fig. 2.2). However, unmulched plots had significantly greater carabid activity density for late season dates ($F_{1,77}$>6.5, P<0.02). The interaction between tillage and mulch treatment was not significant for carabid activity density during the entire season ($F_{1,32}$<8.2, P>0.05) (Fig. 2.2).

In 2014, the majority of carabids collected were of the genus *Harpalus* (51%, n=635). Early season activity density of *Harpalus* spp. was not significantly affected by tillage, mulch, or their interaction ($F_{1,27}$<1.18, P>0.05) (Fig. 2.2). Mid-season activity density of *Harpalus* spp. was marginally significantly increased in unmulched plots ($F_{1,32}$>7.38, P<0.07) (Fig. 2.2). Late-season *Harpalus* spp. activity density was significantly increased in full-tilled unmulched plots compared to strip-tilled mulched plots (t= 3.10, df=92, *P*<0.01) (Fig. 2.2). The activity densities of all other arthropods were not significantly affected by tillage or mulch treatment or their interaction at any point during the season ($F_{1,32}$<1.32, P>0.05).

In 2015, a total of 24,785 arthropods were collected in pitfall traps. Collembola (n=8,292), Staphylinidae (n=3,857), Formicidae (n=2,998), Gryllidae (1,549), and Carabidae (n=864) were the most frequently captured arthropods. Of the carabids captured, 64% of them were identified as members of the genus *Harpalus* (n=551).

Treatment effects were only significant early in the season ($F_{1,66}$ >4.67, P<0.01) The activity density of adult carabids was significantly greater in full-tilled plots than strip-tilled plots early in the season (t=6.74, df=66, P<0.01) (Fig. 2.2). Significantly more spiders, crickets, and grasshoppers were observed in early season mulched plots compared to unmulched plots, regardless of tillage type (t<8.02, df=66, P<0.05) (Fig. 2.2). The activity densities of all other arthropods were not significantly affected by tillage or mulch treatment or their interaction at any point during the season ($F_{1,32}$<1.32, P>0.05).

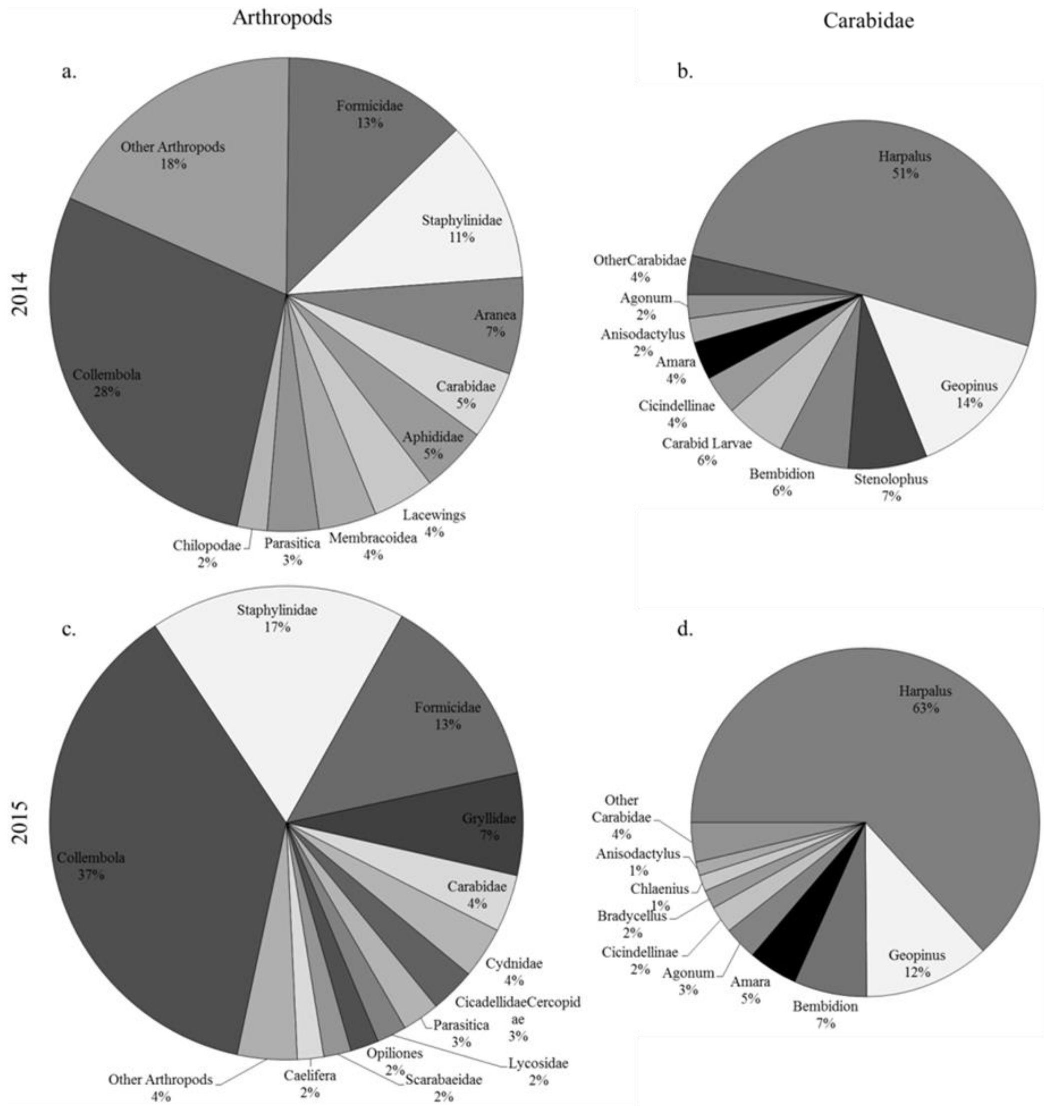

Figure 2.1. Arthropods collected in weekly pitfall traps in the 2014 (a,b) and 2015 (c,d) growing seasons. Traps were deployed in plots that were strip-tilled or full-tilled, with no rye hay added (unmulched) or 0.5kg/m^2 rye hay added (mulched).

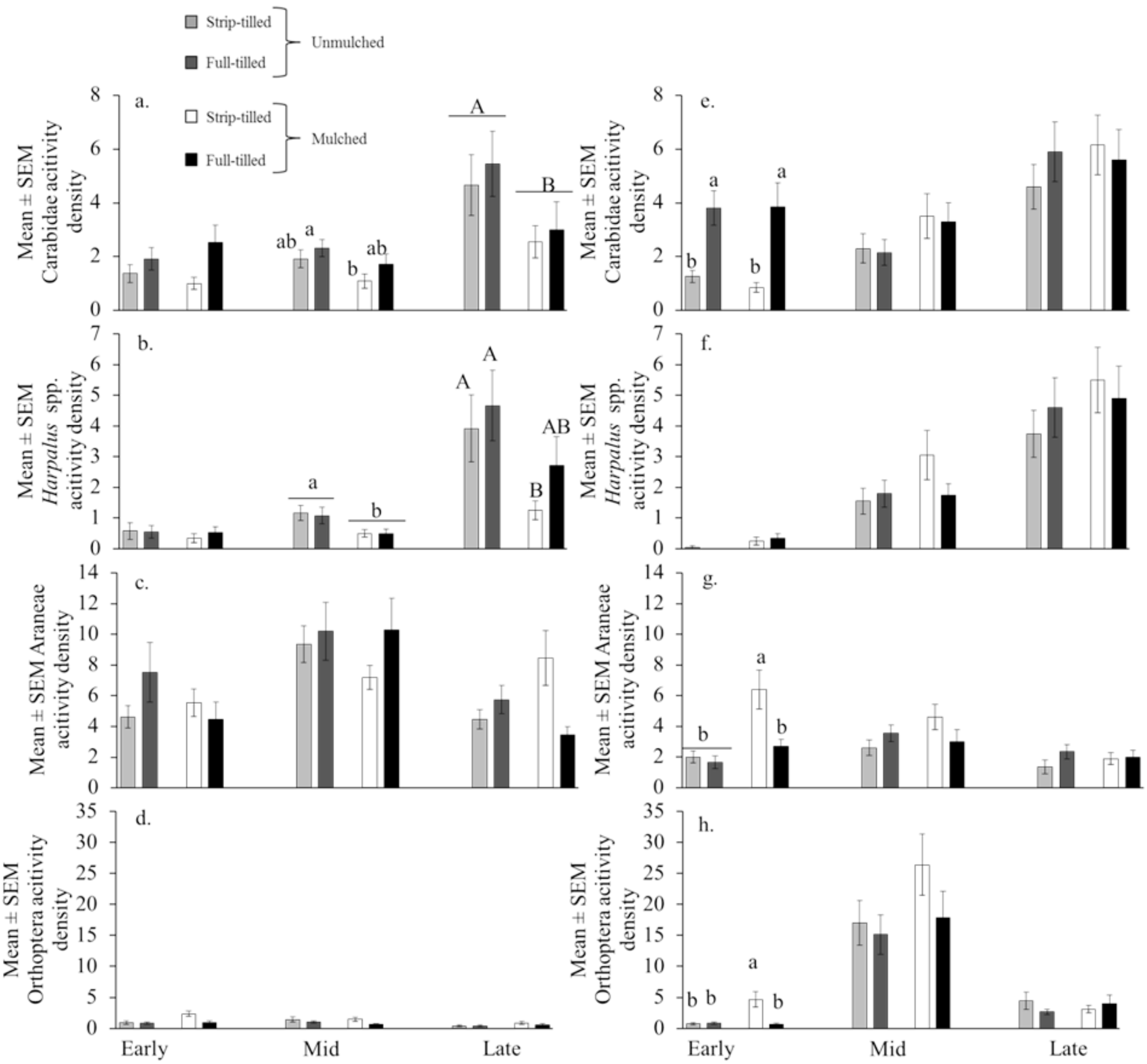

Figure 2.2. Mean (±SEM) activity density of arthropods collected in weekly pitfall traps by time period in the 2014 (a,b,c,d) and 2015 (e,f,g,h) growing seasons. Traps were deployed in plots that were strip-tilled or full-tilled, with no rye hay added (unmulched) or with 0.5 m² rye hay added (mulched). Significant differences are indicated with different letters of the same case (Tukey's HSD, α=0.05).

Weed seed predation. Results from the seed predation trials are summarized in Figures 2.3 and 2.4. In 2014, a total of 203 arthropods were captured during the weed seed predation trials.

Specimens captured included spiders (Araneae, 17%) and ground beetles (Carabidae, 47%), with 27% of all arthropods belonging to the *Harpalus* genus. *Harpalus* spp. had significantly higher activity densities in bare plots than in mulched plots (t=2.74, df=21, P=0.02). The activity densities of all other taxa were not significantly affected by tillage, mulch, or their interaction ($F_{1,41}$<7.30, P>0.05). In 2015, a total of 2,653arthropods were captured during weed seed predation trials over four sampling dates. The majority of specimens captured were Collembola (20%), Formicidae (18%). and *Harpalus* spp. (15%). *Harpalus* spp. had significantly higher activity densities in full-tilled plots than in strip-tilled plots (t=2.24, df=115, P<0.03). Gryllidae demonstrated significantly higher activity densities in strip-tilled plots than in full-tilled plots (t=2.83, df=115, P<0.03). Staphylinidae demonstrated significantly higher activity densities in full-tilled, mulched plots than in strip-tilled and mulched plots (t=0.34, df=115, P<0.01), while collembolans had significantly higher activity densities in in mulched plots (t=3.49, df=115, P<0.01). The activity densities of all other taxa were not significantly affected by tillage, mulch, or their interaction ($F_{1,41}$<7.30, P>0.05).

In 2014, *Amaranthus powellii* and *C. album* seed survival were not significantly affected by tillage or mulch treatment ($F_{1,17}$ <0.38, P>0.05). *Setaria faberi* seed survival was significantly higher in strip-tilled plots compared to full-tilled plots, regardless of mulch treatment (t=-3.14, df=17, P<0.01). In 2015, *A. powellii* survival was significantly higher in mulched plots than in unmulched plots, regardless of tillage (t=-4.31, df=54, P<0.01). Significantly more *C. album* seeds were recovered from strip-tilled plots with rye mulch than all other treatment combinations (t= -5.43, df=58, P<.01). Significantly more *C. album* seeds survived in strip-tilled and unmulched plots than in full-tilled unmulched plots, (t=-2.74, df=54, P<0.04). Survival of *S. faberi* was not affected by treatment ($F_{1,55}$<4.95, P>0.05). Giant foxtail seed removal and

Harpalus spp. activity density were not correlated in 2014 and 2015 (R^2<0.7, df=6, P>0.05). Common lambsquarters seed removal and *Harpalus* spp. activity density were not correlated in 2015 (R^2<0.5, df=7, P>0.05). Giant foxtail seed removal and Gryllidae activity density were not correlated in 2014 and 2015 (R^2<0.7, df=7, P>0.05). Common lambsquarters seed removal and Gryllidae activity density were not correlated in 2015 (R^2<0.5, df=19, P>0.05).

