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HABITAT MANAGEMENT USING NATIVE FLOWERING PERENNIALS TO INCREASE BENEFICIAL INSECTS IN MICHIGAN HIGHBUSH BLUEBERRY

By

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Abstract

Conservation plantings of native wildflowers were established alongside blueberry fields to test the hypothesis that provision of resources for natural enemies and bees increases their abundance in adjacent crop fields. For two growing seasons (2007 and 2008), at four commercial blueberry farms, fields with flowering field borders were compared to control fields where growers maintained field borders of mown grass. In both years, this revealed contrasting effects of the presence of flowering plants on representative groups of natural enemies, pests, and pollinators. Natural enemies, wild bees, and some pests were consistently more abundant in fields adjacent to flower plantings. A laboratory evaluation was also performed to compare the longevity of three different commercially available natural enemies: a lady beetle (Coleoptera: Coccinelidae: *Hippodamia convergens* Guérin-Méneville), a predatory bug (Heteroptera: Anthocoridae: *Orius insidiosus* (Say)), and a generalist aphid parasitoid (Hymenoptera: Braconidae: *Aphidius colemani* Viereck), caged with cut flowers from the border plantings. Natural enemies exhibited a variable pattern of sensitivity to provision of flowers, with *A. colemani* being the most sensitive, *O. insidiosus* intermediate, and *H. convergens* being relatively insensitive to flower availability.

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CHAPTER 1

Habitat management to increase populations of beneficial arthropods in agricultural fields

Introduction. The ecological integrity of the world's ecosystems has become increasingly at-risk from human land use changes (Sanderson et al. 2002, Foley et al. 2005, Hoekstra et al. 2005, Pimentel and Pimentel 2006). The continued deterioration of ecological networks, nutrient cycling, and filtration in these natural systems could have grave consequences for human societies as essential ecosystem services are lost (Lightfoot and Burchell 2004, Losey and Vaughan 2006, Kremen et al. 2007).

Agriculture is the dominant land-use activity around the globe (Foley et al. 2005). In the U.S., about 50% of the total land area is used for food production (Pimentel and Pimentel 2006). Michigan devotes about 28% of its land area to agriculture (10 million acres, NASS 2007). Agricultural lands are both suppliers and consumers of ecosystem services (Swinton et al. 2007, Kroeger and Casey 2007, Zhang et al. 2007) and as such represent an ideal target for changes in land management practices aimed at the mitigation of anthropogenic ecosystem disruption.

There is no lack of evidence that intensive agricultural land use impacts surrounding natural ecosystems (Wilcove et al. 1998, Dale et al. 2005). The effects of fertilizer runoff (Donner et al. 2004), pesticide runoff and drift (Verro et al. 2009), and introduced biocontrol agents (Lewis 1989, Hawkins and Marino

1997, Louda et al. 1997, Pemberton 2000, Lynch and Thomas 2000, Louda et al. 2003, Finlayson et al. 2008) have been well documented.

The impact of changing landscapes, i.e. habitat conversion from wild to agricultural, agricultural to suburban, suburban to urban, etc. had been of less concern until declines in farmland birds in Europe were linked to agricultural intensification (Krebs et al. 1999). Since then, studies have shown declines in birds, syrphid flies, bumblebees, and butterflies; all associated with habitat conversion for agriculture during the latter half of the 20th century (Thomas et al. 2004, Biesmeijer et al. 2006).

One proposed way to mitigate this reduction in natural habitat quantity is to improve the habitat quality of agricultural lands for specific species or groups of species. With this in mind, researchers have investigated the impacts of agricultural practices on ecological interactions within crop fields and between crop fields and surrounding habitats (Van Emden and Williams 1974, Zhao et al. 1992, Hickman and Wratten 1996, Werling and Gratton 2008). This has led to the development of practices such as habitat management for conservation biocontrol (Gurr et al. 2004) and pollinator habitat management (Batra 2001), both of which aim to increase floral diversity in landscapes to provide essential resources for beneficial insects.

Meanwhile, government funding programs have developed to help farmers provide conservation land on their farms. These programs, loosely referred to as agri-environment schemes (Kleijn et al. 2006) provide a means for reaching conservation targets and motivating land conservation within intensively managed farm-dominated regions by providing economic incentives. These programs are often aimed at providing environmental benefits such as erosion control, runoff reduction, or vertebrate conservation, but can lead to increases in the abundance or diversity of beneficial insects as well (Van Buskirk and Willi 2004, Thomas et al. 2004, Kleijn et al. 2006, Carvell et al. 2007). Thus, as more ecological data becomes available about the impacts of agri-environment schemes on the insect fauna of agricultural lands, they might be modified to provide more diverse environmental benefits at a lower cost and increase the likelihood of adoption (Kremen 2005, Swinton et al. 2007).

Conservation of Beneficial Insects in Farmland. This thesis focuses on insects because the impacts of agriculture on insect communities (and *vice versa*) have been investigated for many years, and there is increasing interest in designing farm landscapes to enhance populations of beneficial insects (Pfiffner and Wyss 2004, Landis et al. 2005). Of course, the larger ecological concepts can certainly be applied to other taxa (Albrecht et al. 2007).

One of the goals of conventional pest management programs, has been to reduce the abundance of insects in cropland because they are seen as the primary agents of economic levels of crop damage, and often rightly so (Borlaug 1972). However, it has been recognized for hundreds of years that not all insects cause damage, and that many in fact help to reduce damage (Van Driesche and Bellows 1996) or are absolutely essential to achieve a profitable yield (e.g. pollinators) (Kevan 2001). These facts have led to the growth and prosperity of the biocontrol and pollination industries, respectively. Yet, attempts by growers to provide conditions amenable to beneficial insects on their land are frequently stymied by other management practices that are counterproductive to this goal. These practices can be broadly categorized as agents of disturbance.

Disturbance in agricultural fields comes in a variety of forms: natural (e.g. rain, fire, etc.), mechanical (e.g. tilling), and chemical (e.g. insecticides), all of which potentially have dramatic effects on the different insect populations occurring there (e.g. Way 1970 as cited by Van Emden and Williams 1974). Disturbance regimes vary greatly among and within cropping systems and affect different groups of organisms very differently at different scales, so generalizations may be inappropriate (Norris and Kogan 2005, Shennan 2008). However, for practical purposes generalizations must be made occasionally and here they will be limited to the effects of the two types of disturbance that are within the farmer's control (mechanical and chemical) and specifically to their impacts on beneficial arthropods.

Mechanical Disturbance. Tillage is perhaps the most common mechanical cause of direct insect mortality in crop fields. Tilling or rotovating a field is applied as a pest control measure in some crops and can lead to substantial reductions in emerging adult populations of insects that live below ground as larvae (Norris and Kogan 2000, Szendrei et al. 2005, Szendrei and Isaacs 2006). Although the proximal causes of the correlation between soil-nesting insect abundance and tillage intensity have not been conclusively identified, physical damage to the integument, desiccation, or predation following this type of violent soil disturbance are likely contributors. Thus, tillage cannot be classified as a selective control measure and is probably equally harmful to beneficial as well as pest insects living beneath the soil. Indeed, increasing tillage intensity was a predictor of reduced native bee abundance in melon fields (Shuler et al. 2005), thought to be caused by direct disturbance of their nesting sites.

Indirect impacts of tillage on beneficial insect abundances in crop fields are mainly caused by reduction in the abundance of non-crop plants and include: reductions in alternate forage (e.g. nectar, pollen, prey), microhabitat refuges, and oviposition sites (Norris and Kogan 2005). The indirect effects of mowing are similar in that they work primarily by reducing available forage and habitat complexity (Van Den Bosch and Lagace 1967, Hossain et al. 2000). Direct mortality of beneficial insects by mowing may be less important, at least for flying insects (Landis and Menalled 1998).

Chemical Disturbance. Of all the chemical inputs utilized in modern agriculture, insecticides cause the most direct mortality to beneficial insects (Van Driesche and Bellows 1996, Ruberson et al. 1998). This is reflected in the fact that the use of more selective insecticides and/or application methods has been a cornerstone of integrated pest management and conservation biocontrol programs since their inception (Metcalf 1980, Van Driesche and Bellows 1996, Barbosa 1998). However, even the so-called selective insecticides can reduce the effectiveness of naturally occurring beneficials through sub-lethal effects (Desneux et al. 2007).

In addition to insecticides there are a wide variety of other chemicals applied to crop fields. The direct effects of herbicides, fungicides, and chemical fertilizers on arthropods are generally less well studied than those of insecticides. Herbicides can exhibit a range of toxicity to various arthropods both in the field and laboratory (Freemark and Boutin 1995), but indirect effects from their toxicity to plants are probably more important (McLaughlin and Mineau 1995, Norris and Kogan 2005). This general rule can be applied to the other agricultural chemicals as well, as their impact on arthropods is often the result of complex interactions between soil biota, plants, and fungi (McLaughlin and Mineau 1995, Norris and Kogan 2000, Norris and Kogan 2005).

The importance of refuges of flowering plants. Anthropogenic disturbance regimes in crop fields essentially create a mosaic of hospitable and inhospitable conditions at all spatial and temporal scales within agricultural landscapes. This effect is often described as habitat fragmentation and it is frequently implicated as a contributor to recent declines in arthropod mediated ecosystem services in farmland (Kruess and Tscharntke 1994, Cane 2001, Kremen et al. 2002, Ricketts et al. 2008, Holzschuh et al. 2008).

One way to alleviate the impact of fragmentation on beneficial insects is the establishment of strips of flowering plants in and/or around crop fields (Hickman and Wratten 1996, Barbosa 1998, Gurr et al. 2004, Isaacs et al. 2009).

Flowering plant habitats can provide year-round resources including nectar, pollen, alternate prey, and a complex architecture with multiple niches and microhabitats for beneficial arthropods (Landis et al. 2000, Van Emden 2002).

Experimental manipulation of the environment around cropped areas by establishing flowering plants can increase natural enemy populations (Long et al. 1998, Rebek et al. 2005) and provide forage for wild bees that can increase their abundance (Kells et al. 2001, Buchi 2002). Provision of nectar and pollen by flowering plants benefits parasitoid survival and fecundity (Jervis et al. 1993, Wackers 2004, Lee and Heimpel 2008). Parasitoids have greater mobility in habitats with flowering plants than in nearby habitats without flowers (Van Emden 1962), and lack of sugar nutrition reduces parasitoid host searching efficiency (Wackers 1994, Takasu and Lewis 1995), which leads to reduced effectiveness at regulating pest populations.

Refuges in field perimeters. Flowering cover crops can support beneficial insects populations in crop fields (Bugg and Waddington 1994, Nicholls et al. 2000, Kinkorová and Kocourek 2000). Unfortunately placement of the resource plants inside fields inevitably creates potential for death of beneficial insects if the crop is tilled or treated with insecticide (Lee et al. 2001). Placement of these resources outside the crop area provides a more benign environment for beneficial insects where they can feed on nectar and pollen, utilize alternate hosts, and find refuge in an area not impacted by harmful disturbances (Sotherton 1984, Thomas et al. 1991).

Natural or semi-natural habitat in the landscape outside the cropped area has consistently been shown to support beneficial insects (Kremen et al. 2002, Steffan-Dewenter 2003, Kremen et al. 2004, Bianchi et al. 2006, Greenleaf and Kremen 2006). Unfortunately, individual growers have little control over land management decisions in the surrounding landscape. Lands adjacent to fields are often not owned by the grower, may be managed for various purposes other than to support natural enemies, and may be urbanized. For these farms, integrating refuge and flower resources directly into the field perimeter is more likely to be adopted as a strategy to create habitat for beneficial insects.

The importance of scale. The target insects of habitat management respond at different scales to habitat diversification (Banks 2000, Tscharntke et al. 2007, Fraser et al. 2008, Werling and Gratton 2008). Small parasitoid wasps (≤2mm) for example may respond at a relatively small scale to the addition of flowering resources to a field, whereas larger organisms (e.g. bumblebees (Osborne et al. 2008) and lady beetles (Gardiner et al. 2009) respond to resource availability at larger spatial scales. The scale at which these insects respond is important from a practical standpoint, because farmers are more likely to implement habitat management if there is a measurable benefit at the field-scale (Tilman et al. 2002, Kurkalova et al. 2006, Wossink and Swinton 2007).

Habitat management in Michigan highbush blueberry fields. The effectiveness of habitat management as a means of beneficial insect conservation varies depending on the nature of the disturbance regime in the target crop (Landis et al. 2000). Generally these strategies have had more success in perennial crops, especially orchards and vineyards (Doutt and Nakata 1973, Nicholls et al. 2000, Kinkorová and Kocourek 2000), presumably because less intensive herbicide and tillage regimes lead to increased stability of beneficial insect populations (Van Emden and Williams 1974, Landis and Menalled 1998). Thus, the highbush blueberry (Ericaceae: *Vaccinium corymbosum* L.) cropping system in Michigan is expected to benefit from this habitat management strategy because it is a perennial crop. The average lifetime of a planting is generally greater than 20 years (Shoemaker 1975) and disturbance regimes are generally less intensive than most annual crops.

Furthermore, the pollination biology of blueberry makes it amenable to pollination by wild bees, so conservation of native pollinators through habitat management might be a viable strategy for growers of this crop especially. Most varieties of highbush blueberry are somewhat self-fertile, but require insect pollination because flower morphology prevents transfer of pollen from anther to stigma on the same flower (Gough 1991).

Blueberry flowers are most effectively pollinated by bumble bees (*Bombus* spp.) and ground nesting bees (*Andrena* spp.) on a per visit basis (Dogterom 1999, Javorek et al. 2002), but most growers continue to rent honey bee colonies because they are more efficient economically (Dogterom 1999, MacKenzie 2009). Still, wild native bees provide a cost free contribution to pollination of blueberry flowers, and if this contribution can be increased through habitat management at a low cost-benefit ratio then uptake of conservation practices is expected to increase.

However, pest pressure in Michigan blueberry production can be high, leading to intensive use of fungicides and broad spectrum insecticides, which can reduce beneficial insect populations (O'Neal et al. 2005, Tuell 2007). Thus, one goal of this thesis was to evaluate the effectiveness of this strategy in fields managed under standard commercial production practices, to determine whether habitat manipulation could support beneficial insects in a crop where pesticide use is relatively high.

This thesis reports on the effectiveness of strips of native perennial flowering plants for conservation of pollinators and natural enemies of crop pests over a two-year period. Chapter 2 describes the results of a laboratory study comparing the survival of representative groups of natural enemies provided with flowers of the species contained in the conservation strips. Chapter 3 uses arthropod abundance data from yellow sticky trap sampling at to identify trends in natural enemy and pest abundance in relation to the flowering plant strips. Chapter 4 examines the effect of the flowering strips on pollinator abundance, pollination, and yield in blueberry. Finally, the concluding chapter summarizes the implications of this research for the future of beneficial insect conservation in farmland.

CHAPTER 2

Changes in natural enemy longevity in the presence of native Midwestern flowering plants

Introduction. Conservation biological control can been defined as: "Modification of the environment or existing practices to protect and enhance specific natural enemies or other organisms to reduce the effect of pests" (Hajek 2004). In practice, conservation biocontrol often entails withholding application of insecticides, using selective insecticides, or manipulating the plant community in the field or field margins. The latter two approaches are often referred to as habitat management, a strategy that has grown in popularity in recent years (Landis et al. 2000, Gurr et al. 2004).

Incorporating flowering plants into agricultural landscapes has attracted a significant amount of interest lately, because it simultaneously provides habitat for ground dwelling predators as well as alternative hosts, pollen, and nectar for flying predators and parasitoids (Landis et al. 2000, Pfiffner and Wyss 2004). The effectiveness of a particular flower species for increasing the effectiveness of a specific biocontrol agent in a particular crop can depend on a number of factors, including: timing of flowering, nectar content, nectar composition, pollen characteristics, accessibility, and attractiveness (Hodek 1996, Lee et al. 2004, Venzon et al. 2006, Vattala et al. 2006, Fiedler and Landis 2007b). Nonetheless, the effectiveness of any biocontrol strategy must ultimately be measured by its impact on the target pest (Lavandero et al. 2006). Habitat management using floral resource plants can be expected to have varying impacts on natural enemies and pests depending on their nutritional requirements, behavior, and morphology. Thus, the latest efforts in habitat management using floral resource plants have focused on 'selective food plants' that benefit the natural enemy but not the target pest (Baggen and Gurr 1998, Baggen et al. 1999, Begum et al. 2007).

Since the beginning of the modern era of conservation biological control, researchers have investigated the effects of plant-derived non-host foods on the fecundity and longevity of natural enemies (DeBach 1964, Jervis et al. 1993, Hodek 1996). The overarching conclusion from these many years of research has been that nectar and pollen are generally good food resources for a variety of natural enemies. However, much of the research to date has focused on plants that are not necessarily native to the region where their use is being proposed for habitat management (Fiedler et al. 2008).

Native plants have a number of potential advantages over exotics in that they are less likely to become invasive, better adapted to the local soil and climate conditions, and less likely to benefit exotic pests (Pfiffner and Wyss 2004, Fiedler and Landis 2007a, Tuell et al. 2008, Isaacs et al. 2009). Perennial native plantings additionally provide a more stable habitat that benefits overwintering natural enemies as well as native bees (Long et al. 1998, Svensson et al. 2000, Marshall and Moonen 2002, Carvell et al. 2006a). Of course, careful evaluation of any plant is necessary before it is recommended for widespread use in a habitat management program (Pfiffner and Wyss 2004, Lavandero et al. 2006, Wackers et al. 2007).

The goal of these experiments was to determine the suitability of Michigan native plants as food sources for commercially available natural enemies. Two naturalized exotic plants were also included (*Daucus carota* L. and *Trifolium pratense* L.) for comparison because of their abundance in disturbed areas throughout Michigan (Rabeler 1998). The insects studied were a lady beetle (Coleoptera: Coccinelidae: *Hippodamia convergens* Guérin-Méneville), a predatory bug (Heteroptera: Anthocoridae: *Orius insidiosus* (Say)), and a generalist aphid parasitoid (Hymenoptera: Braconidae: *Aphidius colemani* Viereck). These insects were chosen because they are readily available in large quantities and representative of major natural enemy groups in Michigan. The results of these survival analyses will be used to make inferences about the impacts of a habitat management program using these native plants on natural enemy communities in the field and help guide selection of plants for use in future conservation programs.

Materials and Methods: Flowers. Flowering stems of the native plants *Agastache nepetoides* (L.) Kuntze, *Lobelia siphilitica* L., *Monarda fistulosa* L., *Penstemon hirsutus* (L.) Willd., *Silphium terebinthinaceum* Jacq., *Solidago juncea* Aiton, and *Veronicastrum virginicum* (L.) Farw., were collected from field planted plots in the perimeters of blueberry fields. These plants were supplied by Wildtype nurseries (Mason, MI.) and planted as plugs (one-year-old plants) in

2006. Flowering stems of the naturalized exotics *Daucus carota* L. and *Trifolium pratense* L. were collected from blueberry field perimeters where they occurred naturally. Stems with inflorescences were transported in water to the laboratory and placed in experimental cages on the same day. At least three inflorescences were placed in each cage to provide *ad libitum* flower resources. Before being placed in each cage, inflorescences were shaken upside down repeatedly, inspected visually, and all visible insects were removed.

Cages. Cages were constructed from hexagonal 3.8L polyethylene containers, with holes cut in the sides and covered with mesh or acetate sheet for ventilation and observation, respectively. Three cage (treatment) types were prepared; 1) *Flower* in which flowering stems were placed in floral water vials inserted through holes in the lid of the inverted containers and an additional water vial was filled with water and a piece of dental wick to provide moisture; 2) *water control* in which one vial contained the moist dental wick while the other was sealed with hot glue; and 3) *dry control* in which both vials were sealed with hot glue.

Experimental setup. Cages were placed on wire shelves in a laboratory at Trevor Nichols Research Complex, Fennville, MI at ambient temperature (~23°C) and humidity (~65%). Each shelf held 16-18 cages and had its own light source, which consisted of two 48" fluorescent plant and aquarium bulbs (40W) set on a 16:8 hour light:dark cycle. A total of 48 or 54 cages (6 replicates per treatment) were used in each experiment, depending on the number of treatments that were being evaluated at the time. The position of each cage on the shelves was randomized to minimize biases caused by lighting or temperature variations among shelves.

Experimental procedure. *H. convergens*, *O. insidiosus*, and *A. colemani* were ordered as needed from Koppert Biological Systems, Inc. (Romulus, MI) and were stored at 4°C before the start of each experiment, typically for less than 24h. While still under refrigeration, ten individuals per replicate were transferred with a paintbrush from the shipping substrate into a 1.25oz. plastic deli cup (Solo® Cup Company, Highland Park, IL.). Ten adult individuals of the same species were released into each treatment cage, with six replicates per species and treatment combination. Insects were released into cages by opening the cage, placing the deli cup in the cage, removing the cup lid, and closing the cage. The moment of release marked the beginning of day 0 for each experiment.

Survivorship was assessed daily by counting the number of alive and dead natural enemies in each cage. When all insects could not be accounted for within a 2.5 minute observation period, remaining insects were recorded as missing. Assessments were conducted at the same time each day by 2-3 observers. The order that each cage was counted was random in that the position of each cage was random (see setup), but observers moved systematically along each shelf to reduce the amount of time elapsed between assessment of cages. Observers never counted the same cages that they had counted on the previous day.

Water was added daily with a syringe through small holes drilled near the top of the water vial just below the bottom of the cage. Fresh inflorescences were added when the flowers in the cages began to wilt to maintain *ad libitum* floral resources. This was done by flipping the cages over and removing the bottom to insert a fresh inflorescence. Wilted flowers were left in the cages to prevent inadvertent removal of insects. Experiments were stopped on the twelfth day and all cages were emptied and cleaned with hot soapy water for reuse in subsequent experiments.

Experiments were carried out to coincide with the phenology of the flowers. In 2007, it was assumed that natural enemy longevity would not vary among shipments from the supplier, so controls were run when space and time permitted. However, in 2008, because of concerns about variation in natural enemy longevity among batches of natural enemies, all controls were run simultaneously with flower treatments.

Statistical analysis. Survival analysis was conducted using the Kaplan-Meier method (PROC LIFETEST, (SAS Institute Inc. 2003). Individual insects that went missing during an experiment or were alive at the end of an experiment were recorded as censored observations with a lifespan equal to the number of days that they remained in the experiment. Survival was analyzed separately for each year and for each insect species. Pairwise comparisons of the survival distribution function (SAS Institute Inc. 2004) between treatments were made using the Wilcoxon (Gehan) statistic. Statistical significance was determined with the Bonferoni adjustment for multiple comparisons (α=0.05).

Results: 2007. Natural enemies responded variably to presence of flowering plants in the 2007 experiments (Table 2.1, Figs. 2.1-2.3). *O. insidiosus* lived significantly longer when held in cages containing flowers, as compared to water only or dry treatments (Fig. 2.1). *Aphidius colemani* also responded positively to floral treatments, although only *D. carota* and *L. siphilitica* were significantly better than the water control (Fig. 2.2, *L. siphilitica*: Wilcoxon X^2=21.59 df=1 P=<0.0001; *D. carota*: Wilcoxon X^2=23.57 df=1 P=<0.0001). Few significant differences were found among treatments in the survivorship of *H. convergens* (Fig. 2.3). The exceptions were *M. fistulosa*, on which survival was higher than the dry control (Wilcoxon X^2=10.09 df=1 P=0.0015), and *V. virginicum*, on which survival was lower than all other treatments (Dry vs. *V. virginicum* Wilcoxon X^2=16.46 df=1 P<0.001).

2008. In 2008 natural enemies also responded differently to the presence of flowering plants (Table 2.2, Fig 2.4-2.6). During the early-season experiments, when caged with *P. hirsutus*, *O. insidiosus* failed to live longer than when caged with water only (Fig. 2.4A, Wilcoxon X^2=5.43 df=1 P=0.02), but did live longer than the dry control (Wilcoxon X^2=53.99 df=1 P<0.0001). *A. colemani* in the early-season experiments (Fig. 2.4B) did not live significantly longer in cages with *P. hirsutus* than either the dry or water controls (*P. hirsutus* vs. Water, Wilcoxon X^2=1.94 df=1 P=0.16; *P. hirsutus* vs. Dry, Wilcoxon X^2=1.98 df=1 P=0.16).

During the mid-season experiments, *O. insidiosus* lived significantly longer in cages containing *M. fistulosa* than all other treatments (Fig. 2.5A, *M. fistulosa* vs. *V. virginicum* Wilcoxon X^2=13.6624 df=1 P=0.0002). They also lived significantly longer in cages with *V. virginicum* than water or dry (*V. virginicum* vs. Water, Wilcoxon X^2=34.90 df=1 P<0.0001; *V. virginicum* vs. Dry, Wilcoxon X^2=42.43 df=1 P<0.0001) and in water than dry (Wilcoxon X^2=9.7059 df=1 P=0.0018). In the mid-season experiments *A. colemani* lived significantly longer in cages with *M. fistulosa* than in *V. virginicum*, water, or dry cages (Fig. 2.5B, *M. fistulosa* vs. *V. virginicum* Wilcoxon X^2=11.92 df=1 P=0.0006). *A. colemani* in cages with *V. virginicum* also lived longer than those in water (Wilcoxon X^2=26.25 df=1 P<0.0001) or dry cages (Wilcoxon X^2=29.52 df=1 P<0.0001).

In the late-season experiments, *O. insidiosus* lived longer than water or dry controls when caged with *S. juncea* (Fig. 2.6A, *S. juncea* vs. Water Wilcoxon X^2=53.13 df=1 P<0.0001; *S. juncea* vs. Dry Wilcoxon X^2=53.13 df=1 P<0.0001) and *S. terebinthinaceum* (*S. terebinthinaceum* vs. Water Wilcoxon X^2=43.05 df=1 P<0.0001; *S. terebinthinaceum* vs. Dry Wilcoxon X^2=67.95 df=1 P<0.0001).

There was no significant difference between their survival on *S. juncea* compared to *S. terebinthinaceum* (Wilcoxon X^2=5.24 df=1 P=0.022). During the late-season experiments, *A. colemani* lived significantly longer in cages with *S. juncea* than all other treatments (Fig. 2.6B, *S. juncea* vs. *S. terebinthinaceum* Wilcoxon X^2=17.87 df=1 P<0.0001), and longer in *S. terebinthinaceum* than in water only cages (Wilcoxon X^2=6.21 df=1 P=0.013).

Table 2.1. Lifespans of different insects in cages with flowers and water, water only, or no water (Dry) in 2007. Means separations are based on non-parametric comparisons of the survival distribution function (Bonferoni adjusted P<0.0018). Treatments followed by the same letter are not significantly different (α=0.05). No data were collected for *A. colemani* caged with *M. fistulosa or V. virginicum* in 2007.

2007	**Average Lifespan (days) ± Standard Error**		
Treatment	***Aphidius colemani***	***Orius insidiosus***	***Hippodamia convergens***
M. fistulosa	-	5.58 ± 0.64 a	11.33 ± 0.23 a
V. virginicum	-	5.95 ± 0.64 a	8.37 ± 0.48 c
D. carota	2.19 ± 0.18 a	6.20 ± 0.64 a	11.43 ± 0.26 ab
L. siphilitica	1.87 ± 0.20 a	5.00 ± 0.58 a	11.08 ± 0.36 ab
T. pratense	1.28 ± 0.14 b	5.27 ± 0.63 a	10.50 ± 0.36 ab
A. nepetoides	1.10 ± 0.18 ab	4.33 ± 0.56 a	10.85 ± 0.37 ab
Water	1.08 ± 0.12 bc	1.20 ± 0.17 b	10.90 ± 0.37 ab
Dry	0.56 ± 0.09 c	0.82 ± 0.13 b	10.35 ± 0.41 b

Table 2.2. Lifespans of different insects in cages with flowers and water, water only, or no water (Dry) in 2008. Means separations are based on non-parametric comparisons of the survival distribution function (Bonferoni adjusted P-values; Early, P<0.017; Mid P<0.0083; Late P<0.0083). Treatments followed by the same letter are not significantly different (α=0.05).

2008		**Average Lifespan (days) ± Standard Error**	
Treatment	**Season**	***Orius insidiosus***	***Aphidius colemani***
P. hirsutus	Early	3.35 ± 0.46 a	0.82 ±0.05 ns
Water	Early	0.83 ± 0.18 a	0.77 ± 0.12 ns
Dry	Early	0.57 ± 0.10 b	0.75 ± 0.12 ns
M. fistulosa	Mid	7.43 ± 0.57 a	2.17 ± 0.23 a
V. virginicum	Mid	4.60 ± 0.54 b	1.48 ± 0.22 b
Water	Mid	2.12 ± 0.29 c	0.37 ± 0.14 c
Dry	Mid	0.42 ± 0.14 d	0.40 ± 0.16 c
S. juncea	Late	6.45 ± 0.59 a	1.42 ± 0.22 a
S. terebinthinaceum	Late	4.32 ± 0.57 a	0.47 ± 0.11 b
Water	Late	1.22 ± 0.21 b	0.35 ± 0.11 b
Dry	Late	0.22 ± 0.12 c	0.03 ± 0.03 c

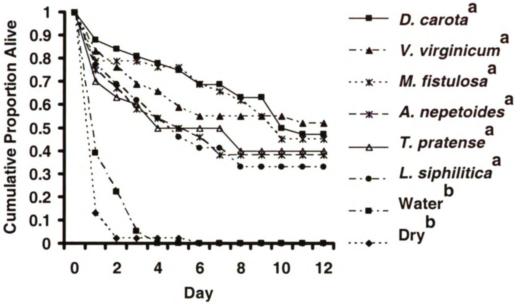

Figure 2.1. 2007 survivorship curves for *O. insidiosus* in cages with different flower species (and water), water only (Water), and no flowers or water (Dry). Cumulative proportion alive is the number of *O. insidiosus* that were alive on that day divided by the number that could be accounted for (alive plus dead) on the last day of the experiment. Means separations are based on non-parametric comparisons of the survival distribution function (Bonferoni adjusted $P<0.0018$). Treatments followed by the same letter are not significantly different ($\alpha=0.05$).

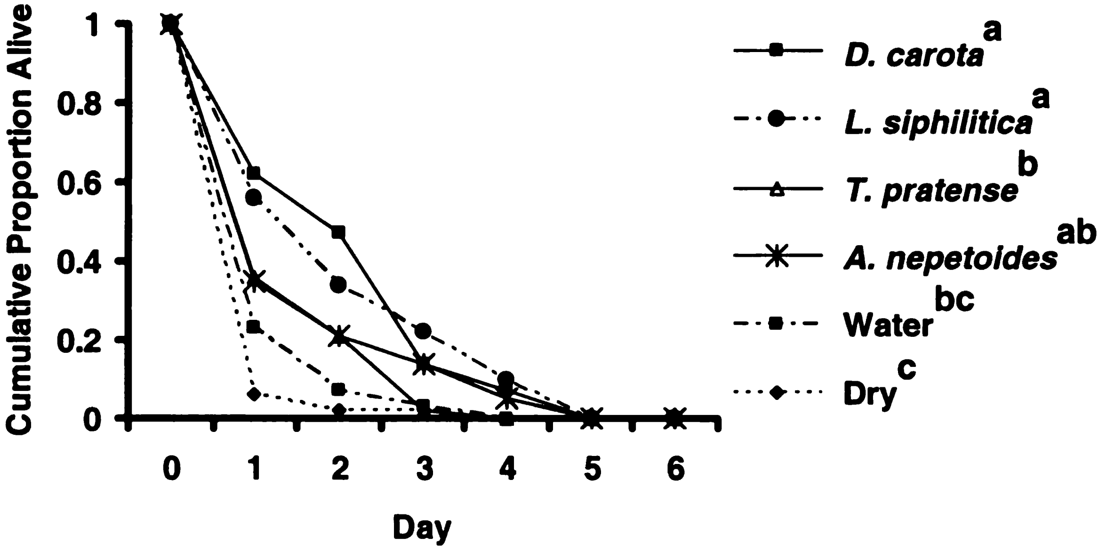

Figure 2.2. 2007 survivorship curves for *A. colemani* in cages with different flower species (and water), water only (Water), and no flowers or water (Dry). Cumulative proportion alive is the number of *A. colemani* that were alive on that day divided by the number that could be accounted for (alive or dead) on the last day of the experiment. Means separations are based on non-parametric comparisons of the survival distribution function (Bonferoni adjusted P<0.0033). Treatments followed by the same letter are not significantly different (α=0.05).