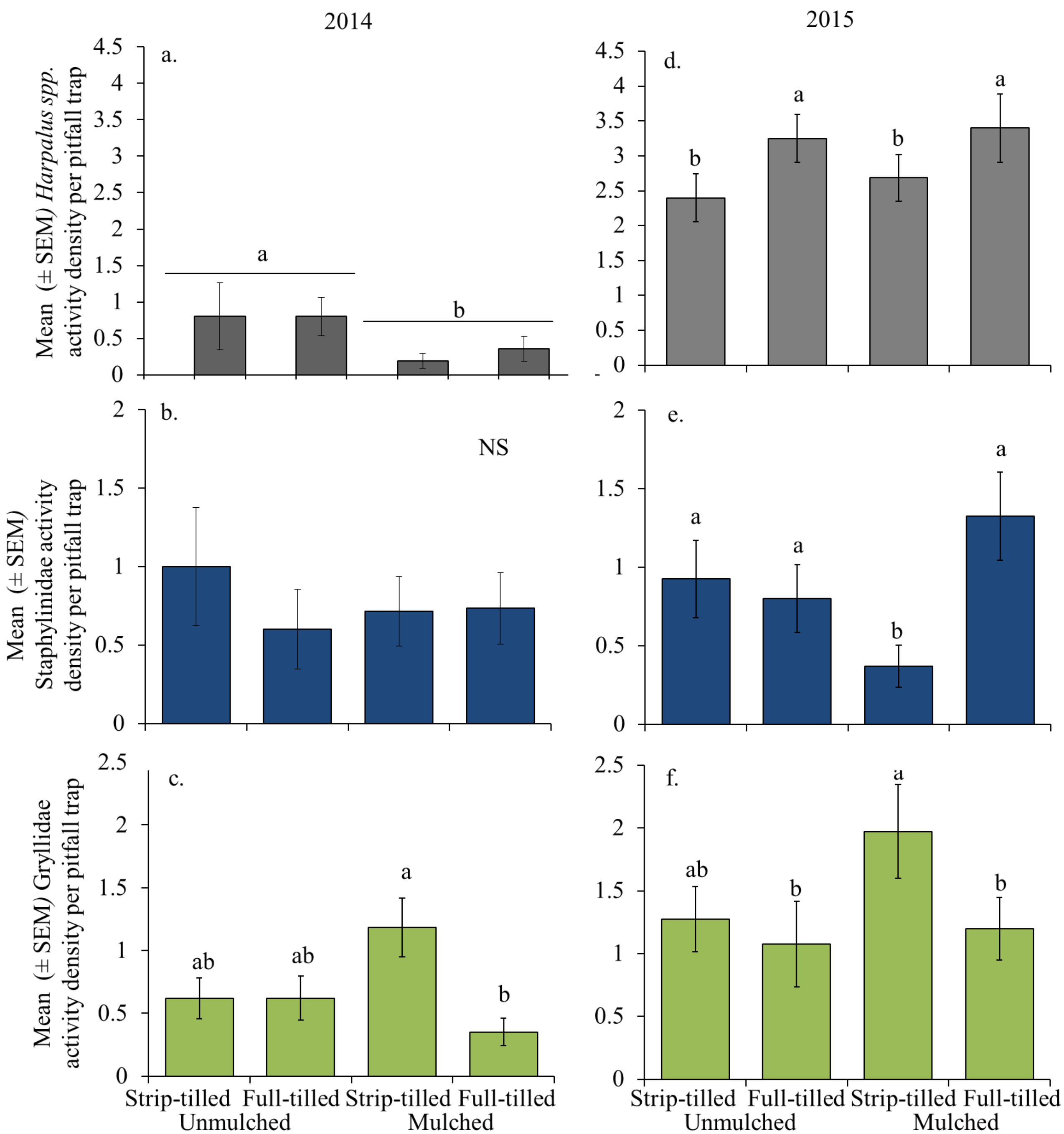

Figure 2.3. Mean (±SEM) activity density of arthropods collected in weekly pitfall traps by time period in the 2014 (a,b,c,d) and 2015 (e,f,g,h) growing seasons. Traps were deployed in plots that were strip-tilled or full-tilled, with no rye hay added (unmulched) or with 0.5 m^2 rye hay added (mulched). Significant differences are indicated with different letters of the same case (Tukey's HSD, α=0.05).

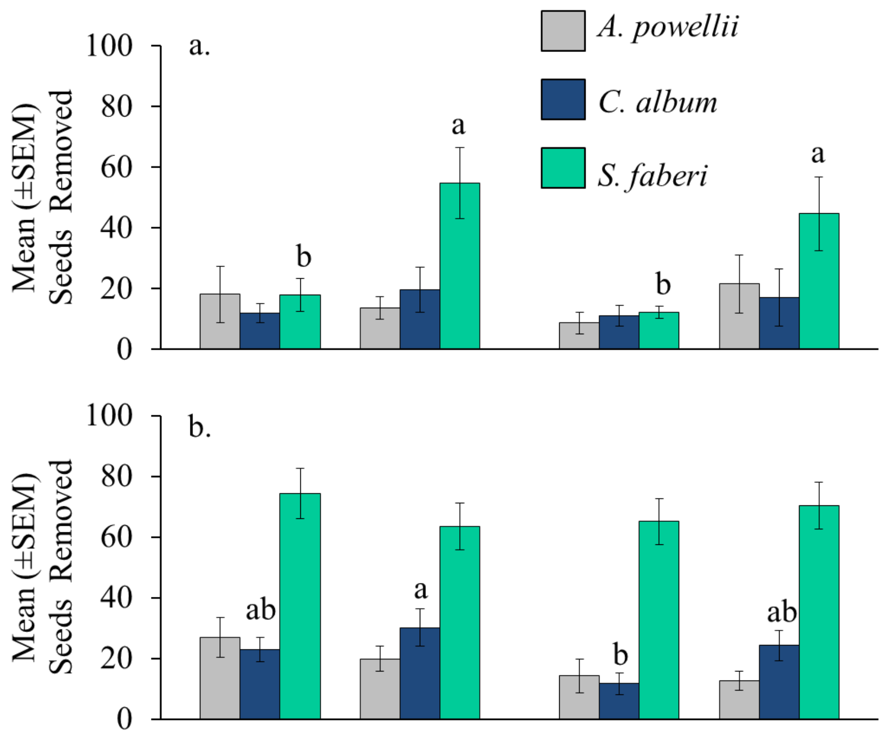

Figure 2.4. Mean (±SEM) seed removal in 2014 (a) and 2015 (b). Arenas contained 100 seeds and were deployed for 48 hours in plots that were strip-tilled or full-tilled, with no rye hay added (unmulched) or 0.5kg/m^2 rye hay added (mulched). Significant differences are indicated with different letters of the same case (Tukey's HSD, α=0.05).

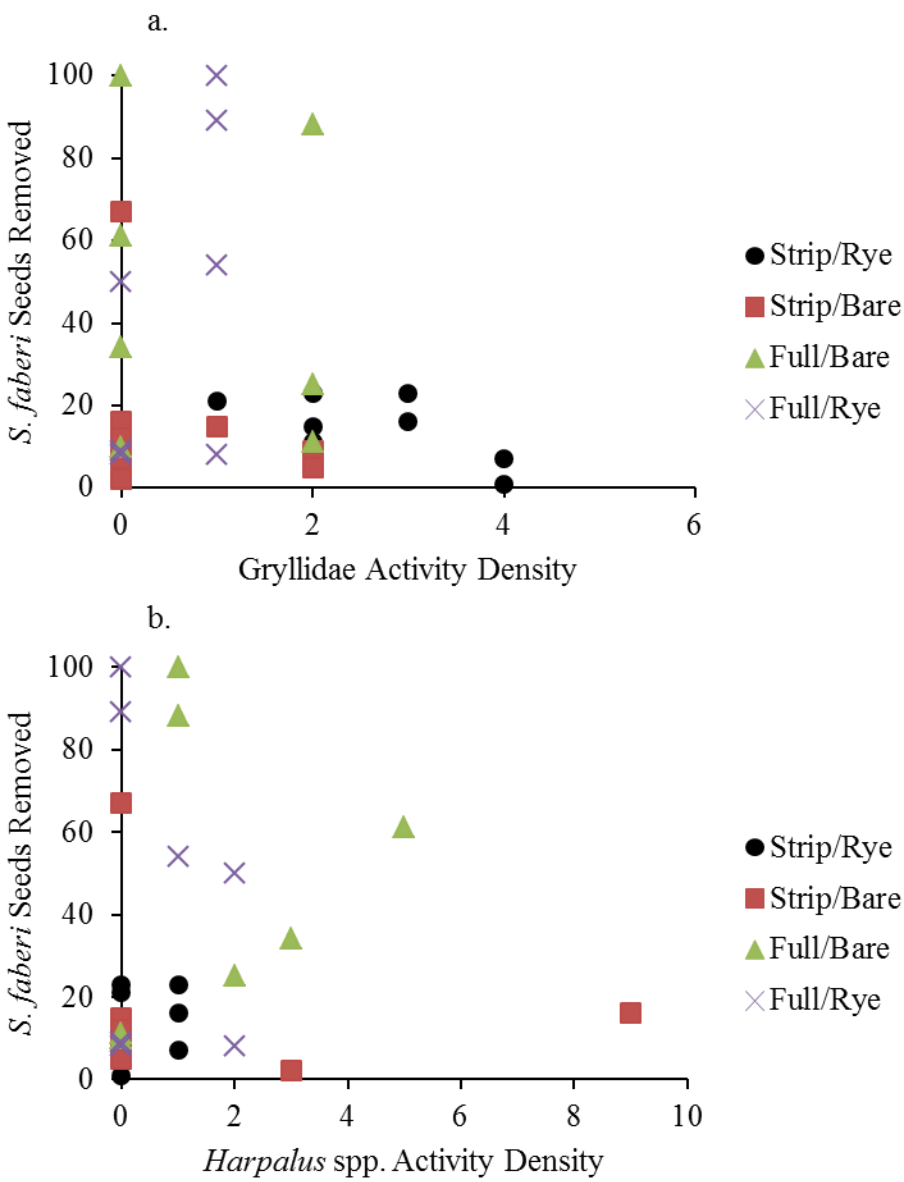

Figure 2.5. Correlation of the activity density of Gryllidae (a) and *Harpalus* spp. (b) and seed removal in 2014. Data were correlated using Pearson correlation coefficients.

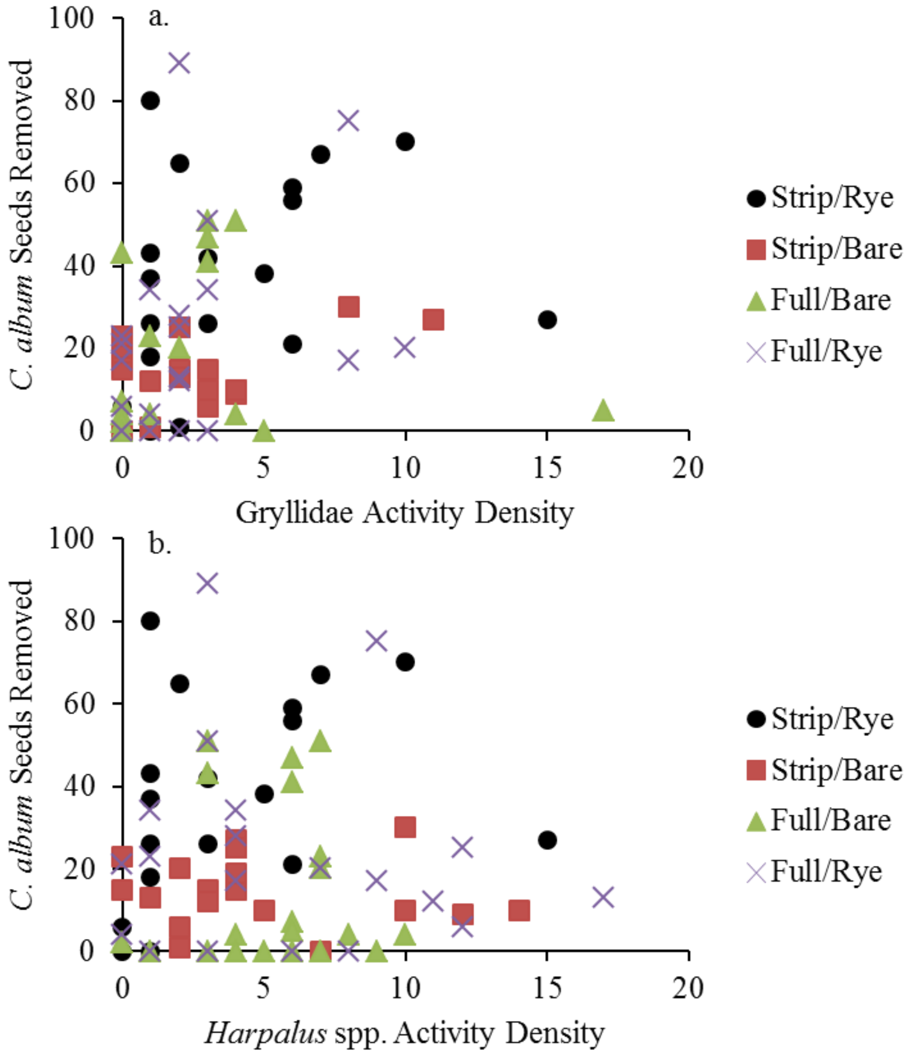

Figure 2.6. Correlation of the activity density of Gryllidae (a) and *Harpalus* spp. (b) and seed removal in 2015. Data were correlated using Pearson correlation coefficients.

Discussion

Overall. Growers are increasingly interested in using conservation tillage techniques, such as strip tillage, and mulches to protect soil quality by reducing runoff, erosion, and soil compaction (Luna *et al.* 2012). Other studies have found that the presence of cover crop residues can improve natural enemy abundance (Hooks *et al.* 2011, Bryant *et al.* 2013) and performance (Lundgren and Fergen 2010, Bryant *et al.* 2014) in other cropping systems. Conservation tillage and mulching may enhance natural enemy activity by reducing disturbance and improving habitat complexity, protecting natural enemies from intraguild predation, environmental extremes, and disturbance (Landis *et al.* 2000, Finke and Denno 2002, Langellotto and Denno 2004). Given this information, natural enemy presence and activity would be expected to be the greatest in strip-tilled plots with rye mulch, as this type of management provides less invasive tillage and greater habitat complexity. While foliar arthropods did not respond to the treatments applied, natural enemies of insects and weed seeds tended to be more abundant in full-tilled plots. Rates of seed predation aligned with this, with fewer seeds surviving in low complexity, high disturbance plots.

When considering pitfall trap data, it is important to keep in mind the limitations of the sampling method itself. Rather than measuring the true abundance or diversity of the arthropods captured, it provides an estimate of the amount of ground-dwelling arthropod movement in the immediate area, with a bias towards larger-bodied specimens such as carabids (Spence and Niemela 1994, Duelli and Obrist 1998). This chapter underlines the importance of considering the context of a given study before generalizing their results to all cropping systems, regions, and years, as arthropod response to tillage and mulch treatment was not found to be consistent between years in this study.

Foliar arthropod sampling. The arthropod community observed on squash leaves was not affected by mulch, tillage, or their combination. Other studies have shown that the use of reduced tillage and mulching can reduce foliar herbivore populations presumably by improving within-field natural enemy habitat (Langellotto and Denno 2004, Bryant *et al.* 2013, Hinds and Hooks 2013). In this study however, significant effects of tillage and mulch on foliar arthropods were not demonstrated. The efficacy of conservation tillage in improving within-field biological control may take several years to take full effect, as is the case with soil health (Abawi and Widmer 2000). Repeating the study in the same field for several years may elucidate the long-term effects of tillage and mulching on the foliar arthropod community.

Weekly activity density sampling. In the 2014 samples, mulch was a more important factor in determining carabid activity density, with sample dates closer to the date of tillage showing stronger tillage effect. The importance of tillage in early season activity density was reinforced by the early season pitfall samples in 2015 (Fig. 2.2). Tillage may be important in long-term population health of carabids and other arthropods because tillage, especially full tillage, may disrupt immature and overwintering stages (Carmona and Landis 1999, Landis *et al.* 2000, Blubaugh and Kaplan 2015). In the short term however, it may make movement and digging, and thus finding prey, easier. The effect of tillage and mulch on spiders was variable between years. Spiders were not affected by treatment in 2014, but had significantly higher activity densities in mulched plots in early 2015. As ground-dwelling predators, spiders typically exhibit strong sensitivities to tillage and mulching practices. Increased habitat complexity, provided by mulch in this case, is typically favored by spiders and other predators (Riechert *et al.* 1990, Rypstra *et al.* 1999, Landis *et al.* 2000, Snyder and Wise 2000, Bryant *et al.* 2013, Schmidt *et al*. 2014).

Seed predation. In both years, weed seed survival tended to be the greatest in mulched plots, with the survival of seeds based on tillage treatment being more variable (Fig. 2.4). This indicates that seeds tended to be removed at a higher rate in unmulched plots. Perhaps mulch in this case reduced measured activity density of granivorous arthropods by making it more time consuming to forage as they navigated through the mulch. Alternative food sources may have also been available either in the form of the seedheads of the rye mulch itself or the insects or organic matter contained therein. Unmulched plots in this study and in general tended to be weedier, providing additional habitat complexity, and alternative food sources, such as weed seeds. Granivorous arthropod activity as measured by the 48 hour pitfall traps also proved to be variable between seasons. Rates of seed predation and the activity densities of several granivorous species were increased rom high disturbance plots, though there was no correlation between the two responses (Fig 2.3, 2.4, 2.5, 2.6). The number of seeds removed from a given area is a result of a complex of species and their interaction with the treatments applied, along with other environmental factors. Full tillage can reduce the number of seeds on the surface (Brainard *et al.* 2013, Blubaugh and Kaplan 2015). This could increase granivore activity in full-tilled plots, as weed seeds would be relatively scarce in those areas compared to strip-tilled areas where more seeds have accumulated on the soil surface. In both years, the number of Powell amaranth and common lambsquarters seeds recovered undamaged was numerically greater than the number of intact Giant foxtail seeds recovered. Smaller seeds tend to be preferred by granivorous insects, while larger seeds are preferred by vertebrates (Honek *et al.* 2003, Westerman *et al.* 2003, Honek *et al.* 2007). This suggests that in this case, vertebrate seed predation pressure may have been higher than invertebrate predation. Crop type has been shown to have a bigger impact on granivore assemblages than field management, meaning that what works well in one crop may be less effective in another (Bourassa *et al.* 2008). Rates of seed predation also tend to be patchy, making it difficult to estimate (Marino *et al.* 1997). Optimizing weed seed predation may be a matter of adjusting the amount of mulch applied to the field so that it provides appropriate amounts of cover without hindering seed predator movement (Cromat *et al*. 1999). Dependable enhancement of seed predation by insects in squash agroecosystems may require more specialized management, indicating a need for further study.

CHAPTER 3:

Integrating flower strips for beneficial insects in cucumber (*Cucumis sativus*).

Introduction

Beneficial insects in agriculture. In response to decreasing beneficial insect populations worldwide, attracting and maximizing the efficacy of native pollinators and natural enemies has become of increasing interest (Isaacs and Kirk 2010, Petersen *et al.* 2013, Shackelford *et al.* 2013, Garibaldi *et al.* 2014, Giannini *et al.* 2015). A recent review suggests that the decline in managed and wild pollinators can be attributed to the combined effects of multiple stressors, including repeated long-distance transport, increased disease transmission, exposure to a variety of fungicides and insecticides, and limited floral resources, which culminate in reduced pollinator abundance and diversity (Goulson *et al.* 2015). Fewer pollinators could result in decreased crop production, as approximately 35% of food crops are pollination-dependent (Klein *et al*. 2007). Maintaining habitat that supports resilient and effective pollinator complexes will be crucial to ensuring continued, sustainable food production.

In cucumbers, pollination is essential for fruit set, with inadequate pollination being associated with fruit abortion and low fruit quality (McGregor 1976, Stanghellini *et al.* 1997). The main pollinators of cucumber are honey bees (*Apis mellifera*), the common bumble bee (*Bombus impatiens*), though the role of other pollinators is not well-understood (Smith *et al.* 2012). The squash bee (*Peponapis pruinosa*), another visitor to cucumber plants, are cucurbit specialists that are among the most effective pollinators of cucurbit crops (Hurd *et al*. 1974, Terpedino 1981, Canto-Aguilar and Parra-Tabla 2000, Lowenstein *et al.* 2012). Information on squash bee biology is generally limited. They are wild, solitary bees that nest gregariously in the soil at depths of 12-30cm below the surface in vertical burrows (Mathewson 1968, Hurd *et al*. 1974). Their nests are typically found among suitable host plants (Mathewson 1968, Hurd *et al*. 1974). They are typically considered oligolectic, collecting pollen only from *Cucurbita*, though they have been known to visit other hosts including cucumbers (Mathewson 1968, Hurd *et al*. 1974, Lowenstein 2012). They begin foraging as early as an hour before sunrise in synchrony with the opening of cucurbit flowers (Hurd *et al*. 1974). They are univoltine; females may construct multiple nests each year, with overwintering prepupae emerging as adults the following year (Mathewson 1968). Squash bees appear to be highly sensitive to field management practices, such as tillage and irrigation (Shuler *et al.* 2005, Julier and Roulston 2009). The effect of floral provisioning on squash bees is relatively unknown, though recent studies suggest that they may be unaffected by additional floral provisioning (Phillips and Gardiner 2015). Other wild pollinators have demonstrated higher cucurbit pollination rates than managed pollinators in several cases (Garibaldi *et al.* 2013, Holzschuh *et al*. 2014, Blaauw and Isaacs 2014). In cucumbers, wild bumble bees have been shown to pollinate cucumbers more effectively than honey bees, even when managed honey bee hives are added to the field (Gajc-Wolska *et al.* 2011). Bumble bees and squash bees are more effective pollinators of cucurbits than honey bees (Artz and Nault 2011, Petersen and Nault 2011). The addition of managed honey bee hives adjacent to or within cucurbit fields does not necessarily increase their abundance or density (Shuler *et al.* 2005). Therefore, attracting wild pollinators to cucumber fields should be a priority.

Habitat management for pollinators. Increasing pollinator diversity and abundance is a matter of providing sufficient landscape and local scale resources. Landscape level factors include proximity to natural areas or other habitat resources, patch size of the resources, and quality of those resources within the landscape (Kennedy *et al*. 2013). When grown adjacent to wooded or natural areas, the abundance of wild pollinators in cucumber fields increased (Lowenstein *et al.* 2012, Smith *et al.* 2013). This may be due to the fact that native pollinators are often sensitive to environmental disturbances and require additional food and nesting resources that are more easily found in natural areas (Tuell *et al.* 2008, Williams *et al.* 2010, Winfree *et al.* 2011). Proximity to natural areas can increase the amount and diversity of wild bees in agricultural fields by providing nesting and nutritional resources, increasing the landscape's carrying capacity for pollinators. The size and quality of the landscape-level resources available are also factors in pollinator diversity and abundance on crops (Winfree *et al.* 2007, Petersen and Nault 2014, Wray and Elle 2015). Larger patches of undisturbed, diverse floral resources enhance pollinator and natural enemy activity more than small patches of less diverse floral resources or unmanaged areas (Meyer *et* al. 2007).

Local scale management for pollinators is also important. Types of local level management include floral and nesting resources located within or adjacent to cropped areas (Kennedy *et al.* 2013). Bees are central place foragers, meaning that the location of nesting habitat relative to the crop itself is important to their abundance within an agricultural field (Lonsdorf *et al*. 2009). Ground nesting bees typically prefer sloped, bare, uncompacted soil for nesting, which can be difficult to find in conventionally prepared fields (Sardiñas and Kremen 2014). Many wild bees prefer to nest adjacent to or among their preferred host plants (Cresswell *et al.* 2001, Julier and Roulston 2009, Lonsdorf *et al*. 2009, Jakobsson and Ågren 2014). Adding flower strips within the field itself may increase the desirability of the field for nesting and foraging, increasing the abundance and diversity of bees within cropped areas, thus increasing crop pollination.

Floral provisioning for beneficial insects. Non-crop flowering plant species are rarely found adjacent to or within agricultural fields due to intensive herbicide use and the perception of revenue loss from uncultivated space, but there is increasing support for the use of habitat diversification as a means to increase the number, diversity and efficacy of natural enemies and pollinators. (Landis *et al.* 2000, Goverde *et al.* 2002, Carvell *et al.* 2006, Fiedler *et al.* 2008, Blaauw et al 2012). The addition of flowering plants and fallow fields adjacent to cultivation can increase the abundance of beneficial insects found in cropped areas (Long *et al.* 1998, Rebek *et al.* 2005, Wanner *et al.* 2006, Fiedler *et al.* 2008, Woodcock *et al.* 2014). Native pollinators and natural enemies are attracted to both annual and perennial flowering species in Michigan (Fiedler and Landis 2007, Tuell *et al.* 2009). Meta-analyses have indicated that pollinators and natural enemies demonstrate greater abundances from increased local level vegetational diversity and floral availability (Kremen and Miles 2012, Shackelford *et al.* 2013, Riedinger *et al.* 2014). Taken together, the literature suggests that adding flower strips to cropped areas may enhance pollination and pest control in cucumber.

Hypotheses. The inclusion of flower strips in cucumber fields will: 1) increase the abundance of natural enemies 2) decrease the abundance of herbivorous insects, and 3) increase pollinator abundance and diversity, and 4) increase cucumber yield and quality. Additionally, the effect of the flower strips was expected to be the strongest in rows of cucumbers adjacent to the flowers, meaning that there will be greater abundance and diversity of beneficial insects and fewer pests in rows of cucumbers closest to the flowering annuals.