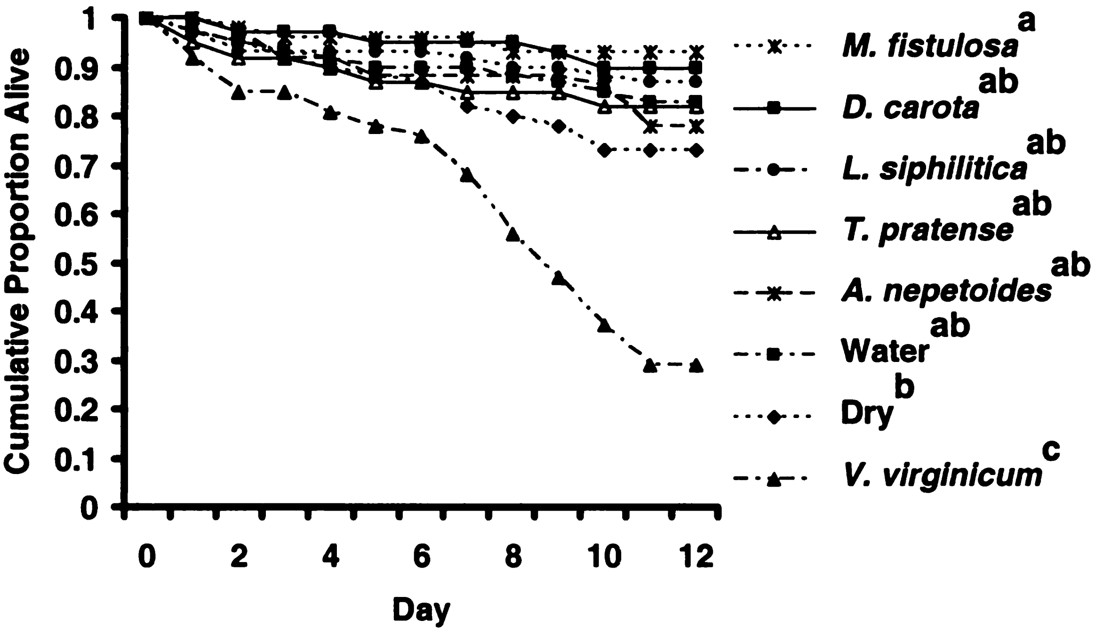

Figure 2.3. 2007 survivorship curves for *H. convergens* in cages with different flower species (and water), water only (Water), and no flowers or water (Dry). Cumulative proportion alive is the number of *H. convergens* that were alive on that day divided by the number that could be accounted for (alive or dead) on the last day of the experiment. Means separations are based on non-parametric comparisons of the survival distribution function (Bonferoni adjusted $P<0.0018$). Treatments followed by the same letter are not significantly different ($\alpha=0.05$).

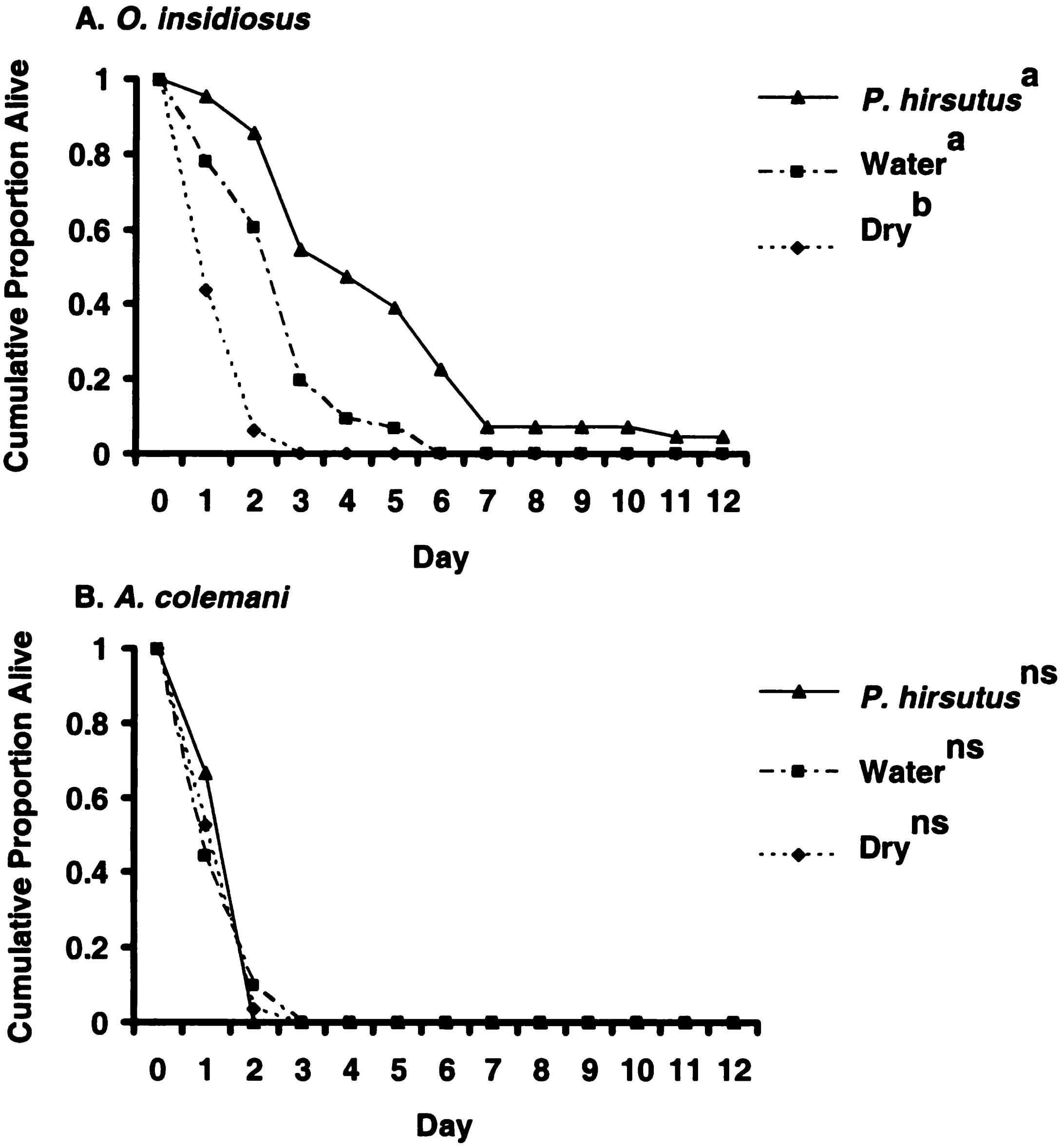

Figure 2.4. 2008 Early season survivorship curves for *O. insidiosus* (A) and *A. colemani* (B) in cages with *P. hirsutus* flowers (and water), water only (Water), and no flowers or water (Dry). Cumulative proportion alive is the number of insects that were alive on that day divided by the number that could be accounted for (alive or dead) on the last day of the experiment. Means separations are based on non-parametric comparisons of the survival distribution function (Bonferoni adjusted $P<0.017$). Treatments followed by the same letter (or ns) are not significantly different ($\alpha=0.05$).

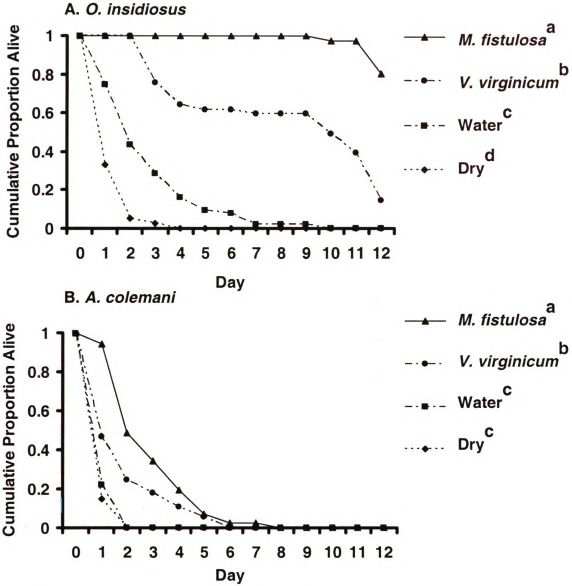

Figure 2.5. 2008 Mid-season survivorship curves for *O. insidiosus* (A) and *A. colemani* (B) in cages with different flowers (and water), water only (Water), and no flowers or water (Dry). Cumulative proportion alive is the number of insects that were alive on that day divided by the number that could be accounted for (alive or dead) on the last day of the experiment. Means separations are based on non-parametric comparisons of the survival distribution function (Bonferoni adjusted $P<0.008$). Treatments followed by the same letter are not significantly different ($\alpha=0.05$).

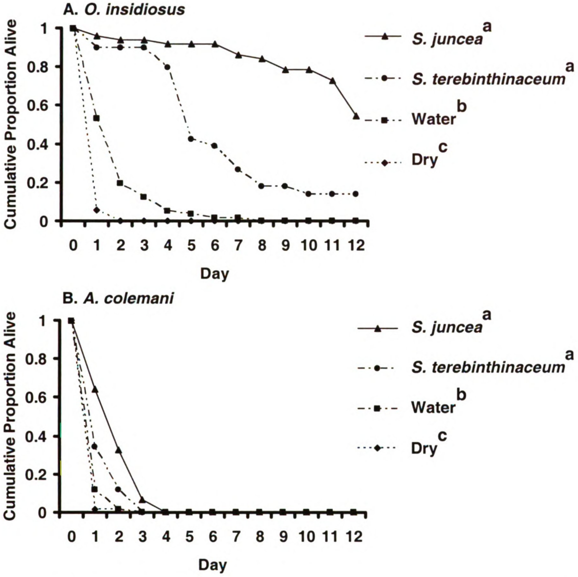

Figure 2.6. 2008 Late season survivorship curves for *O. insidiosus* (A) and *A. colemani* (B) in cages with different flowers (and water), water only (Water), and no flowers or water (Dry). Cumulative proportion alive is the number of insects that were alive on that day divided by the number that could be accounted for (alive or dead) on the last day of the experiment. Means separations are based on non-parametric comparisons of the survival distribution function (Bonferoni adjusted P<0.008). Treatments followed by the same letter are not significantly different (α=0.05).

Discussion. This laboratory evaluation provided some much needed information about an understudied group of flowering plants (Midwestern native perennials) for use in habitat management to conserve natural enemies. Above all, these results show that not all flowering plants are equally beneficial to all natural enemies (Tables 2.1 and 2.2).

For instance, in 2007 *V. virginicum* was the second best treatment in terms of lifespan for *O. insidiosus*, but the worst for *H. convergens* (Table 2.1, no data for *A. colemani* in 2007). *O. insidiosus*, *H. convergens*, and *A. colemani* generally lived the longest in cages with *M. fistulosa* and *D. carota* (Table 2.1 and 2.2), although these treatments were not statistically different from the other flower treatments in 2007 (Table 2.1, except for *H. convergens* with *V. virginicum*). In 2008, *O. insidiosus* and *A. colemani* both lived the longest in cages with *M. fistulosa* and *S. juncea* (Table 2.2). *V. virginicum* and *S. terebinthinaceum* were intermediate in their effect on these insects' survival, and *P. hirsutus* appeared to provide the least benefit over water only (Table 2.2).

P. hirsutus (hairy beardtongue), produces abundant pollen, nectar, and was attractive to bees in a field evaluation (Tuell et al. 2008). However, when *A. colemani* was caged with this flower, their longevity was no better than when they were caged in a dry container (Fig 2.4B). Similarly, *O. insidiosus*, which lived significantly longer on all other flower treatments (Figs. 2.1 and 2.4A – 2.6A), did not live significantly longer than the water only treatment when caged with *P. hirsutus* (Fig. 2.4A). The dense coat of trichomes on the stem, leaves, and flowers of this plant may have presented a physical barrier that prevented these insects from effectively exploiting the resources that the flowers provided (Levin 1973).

The experiments with *H. convergens* caged with *V. virginicum* (Culver's root) in 2007 revealed another unexpected but interesting anomaly. As is the case with most commercially available *H. convergens*, the lady beetles used in this experiment were collected from wild overwintering aggregations. When they were removed from cold storage and placed in experimental cages their diapause was artificially broken. Under these conditions they were frequently observed drinking water from the dental wick or searching for prey on the flowers. However, especially in cages with no resources (Dry treatment), after a period of searching activity, the lady beetles would usually enter a quiescent state, apparently to conserve energy. As a result, *H. convergens* mortality was extremely low in nearly all treatments presumably due to their ability to conserve energy and live off fat reserves (Hodek and Honek 1996).

When caged with *V. virginicum* however, *H. convergens* died at an unusually rapid rate (Fig. 2.3). Repeated experiments with *O. insidiosus* and *A. colemani* in 2008, confirmed that being caged with *V. virginicum* is not in itself harmful to insects (Fig. 2.5). Interestingly, the root of *V. virginicum* is moderately toxic to humans (Foster and Duke 2000), and several compounds that are potentially toxic to insects have been isolated from this plant and its close relatives (Wink 2003, Taskova et al. 2006).

The corolla of *V. virginicum* flowers is too long and narrow to allow *H. convergens* access to floral nectarines (A.K. Reister, unpublished data). Thus, it is possible that *H. convergens* actually ingested these toxins directly by chewing through the flower to access nectar or by chewing on some other plant part. Phytophagy is not unheard of in the Coccinelidae, in fact the importance of plant derived foods to their diets may be frequently underestimated (Hodek 1996). Of course, this type of feeding behavior is probably rare for *H. convergens* in a field setting where the beetles have access to a diversity of nutrient sources.

Omnivory by other natural enemies is not uncommon, and can improve the effectiveness of biological control agents (Coll and Guershon 2002). However, as the case of *H. convergens* caged with *V. virginicum* illustrates, there is at least some potential that habitat management with certain plants could actually be detrimental to omnivorous natural enemies. Alternatively, a habitat management plant that provides food for beneficial insects, but is toxic to pests could have great potential for use as a selective food plant. This is clearly an area that would benefit from further research.

Despite the above exceptions, the majority of the native plants selected for these experiments provided some benefit that extended the longevity of *O. insidiosus* and *A. colemani* in a laboratory setting. The instances where this general rule was violated provide opportunities for improving conservation biocontrol by focusing on plants that will support or deter specific target insects. Almost all of these plants provide valuable food resources to natural enemies and should be further investigated for use in habitat management programs.

CHAPTER 3

Influence of native flowering plant strips on natural enemies in blueberry fields

Introduction. There has been growing interest in recent years regarding the economic and environmental benefits of re-incorporating natural habitats into agricultural systems (Jackson and Jackson 2002, Kleijn and Sutherland 2003, Landis et al. 2005, Bianchi et al. 2006), in part because of the documented declines in populations of beneficial insects (Biesmeijer et al. 2006). The suspected reasons for these declines include pesticide use, loss of habitat, and a paucity of flowering plants within agricultural landscapes (Landis et al. 2000, Carvell et al. 2006b).

Many agricultural landscapes are lacking in the habitats that historically provided resources to beneficial insects, and this has compromised the ability of farmers to rely on natural enemies for pest control or on native pollinators for crop pollination (Tilman et al. 2002, Landis et al. 2005, Tscharntke et al. 2005, Losey and Vaughan 2006). To counteract this trend, habitat management proponents increasingly propose establishment of conservation strips of flowering plants in and around crop fields (Hickman and Wratten 1996, Barbosa 1998, Gurr et al. 2004, Isaacs et al. 2009). Flowering plant habitats can provide resources including nectar, pollen, alternate prey, and a complex architecture with multiple niches for beneficial arthropods (Landis et al. 2000, Van Emden 2002).

Cover crops can be a useful tactic to support natural enemies in crop fields (Bugg and Waddington 1994, Nicholls et al. 2000, Kinkorová and Kocourek 2000). Unfortunately, placement of the resource plants inside conventional crop fields inevitably creates potential for disturbance or death of beneficial insects when the crop is cultivated or treated with insecticide (Lee et al. 2001). Placement of these resources outside the crop area provides a more benign environment for beneficial insects where they can feed on nectar and pollen, utilize alternate hosts, and find refuge in an area not impacted by harmful disturbances (Sotherton 1984, Thomas et al. 1991).

Natural or semi-natural habitat outside the cropped area has consistently been shown to support beneficial insects (Kremen et al. 2002, Steffan-Dewenter 2003, Kremen et al. 2004, Bianchi et al. 2006, Greenleaf and Kremen 2006), but this is something that most growers cannot manipulate easily. Lands adjacent to fields are often not owned by the grower, may be managed for purposes other than to support natural enemies, or may be urbanized. For these farms, integrating refuge and flower resources directly into the field border is more likely to be adopted as a strategy to create habitat for beneficial insects.

Manipulation of the environment around cropped areas by establishing flowering plants can increase natural enemy populations (Long et al. 1998, Rebek et al. 2005) and provide forage for wild bees that can increase their abundance (Kells et al. 2001, Buchi 2002). Provision of nectar and pollen by these plants can lead to greater parasitoid survival and fecundity (Jervis et al. 1993, Wackers 2004, Lee and Heimpel 2008), and parasitoids have greater mobility in habitats with flowering plants than in nearby habitats without flowers (Van Emden 1962). Lack of sugar nutrition reduces parasitoid host searching behavior due to decreased activity and searching for food rather than host insects (Wackers 1994, Takasu and Lewis 1995).

The insect targets of habitat management respond at different scales to habitat diversification (Banks 2000, Tscharntke et al. 2007, Fraser et al. 2008, Werling and Gratton 2008). Small parasitoid wasps (≤2mm) for example may respond at a relatively small scale to the addition of flowering resources to a field, whereas larger organisms (e.g. bumblebees, ((Osborne et al. 2008)) and lady beetles ((Gardiner et al. 2009) respond to resource availability at larger spatial scales. The scale at which these insects respond is important from a practical standpoint, because farmers are more likely to implement habitat management if there is a measurable benefit at the field-scale (Tilman et al. 2002, Kurkalova et al. 2006, Wossink and Swinton 2007).

The effectiveness of habitat management as a means of conservation biological control can also vary depending on the nature of the disturbance regime of the target crop (Landis et al. 2000). Generally these strategies have had more success in perennial crops, especially orchards and vineyards (Doutt and Nakata 1973, Nicholls et al. 2000, Kinkorová and Kocourek 2000), where less intensive herbicide and tillage regimes lead to increased stability of beneficial insect populations (Van Emden and Williams 1974, Landis and Menalled 1998).

The highbush blueberry cropping system in Michigan is expected to benefit from this habitat management approach because the average lifetime of a planting is generally greater than 20 years (Shoemaker 1975) and disturbance regimes are generally less intensive than most annual crops. However, pest pressure in Michigan can be high, leading to intensive use of broad spectrum insecticides, which are detrimental to beneficial insect populations in the field (O'Neal et al. 2005, Tuell 2007). The most economically injurious insect pests in Michigan highbush blueberry include cranberry fruitworm (Lepidoptera: Pyralidae: *Acrobasis vaccinii* Riley), blueberry maggot (Diptera: Tephritidae: *Rhagoletis mendax* Curran), Japanese beetle (Coleoptera: Scarabaeidae: *Popillia japonica* Newman), and blueberry aphid *Illinoia pepperi* (MacGillivray).

This study was focused on potential control agents of *Illinoia pepperi*, because it is a *Vaccinium* specialist (Elsner and Kriegel 1989) and may be controlled by small parasitoid wasps, which are expected to respond at the local scale to a supplemental wildflower planting (Langhof et al. 2005). The impact of wildflower strips on other groups of insects was also examined; including other pest groups because of their potential to benefit from increased floral resources (Norris and Kogan 2000, Norris and Kogan 2005, Lavandero et al. 2006).

To evaluate the impact of native flowers on the insect community in Michigan blueberry fields, strips of 9 native flowering plants that bloom sequentially throughout the season and one native grass were planted in the field margins on four commercial blueberry farms. The response of the insect community to the presence of these flower strips was measured over two years to test the hypotheses that: (1) natural enemy populations will benefit from the presence of additional flower resources, (2) pest populations will benefit from the presence of additional flower resources, (3) a flower strip in the field margin will not pull beneficial insects out of the field, (4) a flower strip in the field margin will buffer beneficial insect populations from the effects of disturbance in the crop, and (5) biological control will be increased by the presence of a flowering plant strip.

Materials and Methods: Flowering Plant Strips. Nine species of native flowering plants that rated highly for attraction of beneficial arthropods and bloom at different times of the season (Fiedler and Landis 2007a, Fiedler and Landis 2007b, Tuell et al. 2008), plus one native grass control (Table 3.1) were planted as plugs (one-year-old plants) in spring 2006. Each plot was planted with 20 plants of each species, supplied by WildType nurseries (Mason, Michigan). Each species was replicated three times within each strip in 2 x 2 m plots, in a randomized complete block design (Fig. 3.1), to create a 60 x 2 m strip of flowering plants (Fig. 3.1). These strips were established at four commercial blueberry farms in Van Buren county (2 farms; 42°53'6.52"N, 86° 9'12.86"W, and 42°52'13.69"N, 86°7'32.41"W) and Ottawa county (2 farms; 42°24'27.60"N, 86°6'36.86"W, and 42°15'28.52"N, 86°13'51.66"W) (Figs. 3.2- 3.3).

Sampling. At each blueberry farm, two fields were selected, so that at each farm one field was adjacent to a flower strip (flower) and one was adjacent to a typical mown field border (control) (Figs. 3.2 -3.3). The flower strips were separated from the crop by a narrow drive lane (Fig. 3.4). At all fields (n=8), unbaited yellow sticky traps (Great Lakes IPM, Vestaburg, MI) were placed along three transects into the field (Fig. 3.4) in four positions: field perimeter, first blueberry bush (0m), and 20m and 40m into the field. In 2007, yellow sticky traps were also placed at the 10m distance along transects, but not in 2008.

Yellow sticky traps were deployed for one week intervals from late June to mid-August in 2007. Sample dates in 2008 were selected to match the growing degree day accumulation for the first 2007 sample to minimize annual variations in insect abundance due to climatic variation between years.

In 2007 only, insects were also sampled from flower and control field perimeters using a leaf blower (Stihl model BG-55) converted into a vacuum (Fiedler and Landis 2007a). Flower plots were sampled by placing a 1m^2 quadrat frame haphazardly within the plot and vacuuming the area within the quadrat for 30 seconds. Control quadrats were placed haphazardly within the control perimeters and vacuumed in the same way. Insects were vacuumed into a mesh bag, which was removed, placed in a cooler, and later placed in a freezer. Vacuum samples were taken during peak bloom for each flower plot. An equal sampling effort for flower (n=84) and control (n=84) perimeters was achieved by always sampling an equal number of control and flower quadrats at each farm on the same day.

Natural enemies trapped with yellow sticky traps and vacuum samples were counted in the laboratory using a magnifier lamp and/or dissecting scope as needed. A combination of taxonomic keys, photographic guides, and natural history references were used to sort insects into major groups (Borror et al. 1992, Flint and Dreistadt 1998, Marshall 2006). Identification was done to the level necessary for determination of whether a particular specimen was a natural enemy (i.e. predator or parasitoid) or a pest (i.e. herbivore of concern to agriculture).

Aphid predation. In order to estimate the impact of the flowering plant strips on biological control, predator exclusion experiments were performed in both years. Shoots on potted two-year-old blueberry bushes (c.v. Bluecrop) were infested with aphids and placed in fields adjacent to flower or control perimeters. On each plant, two shoots were infested and one of two treatments was applied to each shoot. Predator exclusion shoots were covered in a paint strainer bag (hole size <0.25mm) the entire time that they were in the field, whereas on Open shoots, the bag was removed when the plant was placed in the field. Aphids were counted on the first day plants were placed in the fields and on the sixth day, when plants were removed. In 2007, shoots started with different numbers of aphids (Mean = 6.6, Range = 8.0), but in 2008 all shoots had 10 aphids on the first day of the experiment. In 2007, 9.91mm of rain fell during the course of the experiment (MAWN weather station in West Olive MI). In 2008, rain shelters were constructed from bamboo stakes and 2mm thick clear polyethylene sheeting to prevent loss of aphids due to rain. Tangle-Trap® (The Tanglefoot Company, Grand Rapids, MI) was applied to the sides of the plastic pots and to the bases of the bamboo stakes to prevent aphids from leaving and to prevent ants and other crawling insects from accessing the plants.

Statistical Analysis. For the first three samples of 2007, yellow sticky traps were only in the field for three days, so data were standardized prior to analysis by dividing all counts by the number of days that traps were in the field. Insect counts were then log(x+1) transformed to meet assumptions of normality. Analysis of insect counts was performed by repeated measures ANOVA (PROC MIXED, SAS Institute Inc. 2003). The full model included farm as a random variable, and treatment (flower vs. control), distance, week and all possible interactions as fixed effects. Week was specified as the repeated measure effect with the transect by distance interaction as the subject (nested within farm by treatment by distance) and a compound symmetry covariance structure. Predator exclusion data were analyzed by ANOVA (PROC ANOVA, SAS Institute Inc. 2003).

Figure 3.1. Photographs of the two study fields and field perimeters at a farm in Van Buren County (MI) in late July 2008. Flowers shown blooming in the perennial flowering plant strip (left) include Bee Balm (*Monarda fistulosa* L. foreground), Culver's Root (*Veronicastrum virginicum* L.), and Prairie Dock (*Silphium terebinthinaceum* Jacq.).

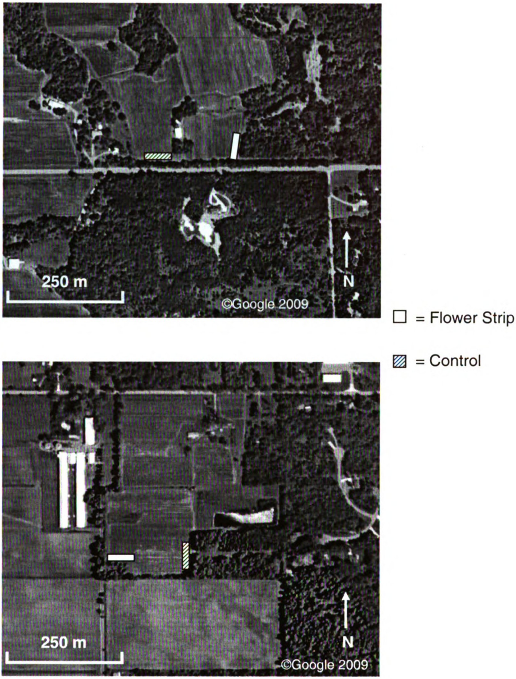

Figure 3.2. Aerial photographs of the two study farms in Ottawa County. Images are from Google Earth (Google™ 2009). Scales are approximate.

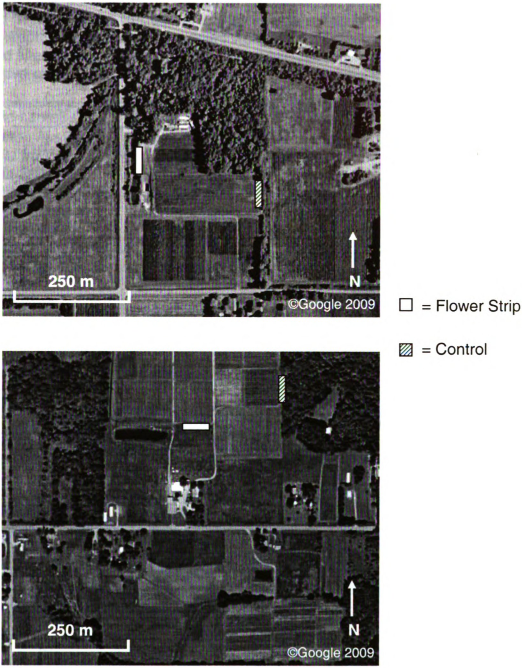

Figure 3.3. Aerial photographs of the two study farms in Van Buren County. Images are from Google Earth (Google™ 2009). Scales are approximate.

Table 3.1. The scientific and common names of the 10 plant species planted in 2006 in the wildflower conservation strips next to blueberry fields. Approximate peak bloom dates were estimated from observations at the four field sites during 2007 and 2008. One species (*S. scoparius*) was included as a native grass control; no bloom data were recorded for this plant.

Scientific name	Common name	Approx. peak bloom date
Penstemon hirsutus	Hairy Beardtongue	June 8th
Potentilla fruticosa	Shrubby Cinquefoil	July 1st
Monarda fistulosa	Bee Balm	July 12th
Veronicastrum virginicum	Culver's Root	July 30th
Solidago juncea	Early Goldenrod	August 3rd
Lobelia siphilitica	Blue Lobelia	August 15th
Silphium terebinthinaceum	Prairie Dock	August 16th
Agastache nepetoides	Yellow Giant Hyssop	August 17th
Aster laevis	Smooth Aster	September 17th
Schizachyrium scoparius	Little Bluestem	-

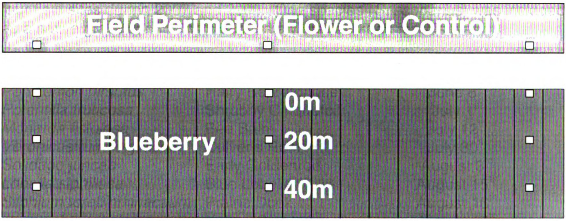

Figure 3.4. Diagram of a field site showing the placement of yellow sticky traps with respect to the wildflower conservation strips or control perimeters (not to scale).

Results: Natural Enemies. Table 3.2 summarizes the insect community captured on yellow sticky traps in both years. In two years of sampling a total of 20,961 natural enemies (i.e. beneficial insects not including bees) were collected on sticky traps. Of these, the majority were parasitoid wasps (91% and 93% in 2007 and 2008, respectively). Other important groups included *Orius spp.* (3% of the sample in 2007 and 1% in 2008) and Syrphid flies (1% in 2007 and 2% in 2008).

In both years, natural enemy abundance was significantly affected by distance from the field perimeter (Fig. 3.5, 2007: F=18.64 df=4, 24 P<0.0001; 2008: F=20.07 df=3, 18 P<0.0001), week (Fig. 3.6, 2007: F=86.19 df=5, 624 P<0.0001; 2008: F=40.18 df=5, 503 P<0.0001), and the week by treatment interaction (Fig. 3.6, 2007: F=5.13 df=5, 624 P=0.0001; 2008: F=2.28 df=5, 503 P=0.046).

Examination of the strength of the week by treatment interaction during different weeks in 2007 revealed that there were significantly more natural enemies in the fields near flower strips compared to control fields in the last two weeks of 2007 (Fig. 3.6, 8/10, t=2.2 df=624 P=0.028; 8/17, t=2.77 df=624 P=0.006). In 2008, there were significantly more natural enemies in fields near flower strips compared to controls during the first week and last two weeks (Fig. 3.6, 7/2, t=2.43 df=503 P=0.015; 8/20, t=2.35 df=503 P=0.019; 8/27, t=2.7 df=503 P=0.007).

A significant treatment by distance by week interaction was detected in 2007, but not in 2008 (Fig. 3.5, 2007: F=1.65 df=20, 624 P=0.0365; 2008: F=0.24 df=15, 503 P=0.99). Examination of the strength of this interaction at different distances and weeks, revealed significantly fewer natural enemies in the flower strips compared to control perimeters in the first two weeks of 2007 (Fig. 3.5, 6/15, field perimeter: t=-2.23 df=624 P=0.026 6/24, field perimeter: t=-2.09 df=624 P=0.037), but significantly more natural enemies at different distances into the fields adjacent to the flower strips during the first week and last two weeks of that year (Fig. 3.5, 6/15, 40m: t=2.66 df=624 P=0.008 ; 8/10, 20m: t=2.62 df=624 P=0.009; 8/17, 40m: t=2.5 df=624 P=0.012). The main effect of flower strip treatment was not significant for natural enemy abundance in either year (2007: F=1.41 df=1,3 P=0.32; 2008: F=4.19 df=1,3 P=0.13).

Parasitoid wasps comprised greater than 90% of the natural enemy sample in both years, so the above patterns in natural enemy abundance were primarily driven by parasitoid wasp abundance. Parasitoid wasp abundance in both years was significantly affected by distance from the field perimeter (Fig. 3.7, 2007: F=18.64 df=4, 24 P<0.0001; 2008: F=16.57 df=3, 18 P<0.0001), week (Fig. 3.8, F=86.19 df=5, 624 P<0.0001; 2008: F=35.18 df=5, 503 P<0.0001), and the week by treatment interaction (Fig. 3.8, 2007: F=5.13 df=5, 624 P=0.0001; 2008: F=2.65 df=5, 503 P=0.022).

Examination of the strength of the week by treatment interaction during different weeks in 2007 revealed that there were significantly more parasitoid wasps in the fields near flower strips compared to control fields in the last two weeks of 2007 (Fig. 3.6, 8/10, t=2.36 df=624 P=0.018; 8/17, t=2.74 df=624 P=0.006). In 2008, there were significantly more parasitoid wasps in fields near flower strips compared to controls during the first week and the last two weeks (Fig. 3.6, 7/2, t=2.6 df=503 P=0.01; 8/20, t=2.5 df=503 P=0.013; 8/27, t=2.87 df=503 P=0.004).