Materials and Methods

Field plot establishment. The project took place in two commercial cucumber fields at Piggott's and Girls Farm in Benton Harbor, Michigan in 2014 and 2015. In 2014, the field was 201 x 402m and in 2015, it was183 x 366m. A randomized complete block design was implemented in both years. The field was divided into six blocks with five treatments. Major field operation dates are provided in Table S.2. In mid-April, the field was treated with herbicides (1.18L/ha, s-metalochlor, Syngenta Crop Protection, LLC., Greensboro, NC; Command 3ME, 0.8L/ ha, 2-[(2-chlorophenyl)methyl]-4,4-dimethyl-3-isoxazolidinone, FMC Agricultural Solutions, Philadelphia, PA). Slicing cucumbers (*Cucumis sativus*, "Intimidator") were planted at the end of April in 2014 and 2015. Seeds were treated with a seed coat (FarMore, azoxystrobin, fludioxonil, mefenoxam, and thiamethoxam, Syngenta, Basel, Switzerland) and planted with Presidio (0.75L/ha Fluopicolide, Valent U.S.A. Corporation, Walnut Creek, CA) and Admire (0.75L/ha, imidacloprid, Bayer CropScience Inc, Calgary, Alberta). Between rows, Dual II Magnum (1.25L/ ha, s-metalochlor, Syngenta Crop Protection, LLC., Greensboro, NC) and Command 3ME (0.8L/ ha) were applied. For the flower strips, black plastic was removed in 20m long sections that were separated by 40m in rows and 12 rows (46m) between flower-strips in both years. In 2014, all flower strips 20m from the field edge. In 2015, flower strips were a minimum of 10m from the field edge due to an asymmetrical field shape. The following flower treatments were seeded at the end of April 2014 and 2015: 1) *Brassica hirta* (yellow mustard, var. "Tilney"), 2) *Lobularia maritima* (sweet alyssum, var. "Carpet of Snow") 3) *Fagopyrum esculentum* (buckwheat), 4) *Trifolium incarnatum* (crimson clover), or 5) cucumbers (control). In 2014, Cucumber seeds were hand planted and promptly covered with low tunnels using a transparent plastic cover. Low tunnels were not used in 2015. Sweet alyssum and clover was hand seeded while buckwheat and mustard was seeded with a Model JP-3 Clean Seeder using a Y24 disk for mustard and a R12 disk for buckwheat (Jang Automation Co., Ltd, South Korea). In 2014, oats were used as a nurse crop for the alyssum and clover seeds. In 2015, no oats nurse crop was used. At the end of May, the cucumbers' plastic covering was vented and the plastic over the flower-strip was openedand Select 2EC 43560 (Valent USA, Walnut Creek, CA) (0.59L Clethodim /ha) was applied to control the oat nurse crop was applied to control the oat nurse crop In June, harvests began and the grower applied Nu Cop 50 DF (0.027kg/ha copper hydroxide, Albaugh Inc., Ankeny, IA), Initiate 720 (1.183L/ha tetrachloroisophthalonitrile Loveland Products, Inc., Greeley, CO) plus Perm-up (0.0025L/ha permethrin, United Phophorus Inc, Trenton, NJ). In 2015, similar field management was utilized, except that the cucumber beds were not covered with low-tunnels. Sampling transects (0.77x20m) were located within the flower strips (Row 0) and 1.5m (Row 1), 5m (Row 3), and 10m (Row 5) away from the flower strips.

Foliar arthropod abundance. In 2014 only, insects were sampled on the cucumber leaves in each treatment plot. Insects on foliage were visually sampled in each transect on 10 randomly selected whole plants during the first two weeks following cucumber emergence. Once the plants had approximately five leaves each, the numbers of insects on 10 randomly selected cucumber leaves in the each transect were recorded. Insects were identified to major taxonomic groups in the field.

Arthropod abundance on sticky traps. Sticky traps (12x15 cm) were deployed at the center of each flower strip in 2014 and 2015. In 2015, a sticky trap was also deployed in row 3. Traps were collected and redeployed weekly. Traps were frozen at -20C° and identified in the laboratory to the lowest relevant taxonomic unit. Most Diptera, excluding Tachinidae and Syrphidae, were not counted. Voucher specimens of arthropods that were collected as part of this project are kept at Michigan State University's A.J. Cook Arthropod Collection.

Arthropod abundance by sweep net. Flower-strips were sampled weekly via sweep net. When sampled, each 20m flower transect was swept 100 times. Insects were frozen at -20C° and identified in the laboratory to the lowest relevant taxonomic unit. Most Diptera, excluding Tachinidae and Syrphidae, were not considered. Voucher specimens of arthropods that were collected as part of this project are kept at Michigan State University's A.J. Cook Arthropod Collection.

Pollinator observation. Sampling for pollinators occurred between 7:30am and 12:30pm on sunny, calm days, at approximately one week intervals. Pollinators were assessed by walking along each 20m transect and recording the number and identity of all bees observed over a 10 minute period. If sight identification was not possible, pollinators were collected for laboratory identification. In the laboratory, pollinators were pinned and identified according to Mitchell's Bees of the Eastern United States (1962). Voucher specimens of arthropods that were collected as part of this project are kept at Michigan State University's A.J. Cook Arthropod Collection.

Yield. Yield data were collected twice during harvest. The mass of all cucumbers in a 1m section within each transect were used as a measure of yield. The diameter and length of the harvested cucumbers was graded in accordance with the United States Standards for Grades of Cucumbers (USDA 1997).

Statistical analysis. Arthropod abundance by taxonomic group, sampling method, treatment, and row were analyzed with Generalized Linear Mixed Models using a Poisson distribution with treatment and row as independent variables and treatment as the main effect. Treatment was nested within block as a random effect. Where main effects were significant (α=0.05), pairwise Tukey-Kramer adjusted least-square means tests were performed (PROC GLIMMIX, SAS 9.4, SAS Institute, Cary, NC, USA). The effect on total weight and average grade of the cucumbers harvested within the transects by distance from the flowering strips were analyzed with Generalized Linear Mixed Models using a normal distribution with treatment and row as independent variables and treatment as the main effect. Treatment was nested within block as a random effect. Where main effects were significant (α=0.05), pairwise Tukey-Kramer adjusted least-square means tests were performed (PROC GLIMMIX, SAS 9.4, SAS Institute, Cary, NC, USA).

Results

Foliar observation. Flowering treatment, row, and the interaction between treatment and row did not significantly affect the abundance of natural enemies or herbivores found on cucumber leaves in 2014 ($F_{8,5}<0.45$, $P>0.05$).

Sticky traps overall. In 2014, a total of 2,796 insects were collected and identified on 130 sticky traps deployed in the flower strips. An average of 21.5 insects were identified on each trap. The number of traps was increased to 229 traps deployed in 2015. A total of 6,652 insects were collected by sticky trap, 42% more than in 2014. A total of 115 sticky traps were collected from the flower strips in 2015, with 5,132 insects collected on these traps. In the third row of cucumbers away from the flower strips, a total of 114 sticky traps were deployed, catching a total of 1,521 insects. The mean number of insects caught on sticky traps deployed in the flower strips and cucumbers was 44.6 and 13.3 respectively.

Sticky trap herbivores. In 2014, of the 1,498 herbivores, 27.97% were leaf and tree hoppers (Membracoidea), 23.2% were tarnished plant bugs (*Lygus lineolaris*), and 19.2% were leaf beetles (Chrysomelidae) (Fig. 3.1). No significant treatment effects on sticky trap captures were found for the number of arthropods in any of the herbivorous taxa ($F_{4,115}$ <1.95, P>0.05).

In 2015, Membracoidea (39.35%), *Lygus lineolaris* (28.34%), and Alticini (8.13%) were the most commonly occurring herbivores (Fig. 3.1). These herbivores were most frequently trapped on sticky traps located within the mustard flower strips, where 21% of the specimens were captured across rows and treatments. Captures on sticky traps for the most frequently captured herbivores were slightly lower within-cucumber areas than in the flower strips, though overall they were relatively evenly distributed. For *L. lineolaris*, 9.0% fewer specimens were captured outside of the flower strips than inside the strips, 3.1% fewer for the Membracoidea, and 36.8% fewer for the Alticini. No significant treatment or row effects on sticky trap captures were found for any herbivores ($F_{3,206}$ < 0.98, P>0.05).

Sticky trap natural enemies. In 2014, the most abundant of the 1,172 natural enemies collected on sticky traps were minute pirate bugs (*Orius* spp., 40.19%), parasitoids (Parasitica, 34.22%)

and lady beetles (6.72%) (Fig 3.2). Sweet alyssum had the greatest number of natural enemies captured (n=342), while the control treatment had the least (n=128).

Pre and during harvest abundances of lady beetles and minute pirate bugs collected by sticky trap in the floral strips were significantly different among treatments ($F_{4,93}$ >3.39, P<0.02) (Fig. 3.3). Significantly more lady beetles were found on the sticky traps in the buckwheat and sweet alyssum treatments than control cucumber only plots (t>1.32, df=93, P<0.05) (Fig. 3.2). Significantly more minute pirate bugs were found on sticky traps placed in mustard and sweet alyssum strips compared to control cucumber-only plots (t>3.32, df=93, P<0.05) .

In 2015, a total of 3,467 natural enemies were captured on sticky traps. Parasitica (48.41%), *Orius* spp. (37.10%), and Araneae (7.36%) were the most commonly trapped natural enemies (Fig. 3.2). Across the treatments, natural enemies were most frequently captured within the flower strips, where 59.1% of the natural enemies were caught. The greatest number of natural enemies were caught on sticky traps located within mustard flower strips (n=742) and the fewest were caught on traps located within the corresponding area of the control plots (n=250).

Both treatment ($F_{3,206}$>137.04, P<0.01) and row ($F_{3,206}$> 241.83, P<0.01) significantly affected the number of minute pirate bugs on sticky traps (Fig. 3.3, 3.4).. Minute pirate bugs were collected more frequently on traps located within the mustard strips compared to other treatments and rows (t>31.57, df= 206, P<0.0001) Both treatment ($F_{3,206}$> 196.25, P<.0001) and row ($F_{3,206}$ >61.44, P<.0001) location significantly affected whether parasitoids were collected on sticky traps (Fig 3.3). Parasitoids were collected more frequently on traps located within the mustard strips compared to other treatments and rows (t>31.57, df= 206, P<0.0001). They were also significantly more abundant in the cucumber areas of buckwheat flower strips plots than in other treatments ($t > 12.49$, df= 206, $P<0.0001$). All other natural enemy taxa were unaffected by treatment, row, or their interaction ($F_{3,206}<0.77$, $P>0.05$).

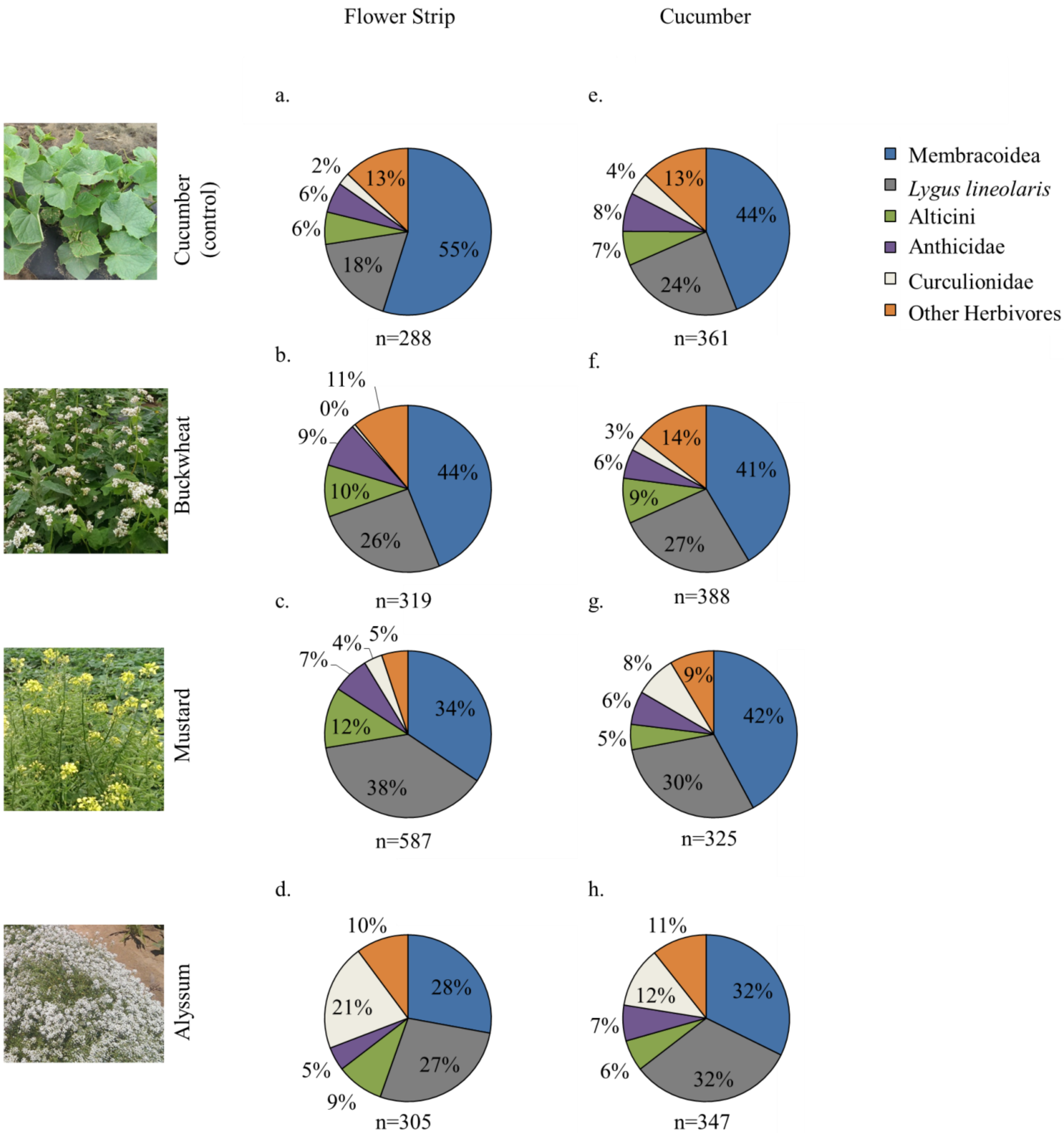

Figure 3.1. Herbivore community composition observed on 12x15cm sticky traps in flower strips (a,b,c,d) and in cucumbers (e,f,g,h) pre and during cucumber harvest by flower treatment and location in 2015. Traps were collected and replaced weekly.