Also in parasitoid wasp abundance, a significant treatment by distance by week interaction was detected in 2007, but not in 2008 (Fig. 3.7, 2007: F=1.65 df=20, 624 P=0.0365; 2008: F=0.24 df=15, 503 P=0.99). Examination of the strength of this interaction at different distances and weeks, revealed significantly fewer parasitoid wasps in the flower strips compared to control perimeters in the first two weeks of 2007 (Fig. 3.7, 6/15, field perimeter: t=-2.55 df=624 P=0.011 6/24, field perimeter: t=-2.69 df=624 P=0.007), but significantly more wasps at different distances into the fields adjacent to the flower strips during the first week and last two weeks of that year (Fig. 3.7, 6/15, 40m: t=2.76 df=624 P=0.006 ; 8/10, 20m: t=2.63 df=624 P=0.009; 8/17, 40m: t=2.31 df=624 P=0.021). The main effect of flower strip treatment was not significant for parasitoid wasp abundance in either year (2007: F=1.41 df=1,3 P=0.32; 2008: F=4.73 df=1,3 P=0.12).

Pests. Flowering plant strips also had a significant effect on pest abundances (Table 3.2). Thrips (Thysanoptera: Thripidae) were the most abundant insects in the pest group. With a total of 192,877 individuals collected over the two years of this study, thrips comprised 57% of the pests sampled in 2007 and 45% of the pests sampled in 2008. Aphids (Hemiptera: Aphididae) were the second most abundant group comprising 38% (108,617 individuals) and 40% (27,798 individuals) of the pests sampled in 2007 and 2008, respectively. Leafhoppers and planthoppers (Hemiptera: Cicadoidea) as the next most abundant group comprised 6% (16, 656 individuals) and 15% (10,139 individuals) of the pests sampled in 2007 and 2008, respectively.

Major pests in blueberry represented a very small proportion of the yellow sticky trap catch. The group containing Blueberry Maggot (Diptera: Tephritidae) was less than 1% of all the pests sampled in both years (2007: 139 individuals, 2008: 7 individuals). The group containing Japanese Beetle (Coleoptera: Scarabidae) made up less than 0.01% of the pests caught in both years (2007: 6 individuals, 2008: 1 individual). The group containing cranberry fruitworm (Lepidoptera) comprised less than 1% of the total sample in both years (2007: 200 individuals, 2008: 110 individuals).

Pest data were analyzed using the same statistical model as natural enemy data. When all pests were analyzed as one group, in both years there was a significant effect of distance (Fig. 3.9, 2007: $F=4.28$ $df=4, 24$ $P=0.01$; 2008: $F=5.69$ $df=3, 18$ $P=0.006$), week (Fig. 3.10, 2007: $F=65.55$ $df=5, 624$ $P<0.0001$; 2008: $F=50.94$ $df=5, 503$ $P<0.0001$), and the week by treatment interaction (Fig. 3.10, 2007: $F=4.28$ $df=5, 624$ $P=0.0008$; 2008: $F=3.73$ $P=0.0025$). Closer examination of the week by treatment interaction revealed that pests were significantly more abundant in fields adjacent to flower strips compared to control fields in the first three weeks of 2007 (Fig. 3.10, 6/15: $t=2.22$

df=624 P=0.03; 6/24: F=4.04 df=624 P<0.0001; 7/5: F=3.03 df=624 P=0.003). In 2008, there were significantly more pests in fields adjacent to flower strips in 4 out of 6 samples (Fig. 3.10, 7/2: t=3.89 df=503 P=0.0001; 7/9: t=3.67 df=503 P=0.0003; 7/16: t=4.22 df=503 P<0.0001; 8/13: t=2.33 df=503 P=0.02), and the remaining two samples had marginally significant differences (8/20: t=1.84 df=503 P=0.067; 8/27: t=1.96 P=0.051). The main effect of treatment was only significant for pest abundance in 2008 (2007: F=6.94 df=1, 3 P=0.078; 2008: F=11.91 df=1, 3 P=0.041) meaning that there were significantly more pests in fields near flower borders in that year.

Analysis of the abundance patterns of each pest group individually could only be performed on the most abundant groups, i.e. aphids and thrips, because data from other groups did not meet the normality assumptions of the model. This analysis revealed that the pattern in overall pest abundance described above was primarily driven by thrips abundance.

Thrips were significantly more abundant early in the season (Fig. 3.11, week effect 2007: F=456.53 df=5, 624 P<0.0001; 2008: F=325.67 df=5, 503 P<0.0001), especially in fields adjacent to the flower strips (week by treatment interaction 2007: F=3.61 df=5, 624 P=0.003; 2008: F=4.94 df=5, 503 P=0.0002). Examination of the strength of this interaction in different weeks showed that thrips were more abundant in fields adjacent to flower strips compared to controls in 5 of 6 samples in 2007 (Fig. 3.11, 6/15: t=2.4 df=624 P=0.017; 6/24: t=4.07 df=624 P<0.0001; 7/5: t=2.78 df=624 P=0.006; 8/10: t=2.71 df=624 P=0.007; 8/17: t=2.68 df=624 P=0.007) and all 6 samples in 2008 (Fig. 3.11, 7/2: t=3.92

df=503 P=0.0001; 7/9: t=3.45 df=503 P=0.0006; 7/16: t=3.76 P=0.0002; 8/13: t=2.01 df=503 P=0.045; 8/20: t=2.09 df=503 P=0.037; 8/27: t=4.49 df=503 P<0.0001). The distance by treatment effect was not significant for thrips abundance in either year (Fig. 3.12, 2007: F=0.59 df=4, 24 P=0.67; 2008: F=1.62 df=3, 18 P=0.22), nor was the main effect of distance significant (2007: F=2.67 df=4, 24 P=0.057; 2008: F=1.56 df= 3, 18 P=0.23), which means that thrips abundance was evenly distributed across all distances within fields in both years (Fig. 3.12).

Aphid abundance was significantly affected by time of year (Fig. 3.13, week effect 2007: F=315.63 df=5, 624 P<0.0001; 2008: F=295.74 df=5, 503 P<0.0001) and distance (Fig. 3.14, 2007: F=9.75 df=4,24 P<0.0001; 2008: F=11.08 df= 3, 18 P=0.0002), but not by the distance by treatment interaction (Fig. 3.14, 2007: F=0.66 df=4, 24 P=0.62; 2008: F=0.21 df=3, 18 P=0.89). The week by treatment interaction was marginally significant for aphid abundance in 2007 but not in 2008 (Fig. 3.13, 2007: F=2.16 df=5, 624 P=0.057; 2008: F=0.34 df=5, 503 P=0.89). Overall, aphids were more abundant in the field perimeters compared to sampling distances inside the fields (Fig. 3.14) in both years, but not more abundant in fields adjacent to flower strips compared to controls in either year (Fig. 3.13 and 3.14, treatment effect 2007: F=1.82 df=1, 3 P=0.27; 2008: F=2.45 df=1, 3 P=0.22).

Vacuum Samples. The vacuum sample insect community composition is summarized in Table 3.3. Of the natural enemies, parasitoid wasps were the most abundant, comprising 55% (211 individuals) of that group in the total sample. The anthocorids were the second most abundant natural enemy in the vacuum samples, representing 29% (112 individuals) of all the natural enemies sampled. Of the pests the mirids were the most abundant, comprising 46% (535 individuals) of pests in the total sample. Aphids were the second most abundant pest group in vacuum samples; they comprised 28% (332 individuals) of the pests sampled. Leaf and Planthoppers (Cicadoidea) represented 14% (172 individuals) of the pests sampled by vacuum, and thrips were only about 6.5% of the sample (75 individuals).

The pest groups of most concern to blueberry growers were poorly represented in the vacuum samples. Only 8 Japanese beetles (Scarabidae) were collected in vacuum samples from the field perimeters, which is less than 1% of the pest sample. Lepidoptera were slightly more abundant, comprising just over 1% (14 individuals) of the pests sampled. Tephritidae were not found in the vacuum samples.

Predator exclusion. Differences in aphid mortality between treatments were estimated by comparing the effect of treatment (predators excluded vs. open) on day 1 to the effect of treatment on day 6 of the experiment for each year separately (Fig. 3.15). There was no significant difference between the number of aphids on predator excluded and open shoots on day 1 of the experiment in either year (Fig. 3.15, 2007: F=0.08 df=1,14 P=0.7803). By day 6, there were significantly fewer aphids on the open shoots than the predator excluded shoots

(Fig. 3.15, 2007: F=6.42 df=1, 14 P=0.02; 2008: F=20.66 df=1, 30 P<0.0001). There was no significant effect of field perimeter (flower fields vs. control fields) on the decrease in aphid abundance in either year (2007: F=0.37 P= 0.55; 2008: F=0.77 P=0.40).

Table 3.2. The arthropod community caught on yellow sticky traps from June to August 2007 and 2008 in Michigan blueberry fields (2007: n=720; 2008: n=576). The indeterminate (Indet.) category contains arthropods whose identity or impact on agriculture could not be determined.

Taxonomic Group		Total Abundance		% of Total		% of Group	
		2007	2008	2007	2008	2007	2008
Beneficials:	Neuroptera	173	103	0.04	0.07	0.84	0.75
	Diptera						
	Syrphidae	289	328	0.08	0.23	1	2
	Coleoptera						
	Coccinelidae	104	65	0.03	0.05	0.50	0.47
	Misc. Predators	74	111	0.02	0.08	0.36	0.81
	Hymenoptera						
	Parasitica	19,100	12,733	5	9	92	93
	Aculeata						
	Apoidea	195	135	0.05	0.10	1	1
	Vespoidea	26	72	0.01	0.05	0.13	0.53
	Hemiptera						
	Anthocoridae	711	136	0.18	0.10	3	1
	Pentatomidae	14	3	<0.01	<0.01	0.07	0.02
	Nabidae	13	12	0.00	0.01	0.06	0.09
Pests:	Hemiptera						
	Miridae	632	488	0.16	0.35	0.21	0.70
	Tingidae	38	7	0.01	<0.01	0.01	0.01
	Cicadoidea	16,656	10,139	4	7	6	15
	Aphididae	108,617	27,798	28	20	38	40
	Thysanoptera						
	Thripidae	161,669	31,208	42	22	56	45
	Coleoptera						
	Scarabidae	6	1	<0.01	<0.01	<0.01	<0.01
	Diptera						
	Tephritidae	139	7	0.04	<0.01	0.05	0.01
	Lepidoptera	200	110	0.05	0.08	0.07	0.29
	Hymenoptera						
	Symphyta	339	78	0.09	0.06	0.12	0.11
Indet.:	Diptera						
	Unknown	57,641	47,641	15	34	76	84
	Dolichopodidae	13,080	6,352	3	5	17	11
	Coleoptera	3,975	2,096	1	1	5	4
	Hymenoptera						
	Formicidae	943	583	0.25	0.42	1	1
	Hemiptera						
	Thyreocoridae	67	20	0.02	0.01	0.09	0.04
	Aranae	130	130	0.03	0.09	0.17	0.23

Table 3.3. The arthropod community caught in vacuum samples from June to September 2007 in field perimeters (Flower n=84, Control n=84). The indeterminate (Indet.) category contains arthropods whose identity or impact on agriculture could not be determined.

Taxonomic Group		Total Abundance		% of Total		% of Group	
		Flower	Control	Flower	Control	Flower	Control
Beneficials:	Neuroptera	6	5	0.36	0.42	2	3
	Diptera						
	Syrphidae	5	0	0.3	0	1.7	0
	Coleoptera						
	Cantharidae	4	3	0.24	0.25	1.3	2
	Hymenoptera						
	Parasitica	124	87	7.4	7.2	42	58
	Aculeata						
	Apoidea	52	12	3	1	17.5	8
	Vespoidea	1	2	0.06	0.17	0.34	1.33
	Hemiptera						
	Anthocoridae	85	27	5	2.24	29	18
	Pentatomidae	14	10	0.84	0.83	4.7	6.7
	Nabidae	7	4	0.42	0.33	2.4	2.7
Pests:	Hemiptera						
	Miridae	420	115	25	9.6	64	22
	Tingidae	33	0	2	0	5	0
	Cicadoidea	82	90	5	7.5	12.6	17
	Aphididae	89	243	5.3	20	13.6	47
	Thysanoptera						
	Thripidae	11	64	0.66	5.3	1.7	12.4
	Coleoptera						
	Scarabidae	8	0	0.5	0	1.23	0
	Lepidoptera	9	5	0.54	0.42	1.38	1
Indet.:	Diptera	461	398	28	33	64	74
	Coleoptera	88	24	5.3	2	12.3	4.5
	Hymenoptera						
	Formicidae	48	34	3	3	6.7	6.3
	Hemiptera						
	Thyreocoridae	60	31	3.6	2.6	8.4	5.8
	Aranae	61	50	3.7	4	8.5	9.3

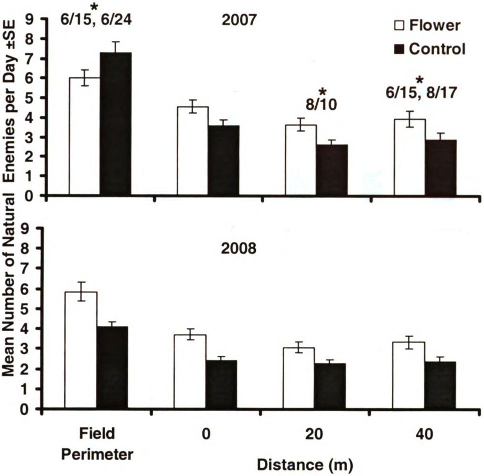

Figure 3.5. Natural enemy abundance in field perimeters and at different distances into blueberry fields adjacent to flower strips and controls. Data shown are averaged across all sampling dates (n=6) and farms (n=4). The overall effect of distance was significant for both years (α=0.05). Asterisks indicate a significant treatment*distance*week interaction; indicating a significant difference between flower and control measurements at that distance for the dates shown (α=0.05).

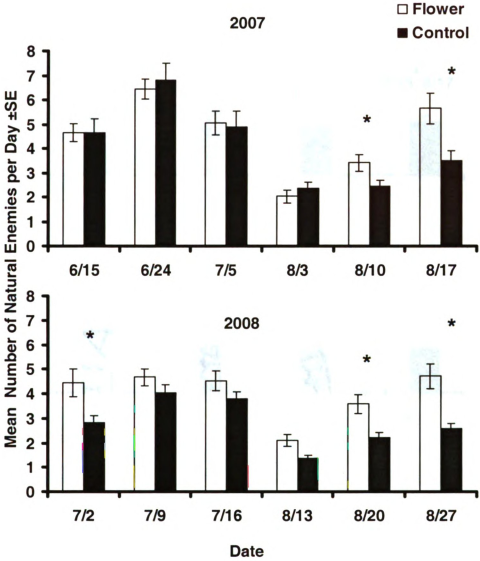

Figure 3.6. Natural enemy (NE) abundance in fields adjacent to flower strips or control perimeters through 2007 and 2008. Data shown are averaged across all sampling distances (n=4) and farms (n=4). Asterisks indicate a significant treatment*week interaction, which indicates that the differences shown were significant for that date (α=0.05).

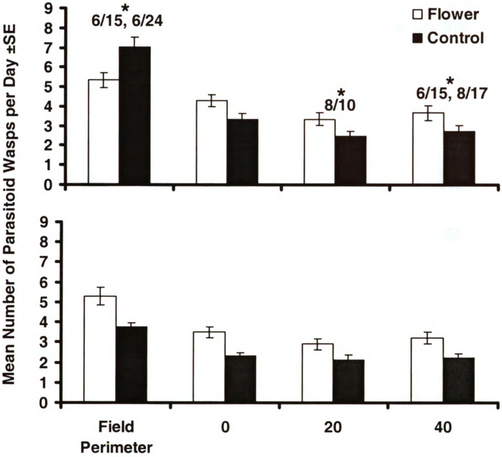

Figure 3.7. Parasitoid wasp abundance in field perimeters and at different distances into blueberry fields adjacent to flower strips and control perimeters. Data shown are averaged across all sampling dates (n=6) and farms (n=4). The overall effect of distance was significant for both years (α=0.05). Asterisks indicate a significant treatment*distance*week interaction; indicating a significant difference between flower and control measurements at that distance for the dates shown (α=0.05).

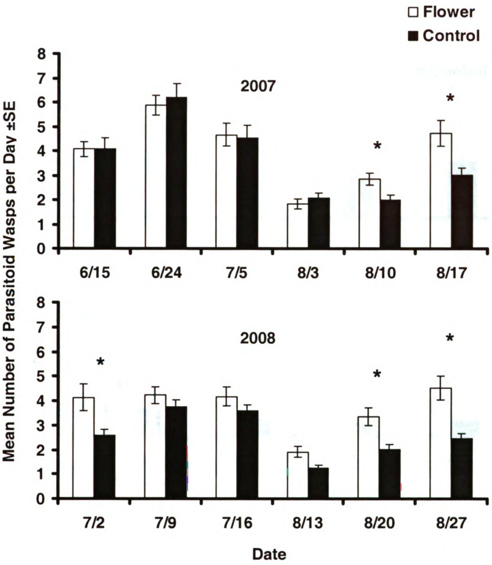

Figure 3.8. Parasitoid wasp abundance in fields adjacent to flower strips or control perimeters through 2007 and 2008. Data shown are averaged across all sampling distances (n=4) and farms (n=4). Asterisks indicate a significant treatment*week interaction, which indicates that the differences shown were significant for that date (α=0.05).

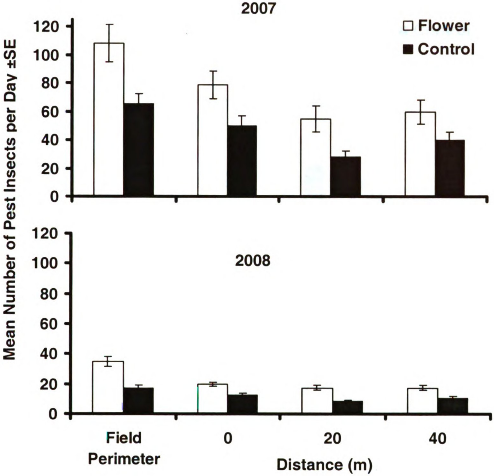

Figure 3.9. Mean pest insect abundance in field perimeters and at different distances into blueberry fields adjacent to flower strips and control perimeters. Data shown are averaged across all sampling dates (n=6) and farms (n=4).

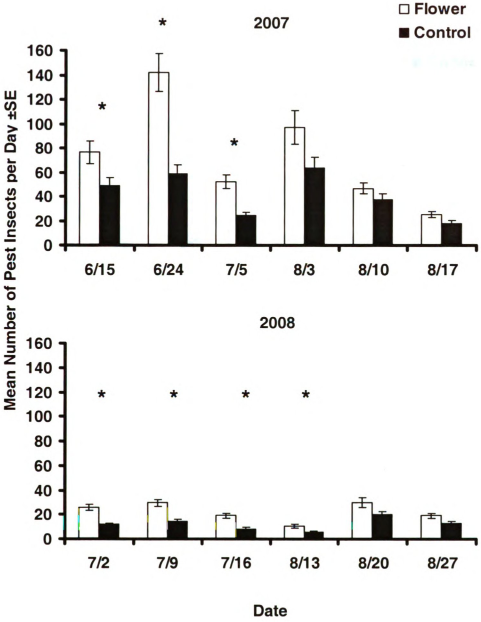

Figure 3.10. Mean pest insect abundance in fields adjacent to flower strips or control perimeters through 2007 and 2008. Data shown are averaged across all sampling distances (n=4) and farms (n=4). Asterisks indicate a significant treatment*week interaction (α=0.05).

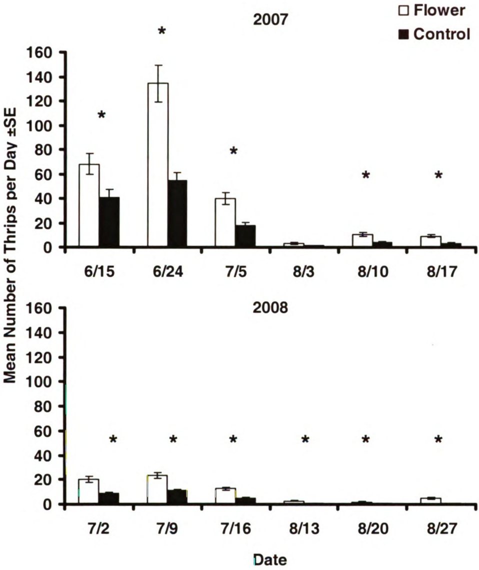

Figure 3.11. Mean thrips abundance in fields adjacent to flower strips or control perimeters through 2007 and 2008. Data shown averaged across all sampling distances (n=4) and farms (n=4). Asterisks indicate a significant treatment*week interaction (α=0.05).

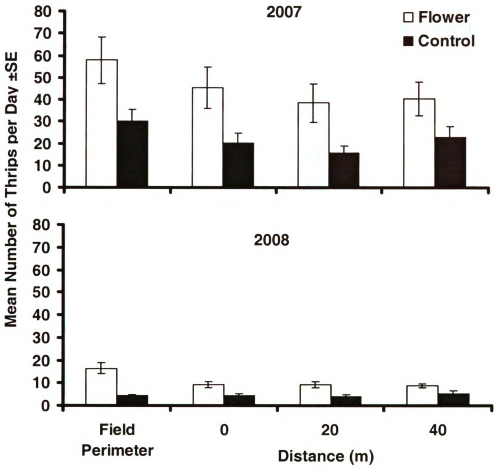

Figure 3.12. Mean thrips abundance in field perimeters and at different distances into blueberry fields adjacent to flower strips and control perimeters. Data shown are averaged across all sampling dates (n=6) and farms (n=4).

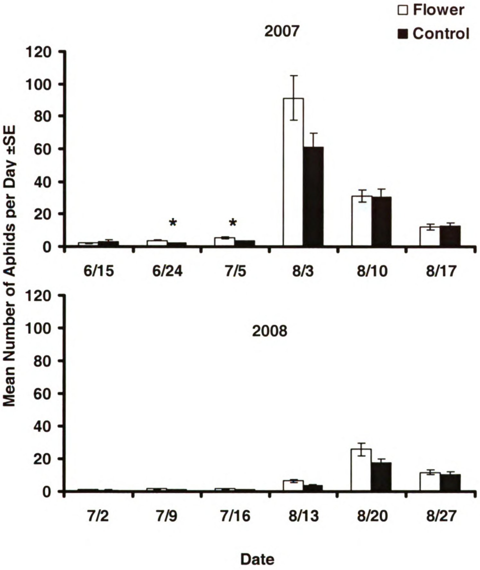

Figure 3.13. Mean aphid abundance in fields adjacent to flower strips or control perimeters through 2007 and 2008. Data shown are averaged across all sampling distances (n=4) and farms (n=4). Asterisks indicate a significant treatment*week interaction (α=0.05).

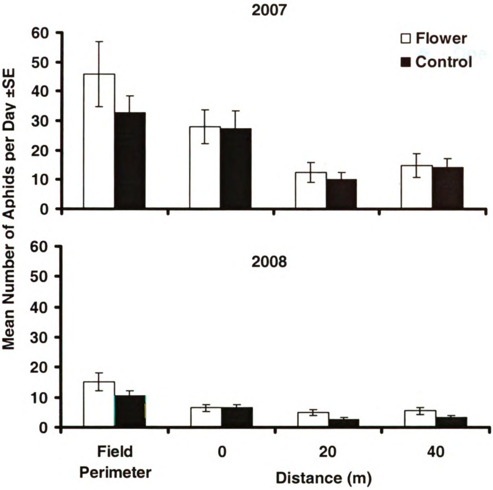

Figure 3.14. Mean aphid abundance in field perimeters and at different distances into blueberry fields adjacent to flower strips and control perimeters. Data shown are averaged across all sampling dates (n=6) and farms (n=4).

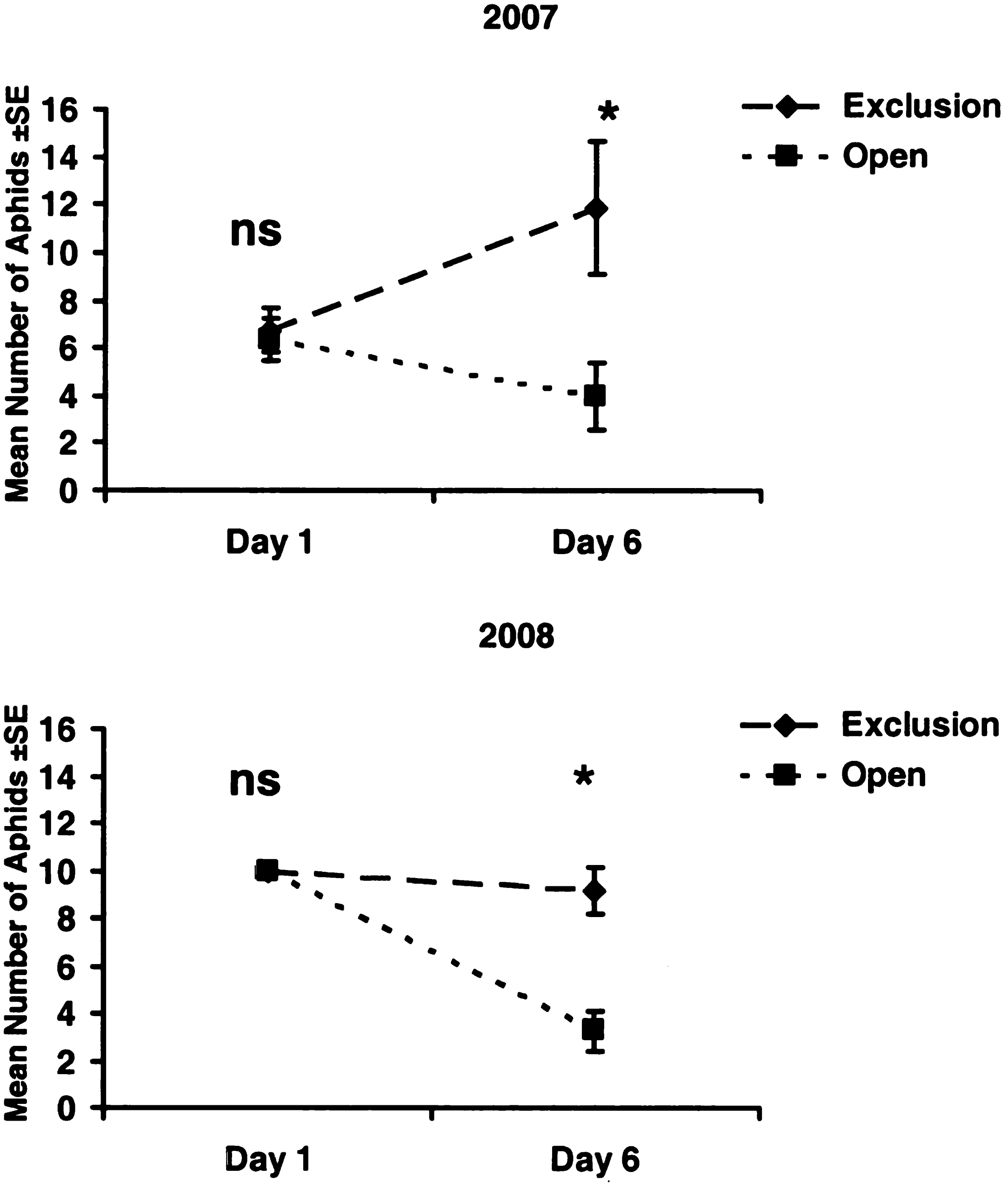

Figure 3.15. The average number of aphids on blueberry shoots with predators excluded (Exclusion) or not excluded (Open) in 2007 (n=16) and 2008 (n=32). *The effect of treatment (exclusion vs. Open) was not significant (ns) on the first day of the experiment, but was significant on Day 6 in both years (α=0.05).

Discussion. This study shows a consistent two-year impact of native perennial flowering plant strips on natural enemy abundance in adjacent commercial blueberry fields (Figs. 3.6-3.8). Overall, these results agree with a number of other studies showing that the introduction of flowering plants in an agricultural setting where they had not been before leads to an increase in arthropod natural enemy abundance (White et al. 1995, Hickman and Wratten 1996, Wyss 1996, Long et al. 1998, Pfiffner and Wyss 2004, Lee and Heimpel 2005, Rebek et al. 2005). This is not surprising given what is known about insects and their use of floral resources (see Chapter 2).

Of course, flowering plant strips can have an impact on a number of herbivorous groups of insects as well (Figs. 3.9 – 3.14) (Wyss 1996, Norris and Kogan 2005). The two most abundant and potentially pestiferous groups in blueberry, thrips and aphids, both showed substantial declines in abundance from 2007 to 2008 (Table 3.2, Figs. 3.11 – 3.14). Whether this was due to predation, parasitism, or abiotic factors cannot be determined from these data, but this trend is certainly contrary to the hypothesis that pests would benefit from the presence of the flowering plant strips.

Similarly, a decrease was seen in total abundance of natural enemies between the two years (Table 3.2). However, the magnitude of the decrease was lower for natural enemies than for pests between the two years. For example, parasitoid wasp abundance was 34% lower in 2008 than 2007, whereas thrips and aphid abundances declined by 81% and 74% from 2007 to 2008, respectively (Table 3.2). This is consistent with a hypothesis that whatever factors contributed to declines in pest abundance between years, the effect of these same factors on natural enemies was mitigated by the presence of the flowering plant strips.

The abundance data presented in this chapter can also be interpreted as a measurement of the activity density of the different insect groups at different times of the year and at increasing distances from the field perimeters (Greenslade 1964, Horton and Lewis 1997). In other words a higher abundance on sticky cards at a particular sampling distance can also be interpreted as a higher activity and/or density at that distance.

The hypothesis that the flowering plant strips would pull beneficial insects out of the field was not supported by this data. As indicated by the significant distance effect, natural enemies had a higher activity density in field perimeters than field interiors (Fig. 3.5). However, there was no significant distance by treatment interaction, which means that the increased activity density observed in field perimeters was due to factors other than the presence of a flowering plant strip.

The hypothesis that the flowering plant strips would buffer natural enemies from the effects of insecticide use in the crop was supported by late season differences between the abundance of natural enemies in control and flower fields (Fig. 3.6). Blueberry harvest across the study region in West Michigan generally lasts from mid-July to mid-August, and is a period of intensive broad-spectrum insecticide and fungicide use (Isaacs and Mason 2008). The observed decrease in natural enemy abundance between early July and August in both years is likely related to these disturbances in crop fields at this time (Fig. 3.6). However, the late season recovery of natural enemies following harvest in both years was disproportionately faster and of a greater magnitude in fields adjacent to flowering plant strips (Fig. 3.6). The presence of alternative hosts and nutritional resources in the flowering plant strips may have facilitated this rebound in activity density of natural enemies following disturbance, which has also been reported for carabids in corn planted with refuge strips (Lee et al. 2001).

The results of the aphid predator exclusion experiment also provide evidence that pests will not be benefited by the presence of flowering plant strips (Fig. 3.15). Although the direct cause of the observed decrease in aphid populations on the open shoots cannot be inconclusively determined it was likely due to the activity of predatory insects (Costamagna and Landis 2006, Costamagna et al. 2008). The lack of a significant effect of field perimeter on aphid numbers on these experimental plants means that the observed decrease was not affected by the presence of a flowering plant strip. This can be interpreted as meaning that the flowering plant strips did not increase aphid predation, that the presence of a flowering plant strip did not decrease aphid predation, or that the flowering plant strips increased aphid predation but had an effect beyond the scale of the experiment. Unfortunately, the most likely of these alternatives cannot be determined without further experimentation.

Recent studies investigating landscape effects on arthropod conservation and biological control have emphasized the importance of the surrounding landscape (e.g. scale greater than 1km) on the success of habitat management projects (Tscharntke et al. 2005, Tscharntke et al. 2007). Landscape ecology theory predicts that habitat management schemes aimed at increasing biodiversity will have varying success in different landscape contexts, because different species experience the landscape at different scales depending on their dispersal ability and behavior (Tscharntke et al. 2005). These studies have also focused on larger organisms that are more likely to be impacted at these scales e.g.(Gardiner et al. 2009) and/or have focused on biodiversity as a measure of success (Tscharntke et al. 2007).

We did not quantify the landscape features surrounding our study sites, but the lansdscape context may have been important. The west Michigan landscape where this study was undertaken is a matrix of blueberry dominated agricultural fields, forest, wetland, and urban or residential development. However, this study focused on abundance rather than diversity, which may be more affected by local factors such as the presence of a flower planting (Wyss 1996). Diversity depends largely on the number of species available in the regional species pool (Letourneau and Bothwell 2008), and as such is inherently less likely to be affected within the spatial and temporal scale of this study. Abundance, on the other hand, is more a measure of attractiveness or suitability of resources and as such is more likely to show a short-term impact of an influx of resources at a local scale.