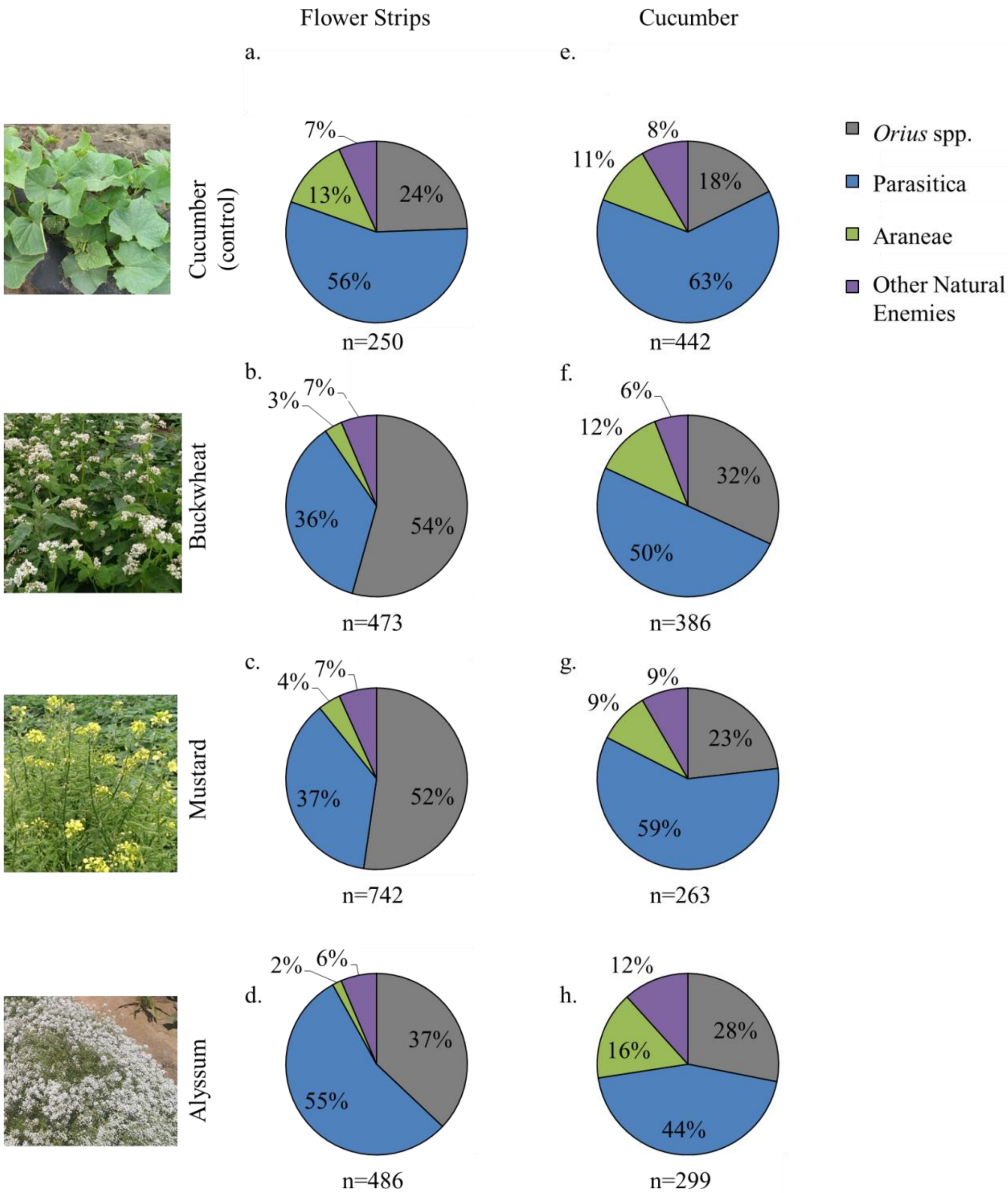

Figure 3.2. Natural enemy community composition observed on 12x15cm sticky traps in flower strips (a,b,c,d) and in cucumbers (e,f,g,h) pre and during cucumber harvest by flower treatment and location in 2015. Traps were collected and replaced weekly.

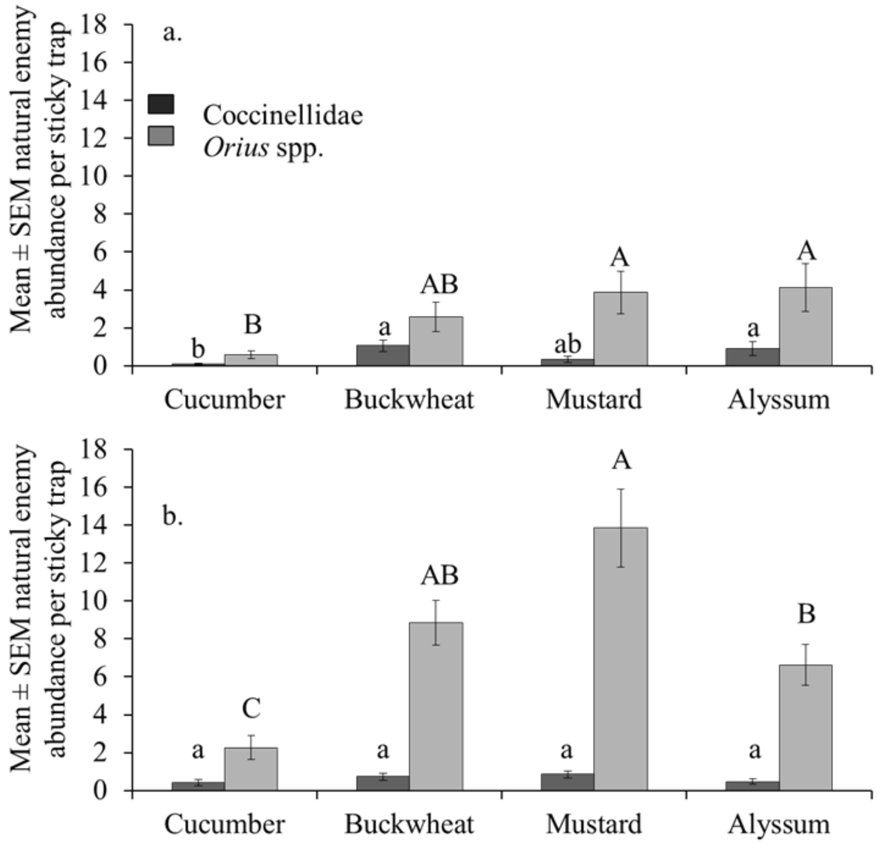

Figure 3.3. Mean (±SEM) number of lady beetles (Coccinellidae) and minute pirate bugs (*Orius* spp.) observed on 12x15cm sticky traps in the flower strips (Row 0) pre and during cucumber harvest by flower treatment in 2014 (a) and 2015 (b). Traps were collected and replaced weekly. Bars with different letters of the same case are significantly different from one another (Tukey's HSD, $\alpha = 0.05$).

Sweep net overall. In 2014, a total of 2,863 arthropods were collected and identified from 90 sweep net samples collected from the flower strips over a five week sampling period. An average of 30.1 arthropods were identified from each transect. Sweet alyssum transects yielded nearly half (47.6%) of all arthropods collected by sweep net (n=1,363).

A total of 90 sweep samples were collected from the flower strips in 2015 over a five week sampling period, with 3,629 arthropods collected. A mean of 40.2 arthropods per sample were captured. The greatest number of arthropods were found samples from mustard (n=1,494), followed by sweet alyssum (n=1,076), and buckwheat (n=1,059).

Sweep net herbivores. A total of 2,305 herbivores were collected by sweep net in 2014. The most abundant arthropods sampled were *Lygus lineolaris* (40.56%), Miridae (38.74%), and Curculionidae (4.25%). The numerically greatest number of herbivores were found in samples collected from sweet alyssum transects (n= 1,119) while buckwheat had the fewest (n=375). Flowering treatment did not significantly affect the abundance of herbivores collected by sweep net from the flower strips pre and during cucumber harvest ($F_{4,70}$ <0.21, P>0.05).

In 2015, 2,322 herbivores were collected, the majority of which were Membracoidea, (37.7%), *Lygus lineolaris* (28.0%), and Alticini (9.4%). The greatest number of herbivores were found in samples collected from mustard transects (n= 1,006) while buckwheat had the fewest (n=614). Flowering treatment did not significantly affect the abundance of herbivores collected by sweep net from the flower strips pre and during cucumber harvest ($F_{2,78}$ <0.01, P>0.05).

Sweep net natural enemies. A total of 593 natural enemies were collected via sweep net in 2014. The most abundant arthropods sampled were identified as *Orius* spp. (40.12%), Parasitica (34.16%), and Coccinellidae (6.73%). The raw abundance of natural enemies found in sweep samples was relatively even among treatments, with mustard having the most natural enemies (n=184), followed by sweet alyssum (n=175), and buckwheat (n=153). Flowering treatment did not significantly affect the abundance of natural enemies collected by sweep net from the flower strips ($F_{2,70}$ <0.22, P>0.05).

In 2015, 1,145 natural enemies were collected, with *Orius* spp. (48.38%), Parasitica (37.07%), and Coccinellidae (7.36%) having the highest abundances. As in the previous season, natural enemies were relatively even among treatments. Buckwheat had the most natural enemies (n=405), followed by mustard (n=391), and sweet alyssum (n=349). Flowering treatment did not significantly affect the abundance of natural enemies collected by sweep net from the flower strips ($F_{2,78} <0.01$, $P>0.05$).

Sweep net pollinators. In 2014, 126 pollinators were collected by sweep net. The most abundant pollinators were native bees (87.30%), the majority of which were Halictidae and Andrenidae. Flowering treatment did not significantly affect the abundance of pollinators collected by sweep net from the flower strips pre and during cucumber harvest in either year ($F_{4,70} <0.21$, $P>0.8$).

Diversity. The diversity of insects collected in sweep net samples in 2014 and 2015 was relatively even between years, with numerically greater diversity overall observed in 2014 (Table 3.1). However, the trends between years were similar, with the greatest arthropod diversity observed in mustard samples.

Table 3.1. Shannon's diversity indices for sweep net and sticky trap data in 2014 and 2015. Each 0.77x20m flower strip was swept 100 times once a week for five weeks. Sticky traps were deployed in the center of the flower strips at canopy height for a week. Diversity indices were calculated with PC-ORD.

	Shannon's Diversity Index (H)	
	2014	**2015**
Sweep Net		
Buckwheat	0.58	0.34
Mustard	0.63	0.40
Alyssum	0.66	0.37
Sticky Traps		
Buckwheat	0.77	0.31
Mustard	0.80	0.46
Alyssum	0.65	0.38

Pollinator observation. A total of 478 pollinators were observed on cucumber plants in 2014. The majority of the bees observed were squash bees (*Peponapis pruinosa*) (n=332) and honey bees (*Apis mellifera*) (n=132). The remaining bees were native species of the genera *Bombus* (n=7), *Agapostemon* (n=5), and *Lasioglossum* (n=2). Flowering treatment, row, and the interaction between treatment and row did not significantly affect the abundance of observed honey bees or native bees 1, 3, or 5 rows away from the flower treatments before cucumber harvest ($F_{8,64}$<0.45, P>0.3) (Fig. 3.4). However, significantly fewer squash bees were observed near buckwheat and mustard plots than near cucumber only plots, regardless of distance from the flowering treatment (t>3.25, df=93, *P*<0.02) (Fig. 3.4). Row and the interaction between treatment and row did not significantly affect the abundance of any bees observed ($F_{2,64}$ <1.23, P>0.05).

In 2015, a total of 5,068 pollinators were observed. *Apis mellifera* (61.27%), Syrphidae (36.50%), *and Peponapis pruinosa* (0.32%) were the most frequently observed. Of those, a total of 767 pollinators were observed on cucumber plants. Honey bees (n=617) were the most frequently observed, followed by syrphids (n=121), native bees (n=17), and squash bees (n=12). Significantly more honey bees were observed in the flower strips of the mustard and buckwheat treatments than in other rows and treatments ($t>-5.02$, df=361, $P<0.01$) (Fig 3.4, 3.5).. The most syrphids were observed in the alyssum flower strips, followed by the buckwheat and mustard strips ($t>-10.66$, df=361, $P<0.01$) (Fig 3.4, 3.5). Significantly more native bees were observed within the flower strips of the mustard and buckwheat treatments than in other rows and treatments ($t> -25.97$, df=361, $P<0.01$) (Fig 3.4, 3.5). Squash bees were not significantly affected by treatment, row, or their interaction ($F_{6,361}<0.05$, $P>0.99$) (Fig 3.4, 3.5).

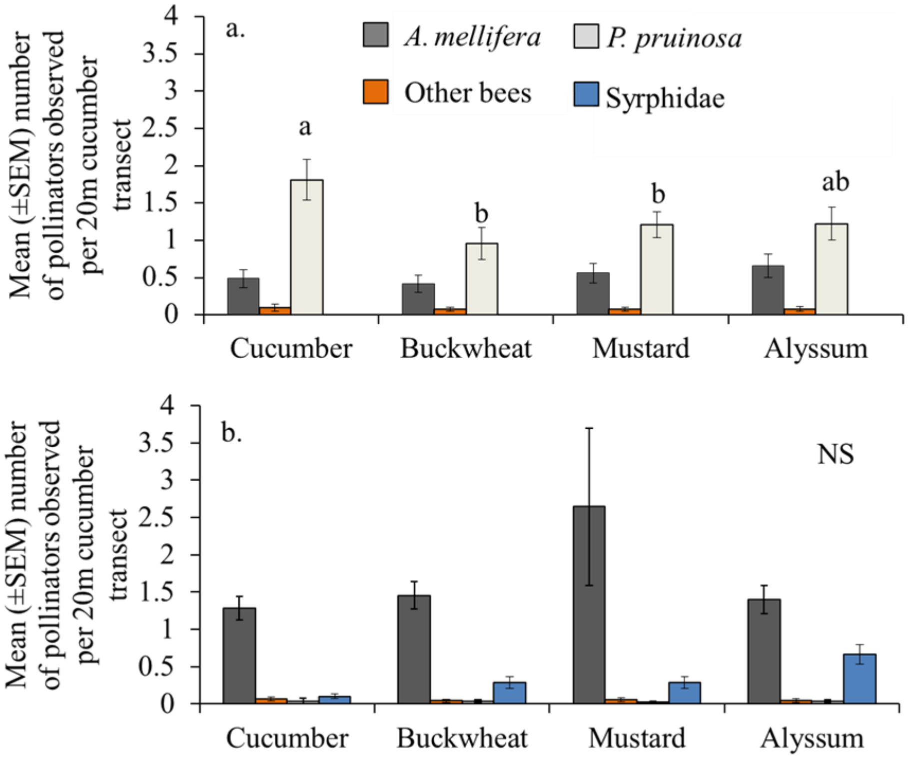

Figure 3.4. Mean (±SEM) number of pollinators observed in cucumbers pre-harvest by treatment in 2014 (a) and 2015 (b). Observations occurred over 10 minute periods in 0.77x20m transects located within the flower strips (Row 0) and 1.5m (Row 1), 5m (Row 3), and 10m (Row 5) away from the flower strips, in cucumbers. Bars show averages across all distances. Bars with different letters across treatments are significantly different from one another (α = 0.05). Bars without letters are not significantly different from one another ($\alpha > 0.05$).

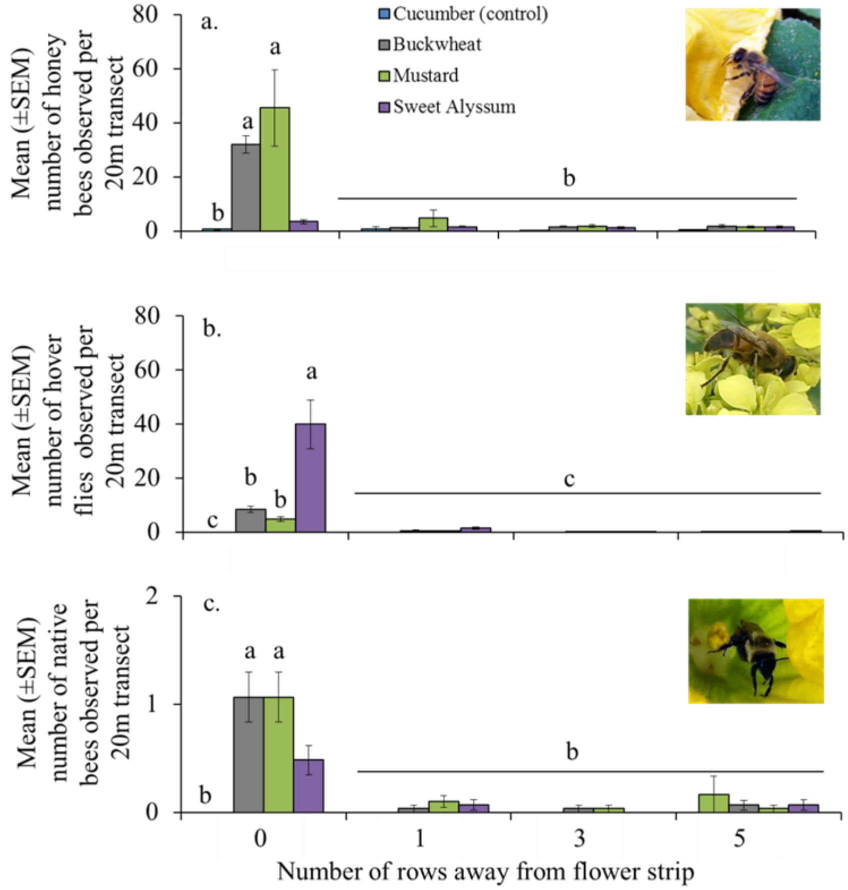

Figure 3.5. Mean (±SEM) number of *Apis mellifera* (a), Syrphidae (b), and native bees (c) observed by treatment and row in 2015. Observations occurred over 10 minute periods in 0.77x20m transects located within the flower strips (Row 0) and 1.5m (Row 1), 5m (Row 3), and 10m (Row 5) away from the flower strips, in cucumbers. Bars show averages across all distances. Bars with different letters across treatments are significantly different from one another (α = 0.05). Bars without letters are not significantly different from one another (α > 0.05).

Yield. In 2014, there were no significant differences by distance from the flower strips in mass harvested per meter ($F_{2,73}$< 2.66, P>0.05) or the interaction between flower treatment and distance ($F_{8,70}$, F=0.46, P>0.05). The percentage of low-grade cucumbers harvested was not affected by treatment ($F_{4,70}$=1.29, *P*>0.05), distance from flower treatment, ($F_{2,70}$ <1.48, *P*>0.05), or their interaction ($F_{8,70}$= 0.46, *P*>0.05). In 2015, significantly more cucumbers were harvested from sweet alyssum plots than the other treatments (t>-2.69, df=122, P<0.01). Significantly more cucumbers were harvested from row 5, the row furthest away from the floral strips, than row 1 (t>-2.64, df=122, P<0.03). However, the interaction between treatment and row did not significantly affect mass harvested ($F_{6,122}$ <0.28, P>0.05). No significant differences in mean grade of cucumbers harvested by treatment or row were observed ($F_{6,87}$ <0.78, P>0.05).

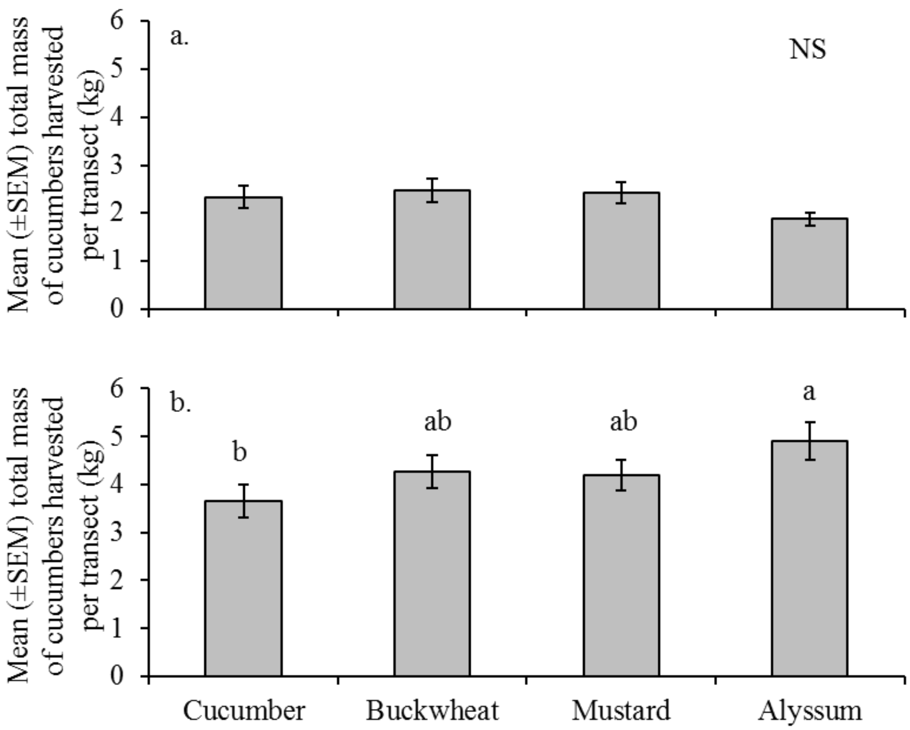

Figure 3.6. Mean (±SEM) total mass (kg) of cucumbers harvested per m^2 in 2014 (a) and 2015 (b). Cucumbers were sampled from rows located 1.5, 5, and 10m away from the flower strips. Bars with different letters are significantly different from one another according to Tukey's HSD (α = 0.05).

Discussion

Arthropods across sampling methods were more abundant in floral strips and less abundant in cropped areas. Cucumber rows closest to the floral strips did not have more insects than those further away. Cucumber yield was slightly increased in sweet alyssum treatments and in the row located farthest away from the floral strips. Fruit quality was not significantly affected.

Herbivores and natural enemies. Contrary to my predictions, the abundance of herbivorous insects was not significantly reduced by the presence of flowers, regardless of sampling methods. The herbivore communities within flower strips were also not significantly different from one another. Few arthropods were observed overall on the cucumber plants or sticky traps in either year, a primary contributing factor to this may be the use of the systemic insecticide imidacloprid at planting in both years.

Greater numbers of natural enemies were detected in the floral strips compared to the cucumbers in both seasons. Insect abundance tends to be highest where the greatest numbers of suitable resources are located, according to the resource concentration hypothesis (Root 1973). While the cucumber flowers provide little nectar and pollen (Southwick *et* al. 1981, Masierowska 2003, Peng *et al* 2004), the floral species used here are well-established insectary plants (Platt *et al.* 1999, Landis *et al.* 2000, Berndt and Wratten 2005, Fiedler *et al.* 2008). It is likely that the flowers concentrated the available natural enemies in the flower strips rather than increasing the total number of natural enemies available for biological control in the whole field. The effect of insectary plant mixes on the natural enemy community found in cucurbit systems can vary from year to year, with some years having higher abundances of key natural enemies in cropped areas while some demonstrate little effect (Grasswitz 2013). An important factor to be considered here is the use of annual versus perennial flowers. Perennial insectary mixes are thought to improve natural enemy diversity and abundance by increasing the carrying capacity of the area over time (Landis *et al.* 2000, Iverson *et al.* 2014). However, cucumbers are rotated annual crops making the improvement of the beneficial insect community with perennial plants a challenge. Another consideration is the scale of resources provided. Generally, larger areas of floral resources support greater beneficial insect abundance and diversity (Blaauw and Isaacs 2012). Relative to the entire field, the total area of the flower strips was small in both years, comprising less than 0.001% of the total area of the field. Increasing the size of the within-field floral areas may improve the total number of natural enemies dispersing into cropped areas of the field; however this may be impractical for economical farming in cucurbits. However, floral provisioning has been employed in other agroecosystems with some success (Long *et al.* 1998, Walton and Isaacs 2011, Brennan 2013, Garibaldi *et al* 2014, Nayak *et al.*2015), so it may be a matter of finding the optimal species and deployment of these resources.

Pollinators. Generally, pollinators were more abundant within the floral strips than in cropped areas. The distance away from the strips did not appear to significantly affect pollinator foraging on cucumber plants. Native bees occurred at lower levels than honey bees in the cucumber field overall, but showed a similar pattern, favoring the floral strips over the cucumbers. Honey bees and many native bees are generalists, but prefer to visit flowers with high-quality resources (Cook *et al.* 2003, Cnaani *et al.* 2006). As with the natural enemies, providing larger patches of high-quality floral resources may better support pollinator populations (Blaauw 2013). Pollinators are highly mobile, and can cover relatively large distances proportional to their body size in search of their preferred floral resources (Greenleaf *et al.* 2007, Benjamin *et al.* 2014, Danner *et al.* 2014, Geib *et al.* 2015, Wright *et al.* 2015). The distance between rows may have been too small to detect a distance effect, since bees may forage as far as several kilometers away from their nests (Greenleaf and Kremen 2006, Greenleaf *et al.* 2007, Londsdorf *et al.* 2009). Honey bees are one of the primary pollinators of cucumbers in North America, yet they do not appear to have been drawn to the cucumbers by the floral resources provided. Rather, they appear to have concentrated within the flower strips without dispersing into the surrounding cropped areas or being drawn away from the cucumbers (Fig. 3.5). Bees and other highly mobile insects have demonstrated sensitivities to the quality of the landscape as a whole, meaning that local-scale management may be insufficient support for their populations (Shackelford *et al.* 2013, Petersen and Nault 2014, Kremen et al. 2015, Park *et al.* 2015). Additionally, the floral strips may have had some exposure to the systemic insecticides applied to the cucumbers at planting, which may have had a repelling effect, though this cannot be known for certain (Easton and Goulson 2013).