For long-term conservation goals, attracting natural enemies in greater abundance to agricultural fields may be just as important as increasing diversity.

For example, in a review of the response of farmland biodiversity to set-aside schemes in the United States and North America, compelling evidence was found for increases in farm biodiversity in the presence of set-aside areas that provide non-sprayed, non-tilled areas for flowering plants (Van Buskirk and Willi 2004). Yet there still seems to be a lack of information supporting the hypothesis that increased biodiversity leads to increased biological control (Norris and Kogan 2005, Tscharntke et al. 2007, Letourneau and Bothwell 2008).

In the absence of a direct relationship between biodiversity and biocontrol, farmers are less likely to invest in biodiversity conservation. Alternatively, if a direct connection between local natural enemy abundance and pest control can be made, then growers will be more likely to implement habitat management strategies and reduce use of broad spectrum insecticides. Ultimately, this will lead to an increase in the quality of farmland as habitat for a variety of species of conservation importance.

CHAPTER 4

Native perennial flowering plant strips as a means of conserving pollinators to benefit nearby agricultural fields

Introduction. At least 20% of global food production comes from crops that rely on animal pollination, while another 15% of global crops rely on pollinators for seed production (Klein et al. 2007). The majority of this pollination is done by bees, especially European honey bees (*Apis mellifera*), but other bee species contribute substantially (James and Pitts-Singer 2008, Winfree et al. 2008b). A number of reports have raised concerns about the status of the world's insect pollinators as agricultural intensification rises to feed the world's growing population (National Research Council 2007, Kluser and Peduzzi 2007). This has spurred the proliferation of websites, research articles, and popular media stories covering pollinators and pollinator conservation strategies (Biesmeijer et al. 2006, Strickler 2007, Aizen et al. 2008, Raver 2008).

Agricultural lands act as both consumers and suppliers of pollination as an ecosystem service (Swinton et al. 2007, Kroeger and Casey 2007, Zhang et al. 2007) and as such they represent an ideal target for pollinator conservation programs. Government funding programs have been developed to help farmers provide conservation land on their farms, termed agri-environment schemes, as a means of reaching conservation targets and motivating land conservation within intensively managed landscapes (Kleijn et al. 2006). Agri-environment schemes aimed at providing different environmental benefits often lead to increases in the abundance or diversity of pollinating insects (Carvell et al. 2004, Kleijn et al. 2004, Van Buskirk and Willi 2004). As more detailed ecological information becomes available about the impacts of different schemes on pollinators in agricultural lands they could be modified to provide more diverse environmental benefits at a lower cost (Kremen 2005, Swinton et al. 2007).

Using perennial native plants is one strategy that can help to reduce the long-term costs of managing such resources (Pfiffner and Wyss 2004, Fiedler and Landis 2007a, Isaacs et al. 2009). Native plants have a number of advantages over exotics in that they are less likely to become invasive, better adapted to the local soil and climate conditions, and less likely to benefit exotic pests (Fiedler and Landis 2007a, Tuell et al. 2008, Isaacs et al. 2009). In addition, perennial native plantings provide a stable habitat that benefits nesting bees and other overwintering beneficial insects (Long et al. 1998, Svensson et al. 2000, Marshall and Moonen 2002, Carvell et al. 2006a). Of course, careful evaluation of any habitat management program is necessary before it is recommended for widespread use in an agri-environment scheme (Carvell et al. 2006a).

Agri-environment schemes may require farmers to withhold production on some of their land, so they are more likely to be adopted if there is a measurable benefit in terms of increased yield or decreased costs (Morandin and Winston 2006). Schemes that target wild native pollinators have the potential to provide this type of benefit by increasing pollination evenness within fields or by reducing the variation in pollination among years due to inclement weather conditions

(Chagnon et al. 1993, Morandin and Winston 2006, Kremen 2008). Thus while pollinator dependent crops can rarely achieve profitable yields in the absence of commercial honey bee colonies (but see (Kremen et al. 2002, Winfree et al. 2008a), wild pollinators can supplement the pollination services provided by honey bees, which may help offset the cost of establishing a habitat management scheme (Morandin and Winston 2006).

Native bees are more abundant in landscapes with a higher proportion of natural habitat where they can find the resources they need to maintain stable populations (Ricketts 2004, Kremen 2008). These resources are primarily food (nectar and pollen), nesting sites, and nesting materials (Kremen 2008). Habitat management for bee conservation aims to provide these resources on the farm, outside of insecticide treated areas, but near enough to allow pollinators to access the crop during bloom (MacKenzie 2009). This may simply mean mowing less frequently to allow wild vegetation to regenerate, planting supplemental flowers, providing artificial nest cavities, or some combination of these and other habitat manipulations (Batra 2001).

Of course, bees respond to the landscape at different scales depending on their foraging range and degree of eusociality (Greenleaf et al. 2007). This means that successful pollinator habitat management programs must consider the landscape context, the biology, and the behavior of the target pollinators when designing a conservation scheme. For example, there is some evidence that in homogenous landscapes dominated by agriculture, extensive habitat restoration would be required to rebuild local native pollinator populations

(Kremen 2008, Isaacs et al. 2009). Alternatively, in heterogenous landscapes, growers may be able to invest relatively little in a habitat management strategy that would provide the desired returns as pollinators colonize the farm from the surrounding natural habitats (Holzschuh et al. 2008, Winfree et al. 2008a).

This chapter examines the impact of conservation strips of native flowering plants on the wild native bee community in commercial highbush blueberry fields and the effect that this has on pollination and yield. Most cultivars of highbush blueberry (Ericaceae: *Vaccinium corymbosum* L.) are self-fertile and exhibit varying degrees of parthenocarpy (MacKenzie 1997). However, all cultivars, even parthenocarpic and self-fertile cultivars have increased berry weights and earlier ripening berries when they are hand cross pollinated or insect pollinated (MacKenzie 1997, Dogterom et al. 2000). In the field, blueberry pollination is primarily insect mediated, because the flower morphology prevents transfer of pollen from anther to stigma on the same flower (Gough 1991).

Blueberry flowers are most effectively pollinated by bumble bees (*Bombus spp.*) and ground nesting bees (*Andrena spp.*) on a per visit basis (Dogterom 1999, Javorek et al. 2002), but most growers continue to rent honey bee colonies because it is more efficient economically (Dogterom 1999, MacKenzie 2009). Still, wild native bees provide a cost free contribution to pollination of blueberry flowers, and if this contribution can be increased through habitat management in and around the farm at a low cost-benefit ratio then uptake of conservation practices will increase (Morandin and Winston 2006, Zhang et al. 2007).

The aim of this study was to determine the effectiveness of native perennial flower strips in supporting local populations of native bees that would in turn provide a measurable pollination service to adjacent blueberry fields. The following predictions were tested: (1) More native bees will be found in fields bordered by a native flower strip compared to fields with a mown grass border, (2) native bee populations will increase from one year to the next as subsequent generations benefit from the resources provided by the native flower strip, and (3) an increase in the local populations of native bees will lead to an increase in blueberry pollination when commercial honey bees are excluded.

Materials and Methods: Flowering Plant Strips. Nine species of native flowering plants that rated highly for attraction of beneficial arthropods and bloom at different times of the season (Fiedler and Landis 2007a, Fiedler and Landis 2007b, Tuell et al. 2008), plus one native grass control (Table 3.1) were planted as plugs (one-year-old plants) in spring 2006 at four commercial blueberry farms in Van Buren (2 farms) and Ottawa (2 farms) counties. Each plot was planted with 20 plants of each species, supplied by WildType nurseries (Mason, Michigan). Each species was replicated three times within each strip in 2 x 2 m plots, in a randomized complete block design (Fig. 3.1), to create a 60 x 2 m strip of flowering plants (Fig. 3.1).

At each farm, two fields were selected, so that at each farm one field was adjacent to a flower strip (flower) and one was adjacent to a typical mown field border (control) (Fig. 4.1). These paired fields (flower and control) on each farm were selected so that each sampling point within a field would be at least 120m from any sampling point in the other field. This distance was chosen based on literature estimates for the maximum foraging range of solitary bees (Gathmann and Tscharntke 2002, Greenleaf et al. 2007). The flower strips were separated from the crop by a narrow mown drive lane (Fig. 4.1).

Bee visits to blueberry flowers. Bees were counted during the two weeks of peak blueberry bloom (May 14-28, 2007, and May 16 – June 4, 2008). Samples were taken on days when the temperature was over 12°C and it was not raining. The average temperature (±SE) during bee counts was 24°C (±0.20) in 2007 and 17°C (±0.15) in 2008. Bees were counted while standing between rows along three transects extending from the field edge to 40 meters into the field (see Fig. 4.1). All bees making legitimate visits to blueberry flowers were counted and identified to family or genus on the wing when possible. A legitimate visit was defined as a visit in which the bee's head or thorax made contact with the stigma of the blueberry flower. Bees were counted for five minute intervals at each sampling position (Fig. 4.1). In both years, 4 counts were taken on different days at each sampling position to give a total of 36 samples per field at a total of 8 fields. During each count the ambient temperature was recorded using a weather meter (Kestrel 2500, Nielsen-Kellerman Company) placed in the shade at a height of 0.5m.

Yield Measurements: Field Bushes. The contribution of bees to blueberry yield was assessed using mesh bags to exclude pollinators in flower and control fields. Bags were constructed from nylon mesh (hole size <1mm) held on to the bush with wire twist ties. Bushes used for pollinator exclusion treatments were haphazardly selected from those at each sampling position (Fig. 4.1, 0, 20, and 40m) along each transect so that 9 bushes per field were sampled. On each selected bush one cluster received a mesh bag and one cluster was left open to pollinators. Only clusters with no open flowers were selected, and at the time of bagging all unopened flowers were counted.

At the end of the bloom period, (i.e. when all flowers had shed their corollas), all clusters were bagged and the number of immature berries in each cluster was counted to determine proportion fruit set. Clusters were harvested when approximately half of the berries in the cluster had ripened. At the time of harvest, each cluster was placed in a plastic bag and transported to the laboratory for measurement of yield parameters.

The total weight of all the berries and the weight of the heaviest berry in each cluster were measured on a digital balance (AE50, Mettler-Toledo International Inc.). The number of berries in each cluster was counted and the heaviest berry was squashed to allow the number of seeds to be counted. Seeds were divided into two categories, mature and immature, based on their size and coloration. Thus, the number of mature and immature seeds in the heaviest berry in each cluster was determined.

Potted Bushes. In an order to exclude commercial honeybees and measure pollination by native bees exclusively, pollination on blueberry bushes was measured at the flower and control fields in each site before the growers placed commercial honey bee hives in their fields. This was accomplished by placing 2-year-old potted 'Bluecrop' bushes in the greenhouse in early spring to induce premature bloom. These plants were then placed in and removed from the four fields before the growers brought in commercial beehives. Potted bushes were in the field for 6 days in 2007 and 3 days in 2008. These plants were placed in the fields along the same transects and at the same positions described above for field bushes in 2007 to provide 3 bushes per field at each of the 3 sampling distances (Fig. 4.1). In 2008, pots were only placed at the 0m and 40m positions, but another transect was added, to provide 4 bushes per field at each of the 2 sampling distances. Yield parameters were measured on potted bushes using the same procedures described above.

Statistical analysis: Bee Counts. Native bee count data did not meet the assumption of normality for either year and transformation did not improve the fit of the model (PROC MIXED, SAS Institute 2003), so means were compared via the Mann-Whitney U-test (PROC NPAR1WAY, SAS Institute 2003). Honey bee data were analyzed using repeated measures ANOVA (PROC MIXED, SAS Institute 2003). The full model included farm as a random variable, and treatment (flower vs. control), distance, year and all possible interactions as fixed effects. Year was specified as the repeated measure effect with the transect by distance interaction as the subject (nested within farm by treatment by distance) and a compound symmetry covariance structure.

Field Bushes. Analysis of yield measurements on field bushes was performed by repeated measures ANOVA (PROC MIXED, SAS Institute, 2003). The full model included farm as a random variable, and treatment (flower vs. control), distance, year and all possible interactions as fixed effects. Year was specified as the repeated measure effect with the transect by distance interaction as the subject (nested within farm by treatment by distance) and a compound symmetry covariance structure.

Potted Bushes. Data from the two years from potted bushes were analyzed separately. Average berry weight was calculated by dividing the weight of each cluster by the number of berries in that cluster. For comparison of average berry weight on potted bushes between flower and control fields, only those clusters that were left open to pollinators were included in the analysis. Average berry weight and proportion fruit set data were analyzed by ANOVA (PROC MIXED, SAS Institute 2003). The main effect of distance and its interactions did not contribute significantly to the model ($\alpha=0.05$), so it was not included in subsequent analyses. The contribution of native bees to average berry weight was compared between flower and control fields by finding the difference between the mean average berry weight in clusters left open to pollinators and those from which pollinators were excluded (PROC MIXED, SAS Institute 2003).

Untransformed data for pollinator-excluded clusters from 2007 did not meet the assumption of normality, so 2007 average berry weights were square root (x+0.375) transformed prior to analysis (Kuehl 2000).

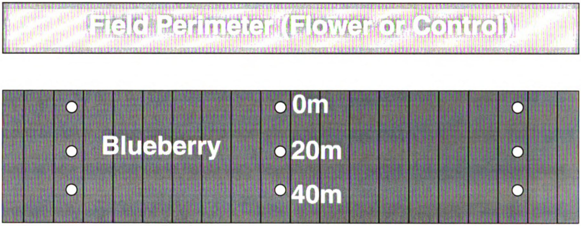

Figure 4.1. Diagram of a field site showing the locations (white circles) along transects where bee counts were performed, where pollinator exclusion bags were placed, and where potted blueberry bushes were place with respect to the wildflower conservation strips or control perimeters (not to scale).

Results: Native Bee Counts. Native bees observed pollinating blueberry flowers were primarily soil-nesting bees (Andrenidae, Halictidae), although bumble bees (*Bombus* spp.) and cavity-nesting bees (Megachilidae) were also observed. In a total of 576 samples (288 per year), an average (±SE) of 0.26 native bees (±0.02) per 5 minute sample were counted (Fig. 4.2). In 2007, an average (±SE) of 0.39 (±0.06) and 0.22 (±0.04) native bees per 5 minute sample were counted in flower and control fields, respectively. In 2008, there was an average (±SE) of 0.26 (±0.05) and 0.15(±0.04) native bees per 5 minute sample in flower and control fields, respectively. The non-parametric analysis revealed that the higher native bee abundance in fields with flowering plant strips during both years was statistically significant (Fig. 4.2, X^2=3.88; df=1; P=0.052 in 2007; X^2=4.54; df=1; P=0.033; in 2008).

Honey Bee Counts. The mixed model analysis of honey bee activity on blueberry bushes revealed a significant effect of year (F=111.70 df=1,114 P<0.0001) and the year by treatment interaction (F=9.22 df=1,114 P=0.003). There were more honey bees (mean bees/minute ±SE) counted in 2007 (1.84±0.06) than 2008 (0.94± 0.06) (t=10.57 df=114 P<0.0001) and in fields near flower strips in 2008 (Flower: 1.10±0.11 Control: 0.78±0.06; t=2.75 df=114 P=0.007). Further analysis, with temperature as the response variable revealed that temperature (°C±SE) measured during bee samples was significantly higher in 2007 (24.0±0.20) than 2008 (16.8±0.15) (t=29.70 df=114 P<0.0001), but was not different between treatments (treatment effect, F=1.82 df=1, 3 P=0.27). Also, when temperature was included as a covariate in the model with honey bees per minute as the response variable, the effect of year on honey bee abundance was no longer significant (F=1.99 df=1,113 P=0.16). This indicates that temperature was the main factor determining interannual differences in honey bee activity on blueberry bushes in these fields.

Yield on Field Bushes. The mixed model ANOVA using yield data from field bushes revealed no significant effect of year, treatment, or distance on average berry weight (year, F=3.78 df=1, 114 P=0.054; treatment, F=0.05 df=1, 3 P=0.83; distance, F=1.49 df=2, 12 P=0.27). Proportion fruit set on field bushes was significantly affected by year, but none of the other explanatory variables (year, F=9.21 df=1, 114 P=0.003; treatment, F=0.16 df=1, 3 P=0.71; distance, F=0.05 df=2, 12 P=0.94). Weight of the largest berry was also significantly affected by year but none of other explanatory variables (year, F=15.03 df=1, 114 P=0.0002; treatment, F=2.04 df=1, 3 P=0.25; distance, F=0.49 df=2, 12 P=0.63). The number of large seeds in the largest berry was significantly affected by year but by none of the other variables (year, F=5.43 df=1, 114 P=0.022; treatment, F=0.36 df=1, 3 P=0.59; distance, F=0.27 df=2, 12 P=0.76). This likely reflects the importance on the presence of large numbers of commercial honey bee hives placed in the field during bloom, because when honey bee numbers were lower in 2008 the yield measurements on field bushes were also lower.