Squash bees were observed in 2014 and in much lower numbers in 2015. In 2014, they were significantly less abundant in buckwheat and mustard plots than in cucumber only or alyssum plot, a finding that was not repeated in the subsequent year (Fig 3.4). Squash bees are not reliably attracted to non-cucurbit hosts (Phillips and Gardiner 2015). While cucumber is not a preferred host, perhaps the squash bees dispersing from nearby overwintering sites such as winter squash fields from the previous season are moderately attracted to cucumber to obtain nectar at emergence, then seek out their preferred *Cucurbita* hosts. If more squash bees could be attracted to cucumber fields, perhaps with a more attractive floral intercrop or by planting cucumbers in or near old squash fields, cucumber pollination could be possibly be enhanced, though their efficacy in cucumbers compared to other cucurbits is relatively unknown. This could be particularly effective if nesting habitat were conserved over consecutive years (Splawski *et al.* 2014). This may have inadvertently been the case in 2014, when the cucumber field was adjacent to what had been a winter squash field the previous season.

Yield. Properly implemented, habitat management has the potential to increase the abundance and diversity of wild pollinator populations, increasing yield in turn (Garibaldi *et al* 2015). However, in the current study cucumber yield was only significantly affected by the flower treatments in 2015 (Fig. 3.6). The mass of cucumbers harvested from the plots adjacent to sweet alyssum was significantly greater than that of the control plots. This is unexpected, as pollinators were not significantly affected by the floral treatments (Fig. 3.5). Perhaps the buckwheat and mustard strips competed with the cucumbers for abiotic resources, such as light and nutrients, as they are larger, more vigorous plants than the sweet alyssum. Cucumbers tend to be variable in size, weight, and shape and produce fruit for several weeks, during which time cucumbers are harvested daily. Increasing the area of cucumbers harvested for yield could provide a more robust estimate of the amount and quality of cucumber yield. Hydration, pollination, nutritional, and varietal differences can all impact the number and quality of cucumbers harvested (Isamail and Ozawa 2007, Bhardwaj 2014, Rahil and Qanadillo 2015, Motzke *et al.* 2015). The interaction of these factors in combination with the fact that pollinator visitation to cucumber plants was not increased by the treatments applied likely explains the weak treatment effect on yield.

CHAPTER 4:

Conclusions and Future Directions

The purpose of this project was to quantify the effects of habitat management for conservation biological control and pollination in cucurbit fields and its impact on the cucurbit arthropod community. In chapter two, the effects of mulch and reduced tillage on the arthropod community in acorn squash were examined. Natural enemies of weed seeds and insects were expected to be more abundant in strip-tilled, mulched plots than full-tilled, unmulched plots. The abundance of insects detected during foliar observations did not differ among treatments, but treatment effects on ground-dwelling arthropod activity density and weed seed survival were detected. The effects of tillage and mulch on arthropods and seed survival varied by year. Generally, granivore activity density was reduced in strip-tilled plots and seed survival was either unaffected or higher in strip tilled or mulched plots. In the third chapter, the effects of floral intercropping on beneficial insects and yield in a commercial cucumber field were examined. Beneficial insect abundance was expected to greater in plots containing flowers, with more beneficials found in the rows closest to the floral strips. Arthropods in the floral strips were captured with by sweep net and sticky trap, while arthropods in cropped areas were sampled with foliar observations in the first season and sticky traps in the second. Pollinators in all rows were sampled with timed transect observations. Some floral treatments attracted more beneficial insects than others, but the beneficials did not disperse out to the cucumber plants. Cucumber yield was only weakly affected in 2015.

The effects of tillage and mulch treatments on the arthropod community varied by season, possibly due to several important factors. The weather in 2015 was cooler and cloudier than the previous year, both of which can impact insect activity, especially when sampling with pitfall traps (Duelli and Obrist 1998, Enviro-weather - Michigan State University 2015). Another consideration is that the long-term management of the field sites was different. The field used in 2014 had been in cucurbit production for several years, while the field in 2015 had been fallow for an indeterminate amount of time. The baseline local-scale arthropod communities in these areas would thus be expected to be different, as frequency and severity of disturbance can profoundly alter community structure and resilience, impacting beneficial insect activity (Menge and Suterhland 1987, Turner and Dale 1998, Collins 2000, McCabe and Gotelli 2000, Landis *et al.* 2000, Eyre *et al.* 2013). However, the results from this study do not indicate consistent benefits from one tillage and mulch regime over another on natural enemy abundance or activity. In fact, the most consistent effect of strip tillage appears to be the reduction of carabid activity density. While there are many reasons to implement conservation tillage and mulch, arthropod management alone may not be sufficient justification.

Habitat management can be a powerful, sustainable tool for improving beneficial insect activity in agroecosystems. However, different cropping systems, regions, years, even fields can yield markedly different results than might be expected (Bourassa *et al.* 2008, Fiedler *et al.* 2008). In the case of Chapter 2, the effects of tillage and mulch treatments do not suggest consistent benefits of one tillage and mulch regime over another on natural enemy abundance or activity, and may even be detrimental in some cases. However, there can be benefits to using conservation tillage and mulch, meaning that the lack of dependable effects on arthropod activity shown here should not be a deterrent (Brainard *et al.* 2013). Additionally, other studies have shown these techniques to effectively support natural enemy activity across cropping systems, especially in low-input settings (Zehnder *et al* 2007, Schmidt *et al.* 2014, Trichard *et al.* 2014, Blubaugh *et al.* 2015). In the case of seed predation, it may be a matter optimizing the amount of mulch applied to maximize weed suppression and predation (Cromat *et al*. 1999, Brainard *et al.* 2013). Landscape factors, such as proximity to wooded areas, may also be important considerations in determining the potential for tillage or mulch application to impact natural enemies (Menalled *et al.* 2000, Mitchell *et al.* 2014). Perhaps tracking the rates of activity density and seed predation over several growing seasons and crop rotations would elucidate the long term effects of field preparation. It would also be informative to determine if the insects captured in the pitfall traps during the seed predation trials were actually consuming or contacting the seeds deployed, perhaps through gut content analysis or immunomarking of the seeds themselves. The relationship between field management and beneficial insect activity in squash production systems is complex and requires further study.

Habitat management has been established as an effective component of integrated pest management and beneficial insect enhancement for many years (Landis *et al.* 2000). However, this thesis research did not detect benefits of within-field floral intercropping extending out to the field as a whole. Planting the more promising floral species, buckwheat and mustard, in unused areas of the field such as the driveways and field margins may improve the effects on beneficial insects at the local scale, similar to the use of insectary hedgerows (Morandin *et al.* 2014). Flowers planted in the driveways and margins would also be subject to less insecticide exposure, which could also bolster beneficial insect populations. However, they would be at risk for being run over repeatedly by machinery and vehicles used to maintain the field, possibly reducing their efficacy While increasing the total area of the floral strips has the potential to benefit natural enemies, pollinators, and yield, the question of whether or not the benefits of increased habitat management would outweigh the grower costs required for optimal implementation remains (van

Lenteren 2011, McCarthy *et al.* 2012, Kleijn *et al.* 2015). As has been concluded by other studies, the responses of natural enemies and pollinators to the addition of floral resources proved to be similar, meaning that their management is compatible (Long *et* al. 1998, Otieno *et al.* 2011, Nicholls and Altieri 2012, Shackelford *et al.* 2013, Iverson *et al.* 2014, Morandin *et al.* 2014, Duru *et al.* 2015). Planting the more promising floral species, buckwheat and mustard, in larger patches and in unused areas of the field such as the driveways and field margins may improve the effects on beneficial insects at the local scale, similar to the use of insectary hedgerows (Blaauw and Isaacs 2012, Morandin *et al.* 2014). While increasing the total area of the floral strips has the potential to benefit natural enemies, pollinators, and yield, the question of whether or not the benefits of increased habitat management would outweigh the grower costs required for optimal implementation remains (McCarthy *et al.* 2012, Kleijn *et al.* 2015). However, for growers to widely adopt a given habitat management strategy, yield and cost-effectiveness would have to be noticeably improved (Griffiths *et al.* 2008). Yield was not markedly improved by the presence of any of the flowers added, meaning that the justification for removing those areas from cultivation is limited. However, in low-input settings, such as small, organic farms that are not as intensively managed, improvements to the habitat on the arthropod community may become more apparent. Habitat management for beneficial insects still holds a great deal of potential to improve yield, profitability, and sustainability, but many questions as to its application in cucurbit agroecosystems remain.

APPENDICES

APPENDIX A:

Supplementary Data

Table S.1. Major field activities in 2013-2015. The study took place in an acorn squash field at the Southwest Michigan Research and Extension Center in Benton Harbor, MI.

Field Operation	Date		
	2013	2014	2015
Rye planted	14-Oct	13-Oct	
Glyphosate/ammonium sulfate applied to bare plots		10-Oct	27-Apr
Glyphosate/ammonium sulfate applied to bare plots		27-Apr	22-May
Glyphosate/ammonium sulfate applied to all plots		14-May	25-May
200 lbs of 19-19-19 applied to all plots (76 lbs/acre)		14-May	25-May
Mulch treatments applied (0.41kg/m2)		5-Jun	2-Jun
Moldboard plow, dicing, harrowing, applied to full tillage plots		5-Jun	2-Jun
Strip tillage applied to strip-tilled plots		5-Jun	3-Jun
Squash planted		6-Jun	3-Jun
Strategy 3 pints/acre and Dual 1 pint/acre		6-Jun	
Bravo 720		11-Jul	23-Jul
Ranman			23-Jul
Equus			30-Jul
Ranman			30-Jul
NuCop50		11-Jul	30-Jul
Stand counts		16-Jul	
Hand weeding		31-Jul	15-Aug
Copper application		15-Aug	14-Aug
Ranman			14-Aug
Quadris 8 oz/acre		15-Aug	
Equis 1 pts/acre		15-Aug	
NuCop50 3lbs/acre		21-Aug	
Previcur Flex 1.2pt/acre		21-Aug	14-Aug
Bravo 720 2pts/acre		21-Aug	
Ranman			21-Aug
NuCop50 3lbs/acre		5-Sep	21-Aug
Quadris 12 oz/acre		5-Sep	
Piericure Flex 1.2 pts/acre		5-Sep	
Harvest and yield measurements		16-Sep	

Table S.2. Arthopods observed on squash leaves in 2014 (a) and 2015 (b).

2014	**Total insects per 20m flower transect**	**Freq (%)**
Herbivores		
Lygus lineolaris	802	38.61
Miridae	793	38.18
Diabrotica undecimpunctata	110	5.30
Curculionidae	90	4.33
Lepidoptera	86	4.14
Alticini	75	3.61
Cydnidae	55	2.65
Scarabaeidae	22	1.06
Acrididae	13	0.63
Chrysomelidae	10	0.48
Thysanoptera	10	0.48
Aphidae	4	0.19
Membracoidea	3	0.14
Anasa tristis	2	0.10
Pentatomidae	1	0.05
Elateridae	1	0.05
Total	**2077**	**100.00**
Natural Enemies		
Coccinellidae	103	21.50
Orius spp.	87	18.16
Chrysopidae	69	14.41
Parasitica	66	13.78
Staphylinidae	53	11.06
Cantharidae	46	9.60
Geocoridae	14	2.92
Nabidae	14	2.92
Carabidae	6	1.25
Podisus maculiventrus	5	1.04
Araneae	9	1.88
Lampyridae	2	0.42
Salticidae	2	0.42
Formicidae	1	0.21
Reduviidae	**1**	0.21
Berytidae	**1**	0.21
Total	**479**	**100.00**
Pollinators		
Syrphidae	76	66.67
Apis mellifera	26	22.81
Other Anthophilia	10	8.77

Table S.2. (cont'd)

Bombus impatiens	2	1.75
	114	100.00

b.

2015	Total insects per 20m flower transect	Freq (%)
Herbivores		
Membracoidea	610	37.70
Lygus lineolaris	453	28.00
Alticini	152	9.39
Anthicidae	105	6.49
Cuculionidae	101	6.24
Aphididae	58	3.58
Chrysopidae	47	2.90
Chyrsomelidae	25	1.55
Miridae	22	1.36
Cydnidae	18	1.11
Lepidoptera	14	0.87
Acalymma vittatum	4	0.25
Orthoptera	8	0.49
Scarabaeidae	1	0.06
Total	**1618**	**100.00**
Natural Enemies		
Orius spp.	1677	48.38
Parasitica	1285	37.07
Coccinellidae	255	7.36
Cantharidae	132	3.81
Araneae	45	1.30
Nabidae	23	0.66
Formicidae	19	0.55
Geocoridae	12	0.35
Vespidae	9	0.26
Berytidae	2	0.06
Lampyridae	2	0.06
Elateridae	2	0.06
Carabidae	1	0.03
Reduviidae	1	0.03
Staphylinidae	**1**	**0.03**
Total	**3466**	**100.00**
Pollinators		
Apis mellifera	120	50.63
Syrphidae	79	33.33
Other Apoidea	37	15.61
Bombus impatiens	1	0.42

Table S.2. (cont'd)

Total		**237**	**100.00**

Table S.3. Total arthropods captured in weekly pitfall traps in 2014 (a) and 2015 (b).
a.

2014	Total captured	Freq (%)
Herbivores		
Collembola	7,570	59.71%
Aphididae	1,218	9.61%
Membracoidea	1,054	8.31%
Cydnidae	472	3.72%
Orthoptera	468	3.69%
Anthicidae	442	3.49%
Thysanoptera	315	2.48%
Miridae	250	1.97%
Scarabaeidae	230	1.81%
Chrysomelidae	157	1.24%
Elateridae	89	0.70%
Curculionidae	69	0.54%
Anasa tristis	66	0.52%
Alticini	48	0.38%
Lepidoptera	44	0.35%
Leptinotarsi decemlineata	39	0.31%
Acalymma vittatum	39	0.31%
Lygus lineolaris	38	0.30%
Histeridae	28	0.22%
Pentatomidae	20	0.16%
Diplopoda	10	0.08%
Pentatomidae	6	0.05%
Lygaeidae	4	0.03%
Diabrotica undecimpunctata	2	0.02%
Total	**12,678**	**100.00%**
Natural Enemies		
Formicidae	3,357	26.33%
Staphylinidae	3,122	24.48%
Carabidae	1,242	9.74%
Chrysopidae	1,122	8.80%
Parasitica	937	7.35%
Lycosidae	832	6.52%
Chilopodae	544	4.27%
Other Aranea	342	2.68%
Lycosidae	315	2.47%
Opiliones	274	2.15%
Geocoridae	243	1.91%
Coccinellidae	223	1.75%
Nabidae	67	0.53%
Pompilidae	62	0.49%

Table S.3. (cont'd)

Anthocoridae	20	0.16%
Mutilidae	19	0.15%
Vespidae	18	0.14%
Lampyridae	4	0.03%
Reduviidae	3	0.02%
Cantharidae	2	0.02%
Myrmeleontidae	2	0.02%
Asilidae	1	0.01%
Total	**12,751**	**100.00%**
Other Arthropods		
Unknown Larva	525	56.88%
Unknown Coleoptera	174	18.85%
Unknown Hymenoptera	72	7.80%
Apoidea	41	4.44%
Psocoptera	22	2.38%
Isopoda	20	2.17%
Haclictidae	16	1.73%
Apis mellifera	11	1.19%
Syrphidae	9	0.98%
Unknown Hemiptera	9	0.98%
Bombus	6	0.65%
Tipuloidea	3	0.33%
Sphecidae	3	0.33%
Meloidae	3	0.33%
Symphyta	2	0.22%
Eucerini	2	0.22%
Tenthredinidae	2	0.22%
Dermaptera	1	0.11%
Peponapis pruinosa	1	0.11%
Silphidae	1	0.11%
Total	**923**	**100.00%**

Table S.4. Major field activities in 2014 and 2015. The study took place in a conventionally managed cucumber field in Benton Harbor, MI.

Field Operation	Year	
	2014	2015
Dual Magnum and Command 3ME applied	15-Apr	16-Apr
Beds made	25-Apr	27-Apr
Cucumbers and flowers planted	26-Apr	30-Apr
Presidio and Admire application		30-Apr
Dual Magnum and Command 3ME applied		30-Apr
Plastic opened on cover crops	29-May	
Plastic removed	8-Jun	
Harvesting begins	29-Jun	8-Jul
Hand weeding of flower strips		2-Jun
Dual Magnum and Command 3ME applied		28-Apr
Initiate 720 and Nu-cop 50 DF applied	18-Jun	25-May
Mancozeb applied		11-Jun
Nu Cop 50 DF, Initiate 720, Perm-up applied	18-Jun	
Mancozeb applied		2-Jul
Zampro and Initiate 720 applied		4-Aug

Table S.5. Total arthropods captured by sweep net in 2014 (a) and 2015 (b).

a.

2014	Total insects per 20m flower transect	Freq (%)
Herbivores		
Lygus lineolaris	802	38.61
Miridae	793	38.18
Diabrotica undecimpunctata	110	5.30
Curculionidae	90	4.33
Lepidoptera	86	4.14
Alticini	75	3.61
Cydnidae	55	2.65
Scarabaeidae	22	1.06
Acrididae	13	0.63
Chrysomelidae	10	0.48

Table S.5. (cont'd)

Thysanoptera	10	0.48
Aphidae	4	0.19
Membracoidea	3	0.14
Anasa tristis	2	0.10
Pentatomidae	1	0.05
Elateridae	1	0.05
Total	**2077**	**100.00**
Natural Enemies		
Coccinellidae	103	21.50
Orius spp.	87	18.16
Chrysopidae	69	14.41
Parasitica	66	13.78
Staphylinidae	53	11.06
Cantharidae	46	9.60
Geocoridae	14	2.92
Nabidae	14	2.92
Carabidae	6	1.25
Podisus maculiventrus	5	1.04
Araneae	9	1.88
Lampyridae	2	0.42
Salticidae	2	0.42
Formicidae	1	0.21
Reduviidae	**1**	0.21
Berytidae	**1**	0.21
Total	**479**	**100.00**
Pollinators		
Syrphidae	76	66.67
Apis mellifera	26	22.81
Other Anthophilia	10	8.77
Bombus impatiens	2	1.75
	114	100.00

b.

2015	**Total insects per 20m flower transect**	**Freq (%)**
Herbivores		
Membracoidea	610	37.70
Lygus lineolaris	453	28.00
Alticini	152	9.39
Anthicidae	105	6.49
Cuculionidae	101	6.24
Aphididae	58	3.58
Chrysopidae	47	2.90

Table S.5. (cont'd)

Chyrsomelidae	25	1.55
Miridae	22	1.36
Cydnidae	18	1.11
Lepidoptera	14	0.87
Acalymma vittatum	4	0.25
Orthoptera	8	0.49
Scarabaeidae	1	0.06
Total	**1618**	**100.00**
Natural Enemies		
Orius spp.	1677	48.38
Parasitica	1285	37.07
Coccinellidae	255	7.36
Cantharidae	132	3.81
Araneae	45	1.30
Nabidae	23	0.66
Formicidae	19	0.55
Geocoridae	12	0.35
Vespidae	9	0.26
Berytidae	2	0.06
Lampyridae	2	0.06
Elateridae	2	0.06
Carabidae	1	0.03
Reduviidae	1	0.03
Staphylinidae	**1**	**0.03**
Total	**3466**	**100.00**
Pollinators		
Apis mellifera	120	50.63
Syrphidae	79	33.33
Other Apoidea	37	15.61
Bombus impatiens	1	0.42
Total	**237**	**100.00**

Table S.6. Total arthropods captured on sticky traps in 2014 (a) and 2015 (b).

a.

2014	Location		Total	Freq (%)
	Flower strip	Cucumbers		
Herbivores				
Membracoidea	419	n/a	419	27.97
Lygus lineolaris	347	n/a	347	23.16
Chrysomelidae	288	n/a	288	19.23
Alticini	170	n/a	170	11.35
Aphididae	96	n/a	96	6.41
Miridae	72	n/a	72	4.81
Cydnidae	36	n/a	36	2.40
Curculionidae	24	n/a	24	1.60
Diabrotica undecimpunctata	16	n/a	16	1.07
Acalymma vittatum	11	n/a	11	0.73
Acari	7	n/a	7	0.47
Lepidoptera	6	n/a	6	0.40
Scarabaeidae	5	n/a	5	0.33
Pentatomidae	1	n/a	1	0.07
Total			**1,498**	**100.00**
Natural Enemies				
Orius spp.	471	n/a	471	40.19
Parasitica	401	n/a	401	34.22
Coccinellidae	79	n/a	79	6.74
Staphylinidae	57	n/a	57	4.86
Araneae	46	n/a	46	3.92
Chrysopidae	34	n/a	34	2.90
Rove Beetle	26	n/a	26	2.22
Cantharidae	26	n/a	26	2.22
Carabidae	18	n/a	18	1.54
Geocoridae	5	n/a	5	0.43
Elateridae	4	n/a	4	0.34
Nabidae	3	n/a	3	0.26
Formicidae	1	n/a	1	0.09
Reduviidae	1	n/a	1	0.09
Total			**1,172**	**100.00**
Pollinators				
Apis mellifera	0	n/a	0	0.00
Bombus impatiens	1	n/a	1	0.79
Peponapis pruinosa	0	n/a	0	0.00
Syrphidae	15	n/a	15	11.90
Other Apoidea	110	n/a	110	87.30
Total			**126**	**100.00**

Table S.6. (cont'd)
b.

2015	Location		Total	Freq (%)
	Flower strip	Cucumbers		
Herbivores				
Membracoidea	610	591	1,201	39.35
Lygus lineolaris	453	412	865	28.34
Alticini	152	96	248	8.13
Anthicidae	105	94	199	6.52
Cuculionidae	101	95	196	6.42
Aphididae	58	72	130	4.26
Chrysopidae	47	5	52	1.70
Chyrsomelidae	25	16	41	1.34
Miridae	22	14	36	1.18
Cydnidae	18	12	30	0.98
Lepidoptera	14	6	20	0.66
Acalymma vittatum	4	14	18	0.59
Orthoptera	8	6	14	0.46
Scarabaeidae	1	1	2	0.07
Total			**3,052**	**100.00**
Natural Enemies				
Parasitica	898	779	1,677	48.41
Orius spp.	931	354	1,285	37.10
Araneae	88	167	255	7.36
Coccinellidae	71	61	132	3.81
staphylinidae	18	27	45	1.30
Cantharidae	20	3	23	0.66
Nabidae	10	9	19	0.55
Formicidae	4	8	12	0.35
Elateridae	3	6	9	0.26
Hemerobiade	2	0	2	0.06
Lampyridae	1	1	2	0.06
Geocoridae	1	1	2	0.06
Berytidae	0	1	1	0.03
Total			**3,464**	**100.00**
Pollinators				
Apis mellifera	4	6	10	7.35
Bombus impatiens	0	0	0	0.00
Peponapis pruinosa	0	0	0	0.00
Syrphidae	66	37	103	75.74
Other Apoidea	16	7	23	16.91
Total			**136**	**100.00**

Table S.7. Total pollinators observed in 2014 (a) and 2015 (b).

a.

2014	**Row**				**Total**	**%**
	0	**1**	**3**	**5**		
Apis mellifera	n/a	45	40	46	131	24.76
Bombus impatiens	n/a	3	2	2	7	1.32
Peponapis pruinosa	n/a	110	99	122	331	62.57
Syrphidae	n/a	27	26		53	10.02
Other Apoidea	n/a	0	7	0	7	1.32
Total	**n/a**	**185**	**174**	**170**	**529**	**100.00**

b.

2015	**Row**				**Total**	**%**
	0	**1**	**3**	**5**		
Apis mellifera	2488	266	173	178	3105	61.27
Bombus impatiens	0	0	0	0	0	0.00
Peponapis pruinosa	4	3	4	5	16	0.32
Syrphidae	1738	75	22	15	1850	36.50
Other Apoidea	80	8	3	6	97	1.91
Total	**4310**	**352**	**202**	**204**	**5068**	**100.00**

APPENDIX B:

Record of Deposition of Voucher Specimens

The specimens listed below have been deposited in the named museum as samples of those species or other taxa, which were used in this research. Voucher recognition labels bearing the voucher number have been attached or included in fluid preserved specimens.

Voucher Number: __**2015-05**____

Author and Title of thesis:
Author: Nicole F. Quinn
Title: Habitat Management for Beneficial Insects in Michigan Cucurbit Agroecosystems

Museum(s) where deposited:
Albert J. Cook Arthropod Research Collection, Michigan State University (MSU)

Specimens:
**If lowest taxonomic level is above family, lowest classification used for arthropod is indicated

Table S.8. Voucher specimens deposited at the Albert J. Cook Arthropod Research Collection (Michigan State University).

Family	Genus-Species	Life Stage	Quantity	Preservation
Acrididae		Adult	2	pinned
Anthicidae		Adult	2	pinned
Alticini		Adult	2	pinned
Andrenidae	*Andrena wilkella*	Adult	2	pinned
Anthocoridae	*Orius* spp.	Adult	2	pinned
Aphididae		Adult	1	pinned
Apidae	*Apis mellifera*	Adult	2	pinned
Apidae	*Bombus* spp.	Adult	2	pinned
Apidae	*Peponapis pruinosa*	Adult	2	pinned
Berytidae		Adult	1	pinned
Carabidae	*Agonum* spp.	Adult	2	pinned
Carabidae	*Amara* spp.	Adult	2	pinned
Carabidae	*Anisodactylus* spp.	Adult	2	pinned
Carabidae	*Bembidion* spp.	Adult	2	pinned
Carabidae	*Calosoma* spp.	Adult	1	pinned
Carabidae	*Cicindellinae* spp.	Adult	2	pinned

Table S.8. (cont'd)

Carabidae	*Geopinus incrassatus*	Adult	2	pinned
Carabidae	*Harpalus* spp.	Adult	2	pinned
Carabidae	*Pterostichus* spp.	Adult	2	pinned
Carabidae	*Stenolophus* spp.	Adult	2	pinned
Chrysomelidae	*Acalymma vittatum*	Adult	2	pinned
Chrysopidae		Adult	1	pinned
Cicadellidae		Adult	2	pinned
Coccinellidae		Adult	4	pinned
Coreidae	*Anasa tristis*	Adult	2	pinned
Curculionidae		Adult	2	pinned
Cydnidae		Adult	2	pinned
Formicidae		Adult	2	pinned
Geocoridae		Adult	2	pinned
Gryllidae		Adult	2	pinned
Halictidae	*Lasioglossum* spp.	Adult	2	pinned
Ichneumonidae		Adult	2	pinned
Miridae	*Lygus lineolaris*	Adult	2	pinned
Mutilidae		Adult	2	pinned
Nabidae		Adult	2	pinned
Pentatomidae		Adult	2	pinned
Reduviidae		Adult	2	pinned
Scarabaeidae		Adult	2	pinned
Staphylinidae		Adult	2	pinned
Syrphidae		Adult	2	pinned

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