Yield on Potted Bushes. Average berry weight on the potted blueberry plants was statistically indistinguishable between the flower and control fields in both years. In 2007, average berry weight (±SE) was 0.65 g (±0.08) in fields with flower strips and 0.65 g (± 0.07) in control fields (Fig. 4.3). In 2008, average berry weight was 0.49 g (± 0.05) in fields with flower strips and 0.48 g (± 0.06) in control fields (Fig. 4.3). Proportion fruit set was also the same between the potted bushes in the two types of fields in both years (Fig. 4.4). In 2007, average proportion fruit set was 0.29 (± 0.05) in fields with flower strips and 0.34 (± 0.08) in control fields. In 2008, average proportion fruit set was 0.41 (± 0.04) in fields with flower strips and 0.40 (± 0.05) in control fields (Fig. 4.5).

In 2007, the average difference in berry weight between bagged and open clusters on potted bushes was 0.22 g (± 0.04) ($t=6.09$; $df=1,141$; $P< 0.001$) and in 2008 the average difference was 0.11 g (±0.05) ($t=2.14$; $df=1,95$; $P=0.035$) (Fig. 4.5). These differences, because they were measured on potted plants in the field before commercial honey bee hives had been brought in, can be attributed to pollination by indigenous pollinators (Fig. 4.5).

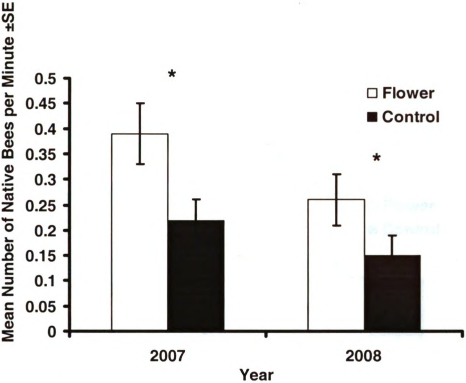

Figure 4.2. Native bees counted visiting blueberry flowers in fields with flowering plant strips (Flower) and fields without flowering plant strips (Control). Asterisks indicate that means for that year are significantly different (α = 0.05).

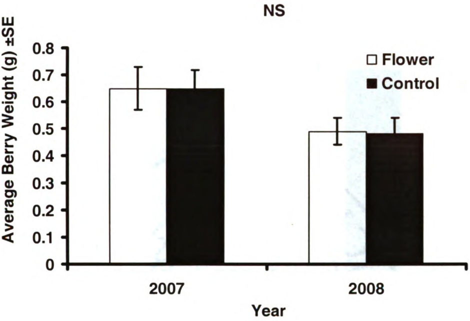

Figure 4.3. Average berry weight (g) in fields with flowering plant strips (Flower) and fields without flowering plant strips (Control). Means within years are not significantly different at the α=0.05 level (NS).

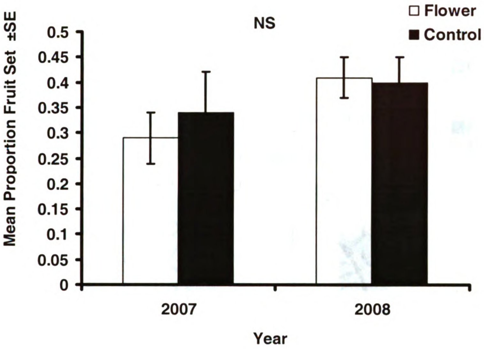

Figure 4.4. Proportion fruit set on potted blueberry plants placed in fields with flowering plant strips (Flower) and in fields without flowering plant strips (Control). Means within years are not significantly different at the α=0.05 level (NS).

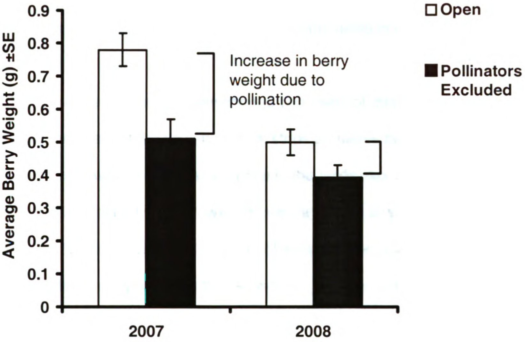

Figure 4.5. Average berry weight on potted blueberry bushes for 2007 and 2008, and the amount of this weight that can be attributed to pollination by native bees (increase in berry weight due to pollination).

Discussion. Fields of blueberry with a flowering plant strip in the perimeter had higher abundance of native bees visiting crop flowers during bloom than fields without this resource (Fig. 4.2). Native bees successfully pollinated blueberry flowers on potted plants in all of the study fields during both years (Figs. 4.3 - 4.5), but this did not translate into measurable differences in pollination or yield between fields with flowering plant strips and control fields in either year (Figs. 4.3 and 4.4).

Temperature differences between the two years of this study likely confounded the effect of the flowering plant strips on native bee abundance. Even honey bees, whose actual abundance in the fields was determined by the stocking density chosen by the grower, showed a decline in activity on blueberry bushes in 2008. This overwhelming effect of temperature essentially made it impossible to test the hypotheses that an increase in floral resources would lead to an interannual increase in native bee abundance and that this in turn would lead to increased blueberry pollination in the absence of honey bees.

Nonetheless, wild bees are important blueberry pollinators (Javorek et al. 2002, Tuell 2007, MacKenzie 2009, Tuell et al. 2009) and this is reflected in the fact that potted bushes placed in the field were pollinated in the absence of commercial honey bee hives (Fig. 4.5). The flowering plant strips in this study were designed to increase bee populations mainly by providing pollen and nectar from the period following blueberry bloom into the late summer. This was expected to primarily benefit social bees (e.g. bumble bees) and solitary bees that might suffer from a lack of food resources immediately following blueberry bloom. However, this habitat management approach did not manipulate other aspects of the blueberry agroecosystem such as nesting habitat for soil nesting bees, which may have been important.

The most abundant native bees in Michigan blueberry fields are primarily soil nesting bees in the families Halictidae and Andrenidae (Tuell et al. 2009). Of these, the most important for blueberry pollination is *Andrena carolina* Viereck, a specialist on ericaceous plants (Tuell 2007, Tuell et al. 2009). Thus, depending on the degree of specialization, providing non-ericaceous floral resources near blueberry fields may not affect populations of this bee and its close relatives. This is certainly consistent with the results showing no interannual effect of the flower strips on native bee abundance during bloom or on pollination by this group (Figs. 4.3-4.5). Manipulation of the habitat in blueberry fields by providing nesting resources (e.g. undisturbed bare soil) would have had a more direct impact on populations of these bees (Shuler et al. 2005).

Bumble bees (*Bombus spp.*) are also effective blueberry pollinators (Javorek et al. 2002, MacKenzie 2009, Rao et al. 2009), and because of their phenology were expected to benefit from the season-long foraging resources provided by the flowering plant strips. Bumble bee queens were significant contributors to the pollinator abundance on blueberry flowers (Fig. 4.2, N. Walton, pers. obs.).

In this case the inability to measure the effect of the flower strips in terms of pollination may have been related to the scale of the study. The paired fields (flower and control) on each farm were selected so that each sampling point would be at least 120m from any sampling point in the other field. This was based on literature estimates for the maximum foraging range of solitary bees (Gathmann and Tscharntke 2002, Greenleaf et al. 2007). However, bumble bees frequently forage at scales up to 1.5km from their nests (Osborne et al. 2008) and even small solitary bees can forage beyond these distances (Beil et al. 2008). Thus, the effect of increased wild bee abundance (Fig. 4.2) was not measured in the potted plant experiment because wild bees were probably able to travel freely between the paired treatment fields, which resulted in equivalent pollination levels between fields (Figs. 4.3 and 4.4).

In conclusion, native bees in agricultural fields during bloom are not likely to be limited by flower resources in the absence of exploitative competition with *A. mellifera* (Butz Huryn 1997, Westphal et al. 2003, Goulson 2003). Thus for bees that are highly specialized to a particular crop, manipulation of other resources (nesting sites) may be more effective for increasing local abundances (Delaplane and Mayer 2000, Batra 2001, Holzschuh et al. 2008). More generalist bees on the other hand benefit from a flower planting that provides resources throughout the season, but the effect of this on pollination needs to be measured at a larger scale.

CHAPTER 5

Multi-function habitat management: conclusions and future research.

Introduction. One of the basic tenets of integrated pest management (IPM) is that conservation of natural enemies through cultural practices or use of selective pesticides will reduce the long term cost of insect pest control. This concept can be extended to include wild pollinators in crops that depend on costly importation of rented honey bee colonies. Thus, a strategy such as habitat management using flowering plants outside of the crop field integrates pest management and pollinator management to maximize the benefit to the farmer.

In addition to benefiting the farmer, increasing the proportion of natural habitat in agricultural fields, provides diverse benefits to society as a whole (Gurr et al. 2003, Olson and Wäckers 2007). This understanding has led to increasing incentives to farmers for conserving or creating these habitats on the farm either through government subsidies or societal pressure. For example in the U.S., a new Farm Services Agency (FSA) program introduced in January of 2008 State Acres for Wildlife Enhancement (CRP-SAFE) provides cost-sharing, rental payments, and implementation incentives to landowners who undertake practices to restore habitats that benefit high priority species conservation. This program and others like it are making the establishment of native perennial flowering plant strips on the farm more economically attractive.

However, many farmers are naturally risk-averse and unlikely to abandon time-tested practices in favor of innovation (Pannell 1999). This thesis evaluated what is essentially a new agricultural technology; incorporating flowering plants into the field border to enhance natural control and natural pollination. The goal was to demonstrate to growers that increased floral resources would increase beneficial insect populations without increasing pest insect populations in blueberry fields.

The results of this two-year agroecological experiment were generally consistent with this goal. Representative groups of herbivorous insects did not increase from 2007 to 2008, and pests specific to blueberry appeared to be unaffected by the presence of flowering plant strips. Of course, the yellow sticky traps may have undersampled these groups, and a more selective trap may have yielded different results (Horton and Lewis 1997, Hoelmer et al. 1998). In other crops, this strategy should be tested, but implemented cautiously. Crops that are more impacted by generalist pests might be more heavily impacted by certain groups of herbivores that showed an affinity for the flowering plant strips (e.g. Miridae, Table 3.3) (Norris and Kogan 2000, Norris and Kogan 2005, Snodgrass et al. 2006, Olson and Wäckers 2007).

Future Research. The spatial and temporal scale of this study made it difficult to measure an effect on pollination, but this study did show a higher density of foraging native bees in fields near flowering plant strips. Future investigations of this habitat management approach for native bees should include soil-nesting bee habitat manipulation and measure pollination trends over larger spatial and temporal scales. Other non-lethal methods for recording rare but important native bee pollination events should also be investigated (e.g. digital video) because of the time investment required for direct human observation in the field.

A similar issue of scale was encountered when attempts were made to measure aphid mortality in relation to the flowering plant strips (Fig. 3.15). No significant difference was found between the two field types (flowers vs. control), presumably because highly mobile predators such as ladybeetles were the primary inflictors of mortality (Costamagna et al. 2008). Future studies of this type should be carried out to measure parasitism only, for example by excluding larger insects. Considering that abundance of parasitoid wasps was consistently higher in fields adjacent to the flower strips (Chapter 3) this effect would have been measurable if predators had been excluded from the experimental plants.

Conclusions. Crop fields supply ecosystem services to the surrounding landscape, but they also supply ecosystem dis-services (Swinton et al. 2007). Conversely, crop fields receive ecosystem services and dis-services from the surrounding landscape (Zhang et al. 2007). Habitat management that utilizes native flowering perennials has the potential to simultaneously increase the ecosystem services and decrease the ecosystem dis-services both to and from agriculture. However, habitat management is not a panacea and it should be incorporated into existing integrated pest and pollinator management programs to maximize the benefit to all concerned parties.

Appendix 1.1

Record of Deposition of Voucher Specimens*

The specimens listed on the following sheet(s) have been deposited in the named museum(s) as samples of those species or other taxa, which were used in this research. Voucher recognition labels bearing the Voucher No. have been attached or included in fluid-preserved specimens.

Voucher No.: 2009-02

Habitat Management using Native Flowering Perennials to Increase Beneficial Insects in Michigan Highbush Blueberry

Museum(s) where deposited and abbreviations for table on following sheets:

Entomology Museum, Michigan State University (MSU)

Other Museums:

Investigator's Name(s) (typed)

Nathaniel J. Walton

Date 15 May 2009

*Reference: Yoshimoto, C. M. 1978. Voucher Specimens for Entomology in North America.
Bull. Entomol. Soc. Amer. 24: 141-42.

Deposit as follows:
Original: Include as Appendix 1 in ribbon copy of thesis or dissertation.

Copies: Include as Appendix 1 in copies of thesis or dissertation.
Museum(s) files.
Research project files.

This form is available from and the Voucher No. is assigned by the Curator, Michigan State University Entomology Museum.

Appendix 1.2

Voucher Specimen Data

Page_1_of_8_Pages

Species or other taxon	Label data for specimens collected or used and deposited	Number of: Eggs	Larvae	Nymphs	Pupae	Adults ♀	Adults ♂	Other	Museum where deposited
Nabidae	Michigan; Ottawa Co., Van Buren St. 1/2 Mi. West of US-31 17-Sep-07							1	MSU
Vespidae	Michigan; Ottawa Co., Van Buren St. 1/2 Mi. West of US-31 19-Mar-07							1	MSU
Miridae	Michigan; Ottawa Co., Van Buren St. 1/2 Mi. West of US-31 17-Sep-07							1	MSU
Aranae	Michigan; Van Buren Co., Pheonix Rd. and 60th St. 18-Sep-07							1	MSU

(Use additional sheets if necessary)

Investigator's Name(s) (typed)

Nathaniel J. Walton

Date 15-May-09

Voucher No. 2009-02

Received the above listed specimens for deposit in the Michigan State University Entomology Museum.

15 MAY 2009

Curator Date

Appendix 1.2

Voucher Specimen Data

Page 4 of 8 Pages

		Number of:							
Species or other taxon	Label data for specimens collected or used and deposited	Eggs	Larvae	Nymphs	Pupae	Adults ♀	Adults ♂	Other	Museum where deposited
Diptera	Michigan; Van Buren Co., CR 376 and 71 1/2 St. 18-Sep-07							1	MSU
Cantharidae	Michigan; Van Buren Co., CR 376 and 71 1/2 St. 18-Sep-07							1	MSU
Coleoptera	Michigan; Van Buren Co., CR 376 and 71 1/2 St. 18-Jul-07							1	MSU
Apis mellifera Linnaeus	Michigan; Van Buren Co., CR 376 and 71 1/2 St. 10-Jul-07							1	MSU

(Use additional sheets if necessary)

Investigator's Name(s) (typed)

Nathaniel J. Walton

Date 15-May-09

Voucher No. 2009-02

Received the above listed specimens for deposit in the Michigan State University Entomology Museum.

Curator Date

Appendix 1.2

Voucher Specimen Data

Page 3 of 8 Pages

		Number of:							
Species or other taxon	Label data for specimens collected or used and deposited	Eggs	Larvae	Nymphs	Pupae	Adults ♀	Adults ♂	Other	Museum where deposited
Lepidoptera	Michigan; Ottawa Co., Port Sheldon St. 1 Mi. West of US-31 9-Jun-07							1	MSU
Pentatomidae	Michigan; Van Buren Co., CR 376 and 71 1/2 St. 18-Jul-07							1	MSU
Neuroptera	Michigan; Van Buren Co., CR 376 and 71 1/2 St. 6-Aug-07							1	MSU
Scarabaeidae	Michigan; Van Buren Co., CR 376 and 71 1/2 St. 10-Jul-07							1	MSU

(Use additional sheets if necessary)

Investigator's Name(s) (typed)

Nathaniel J. Walton

Date 15-May-09

Voucher No. 2009-02

Received the above listed specimens for deposit in the Michigan State University Entomology Museum.

Curator Date

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